FDS+Evac: An Agent Based Fire Evacuation Model

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Summary. In this paper, an evacuation simulation method is presented, which is embedded in a CFD based fire modelling programme. The evacuation programme allows the modelling of high crowd density situations and the interaction between evacuation simulations and state-of-the-art fire simulations. The evacuation process is modelled as a quasi-2D system, where autonomous agents simulating the escaping humans are moving according to equations of motion and decision making processes. The space and time, where the agents are moving, is taken to be continuous, but the building geometry is discretized using fine meshes. The model follows each agent individually and each agent has its own personal properties, like mass, walking velocity, familiar doors, etc. The fire and evacuation calculations interact via the smoke and gas concentrations. A reaction function model is used to select the exit routes. The model is compared to other evacuation simulation models using some test simulations.

1 Introduction

Performance based fire codes allow the use of numerical simulation of fire and evacuation processes to be used to improve fire safety in 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. This paper presents an evacuation simulation method, which is embedded in a Computational Fluid Dynamics (CFD) based fire modelling programme. The state-of-the-art fire simulation environment of Fire Dynamics Simulator (FDS) [1, 2] is used to calculate the development of fire and the existing Smokeview programme [3] is used to visualise the results of the fire and evacuation simulations. The resulting programme, which is capable of simulating evacuation during a fire, is called as FDS+Evac.

In this paper, the major features of the FDS+Evac method are described and some verification and validation results are shown. The predictions of the model are compared to other evacuation models using some relatively

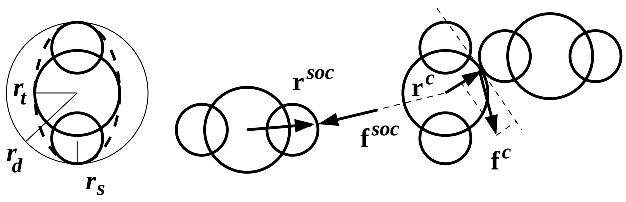

Fig. 1. The shape of a human body is approximated by a combination of three overlapping circles. Shown are also the definitions of the vectors used in the social and contact force calculation.

simple test geometries, which represent some typical egress geometries found on many buildings.

The presented computational tool for evacuation modelling, FDS+Evac, is implemented as a part of the Fire Dynamics Simulator (FDS). FDS+Evac is a subprogram of FDS and, thus, the executable and the source code are obtainable from the FDS (version 5) web page at http://fire.nist.gov/fds/. The documentation of FDS+Evac is found on the web pages of VTT Technical Research Centre of Finland: http://www.vtt.fi/fdsevac/.

2 Method

FDS+Evac follows each person by an equation of motion. This approach allows each person to have his/her own personal properties and escape strategies, *i.e.*, persons are treated as autonomous agents. FDS+Evac allows the modelling of high crowd density situations and the interaction between evacuation simulations and fire simulations. Some social interactions among the agents are introduced in the model and a reaction function model is used to select the exit routes [4].

FDS+Evac treats agents as a combination of three elastic circles moving on a two-dimensional plane. These circles are approximating the elliptical shape of the human body similarly as in the Simulex model [5, 6] and in the MASSEgress model [7], see Fig. 1. Agents experience contact forces and torques as well as psychological and motive forces and torques. The resulting equations of motion for the translational and rotational degrees of freedom are solved using the methods of dissipative particle dynamics [8] on 2D planes representing the floors of a building.

In FDS+Evac method, agents are guided to exit doors by the preferred walking direction vector field, $\mathbf{v}_i^0$, and this field is obtained using the flow solver of FDS. 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

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

door [4, 9]. A field of this kind will always guide agents to the chosen exit door. This route will not be the shortest one, but usually it is quite close to it.

2.1 Movement algorithm

The so called social force method introduced by Helbing's group is used as the starting point of the movement algorithm of FDS+Evac. This model is shortly described below. For a longer description, see the papers by Helbing's group [10–13] and references therein. For the modification of the one-circle representation of an agent to a three-circle one, see the papers by Langston *et al.* [14] and Korhonen *et al.* [15–17]

The movement algorithm of FDS+Evac has many parameters. Some of these are related to the physical description of the agents, like the body size, the mass, the walking speed, and the moment of inertia. Others are the parameters of the chosen movement model, like the parameters of the social force and the contact force. The effect of the different parameters were carefylly analysed and the values of the default parameters were chosen such that the flows through doors and flows in corridors match the experimental findings in the previous papers by the authors [15–17]. Thus, in this paper these default values of the parameters are used in the test simulations.

FDS+Evac uses the laws of mechanics to follow the trajectories of the agents during the calculation. Each agent follows its own equation of motion:

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

where $\mathbf{x}_i(t)$ is the position of the agent i at time t, $\mathbf{f}_i(t)$ is the force exerted on the agent 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 agent, $\mathbf{v}_i(t)$, is given by $d\mathbf{x}_i/dt$.

The force on agent i has many components:

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

where m_i is the mass of agent i, the first sum describes the agent–agent interactions, the sum over w describes agent–wall interactions, and the first term on the right hand side describes the motive force on the evacuating agent. Each agent tries to walk with its 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 an agent to accelerate towards the preferred walking speed and m_i is the mass of the agent. The body sizes, preferred walking speeds, and the parameter τ_i are personalised by choosing them from random distributions. A uniform distribution ranging from 0.8 s to 1.2 s is used for τ_i and the uniform distributions used for the body dimensions and for the walking speeds are shown in Table 1. The mass of a default male is 80 kg and for other agents the mass is obtained by scaling by body size.

The agent–agent interaction force in Eq. 2 has two parts. For the social force term, $\mathbf{f}_{ij}^{soc}$, the anisotropic formula proposed by Helbing *et al.* [12] is used

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

where r_{ij} is the distance between the centres of the circles describing the agents, d_{ij} is the sum of the radii of the circles, and the vector $\mathbf{n}_{ij}$ is the unit vector pointing from agent j to agent i. For a three circle representation of the agents, the circles used in Eq. 3 are those circles of the two agents, which are closest to each other. The angle φ_{ij} is the angle towards agent j measured from the body of agent i. The parameters A_i, B_i describe the strength and spatial extent of the force, respectively. The parameter λ_i controls the anisotropy of the social force. If $\lambda_i = 1$, then the force is symmetric and if it is $0 < \lambda_i < 1$, the force is larger in front of an agent than behind. The parameters A_i, B_i, and λ_i could be different for each agent but in the present version of FDS+Evac they have same values for each agent and their default values are $A_i = 2000\,\mathrm{Max}(0.5, v_i/v_i^0)$ N, $B_i = 0.08$ m, and $\lambda_i = 0.5$. The psychological wall–agent interaction, $\mathbf{f}_{iw}^{soc}$, is treated similarly, but values $A_w = 2000$ N, $B_w = 0.04$ m, and $\lambda_w = 0.2$ are used for the force constants.

The physical contact force between agents, $\mathbf{f}_{ij}^{c}$, is given by

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

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.*, $d_{ij} - r_{ij} \geq 0$. The radial elastic force strength is given by the force constant k and the strength of the frictional force by the force constant κ. Note, that Eq. 4 contains also a physical damping force [14] 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 agents is not an elastic one. The physical wall–agent interaction, $\mathbf{f}_{iw}^c$, is treated similarly and same force constants are used. The 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 agent–agent and for the agent–wall interactions.

Equations 1–4 describe the translational degrees of freedom of the evacuating agents. The rotational degrees of freedom are treated similarly, *i.e.*, each agent has its own rotational equation of motion:

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

where $\varphi_i(t)$ is the angle of the agent 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 agent by its surroundings

$$M_i^z = M_i^c + M_i^{soc} + M_i^\tau \ , \tag{6}$$

where M_i^c, M_i^{soc}, and M_i^τ are the torques of the contact, social and motive forces, respectively. The moment of inertia of a default male agent is $I_i^z =$ 4.0 kg m^2. For other agents, the moment of inertia are obtained by scaling.

The torque of the contact forces is calculated as

$$\mathbf{M}_i^c = \sum_{j \neq i} \left(\mathbf{r}_i^c \times \mathbf{f}_{ij}^c \right) \ , \tag{7}$$

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

$$\mathbf{M}_i^{soc} = \sum_{j \neq i} \left(\mathbf{r}_i^{soc} \times \mathbf{f}_{ij}^{soc} \right) \ , \tag{8}$$

where only the circles, which are closest to each other, are considered. The vector $\mathbf{r}_i^{soc}$ points from the centre of the agent 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

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

where ω_i^0 is the maximum target angular speed of a turning agent, $\omega(t)$ 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. For the angular relaxation time parameter, τ_z, a value of 0.2 s is used. The angular velocity parameter ω_i^0 has a value of 4π s^{-1}.

Note that Langston *et al.* [14] 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 agents to rotate around their axis like harmonic oscillators. This is not desired and, thus, some angular velocity dependent torque is used in FDS+Evac to make the rotational motions of the agents to look more realistic.

2.2 Interaction of the agents and fire

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 agents 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 and to categorise the doors to different preference groups [4].

Smoke reduces the walking speed of humans due to the reduced visibility and its irritating and asphyxiant effects. Recently, Frantzich and Nilsson [18] made experiments on the effect of smoke concentration on the walking speeds of humans. They used larger smoke concentrations than Jin [19] and they fitted the following formula to the experimental values

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

where K_s is the extinction coefficient ($[K_s]$=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 standard deviations are reported to be $\sigma_\alpha = 0.069$ m s^{-1} and $\sigma_\beta = 0.015$ m^{2}s^{-1}, but only the mean values are used in FDS+Evac, *i.e.*, there is no variation between the agents.

The toxic effects of gaseous fire products are treated by using Purser's Fractional Effective Dose (FED) concept [20]. The present version of FDS+Evac uses only the concentrations of the narcotic gases CO, CO_2, and O_2 to calculate the FED value as

$$\mathrm{FED_{tot}} = \mathrm{FED_{CO}} \times \mathrm{HV_{CO_2}} + \mathrm{FED_{O_2}} \tag{11}$$

Note, that the above equation does not contain the effect of HCN, which is also narcotic, and the effect of CO_2 is only due to the hyper-ventilation, *i.e.*, it is assumed that the concentration of CO_2 is such low that it does not have narcotic effects. Carbon dioxide does not have toxic effects at concentrations of up to 5 percent but it stimulates breathing which increases the rate at which the other fire products are inhaled. The fraction of an incapacitating dose of CO is calculated as

$$\mathrm{FED}_{\mathrm{CO}} = 4.607 \cdot 10^{-7} (C_{\mathrm{CO}})^{1.036}\ t\ , \tag{12}$$

where t is time in seconds and C_{CO} is the CO concentration (ppm). The fraction of an incapacitating dose of low O_2 hypoxia is calculated as

$$\mathrm{FED}_{\mathrm{O}_2} = \left\{ 60 \exp\left[8.13 - 0.54(20.9 - C_{\mathrm{O}_2}) \right] \right\}^{-1}\ t\ , \tag{13}$$

where t is time in seconds and C_{O_2} is the O_2 concentration (volume per cent). The carbon dioxide induced hyper-ventilation factor is calculated as

$$\mathrm{HV}_{\mathrm{CO}_2} = 0.141 \exp(0.1930\, C_{\mathrm{CO}_2} + 2.0004)\ , \tag{14}$$

where C_{CO_2} is the CO_2 concentration (percent).

An agent is considered to be incapacitated when the FED value exceeds unity. An incapacitated agent is modelled as an agent, which does not experience any social forces from the other agents and whose target movement speed, v_i^0, is set to zero. The size of an incapacitated agent is not changed, *i.e.*, it remains on its feet. This is a very crude model and it needs to be modified in later versions of FDS+Evac.

3 Results

The presented FDS+Evac method is tested using three different test cases: (A) a large space like a sports hall, (B) a typical open floor office, and (C) a fictitious assembly space. The results of the FDS+Evac simulations are compared to the results of some other evacuation simulation methods. The three test cases are the same ones as was used in the paper by Korhonen *et al.* [9], where the previous version of the FDS+Evac method was introduced. The previous version used only one circle to represent the shape of the agents and it did not have any rotational degrees of freedom.

3.1 Test case A

The first test case is a sports hall, whose geometry is shown in Fig 2. The hall was previously analysed by Paloposki *et al.* [21]. The sports hall is used to practice different kind of sports. 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”), which is 1.8 m wide. 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. It is assumed that a fire starts close to door 3 so that this door cannot be used for egress. 235 persons use the nearest door (“Door 5”), 130 persons use the main entrance (“Door 1”), 60 persons door 2, and 75 persons use

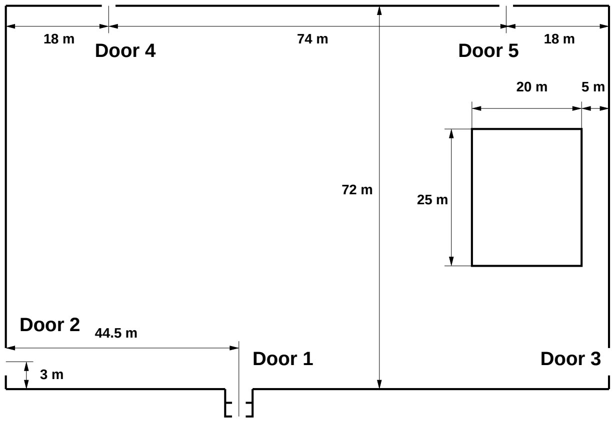

Fig. 2. The geometry of the studied sports hall.

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. 2). The reaction time was modelled by a normal distribution with a standard deviation of 15 s and mean 60 s. The calculations were done also using a much wider distribution for reaction time (log normal) but the results of these calculations are not shown here. This wide reaction time distribution did not produce sizable congestion at the exit doors and, thus, the simulated results merely just reproduced the given input distribution for the reaction time.

The results of the FDS+Evac simulations are compared to Simulex [5, 6] simulations in Fig. 3. Since both FDS+Evac and Simulex are modelling human egress as a stochastic process, the presented results were collected from five different runs per case. The FDS+Evac and Simulex results differ somewhat. The differences arise due to the "Door 5", which is only 0.9 m wide, but through which 235 persons escape. The flow through this door is larger in Simulex than in FDS+Evac. The specific human flow through this door in the FDS+Evac simulations are 1.65 1/p/m. The other doors are not as crowded and there the capacities of the doors do not show up as much.

3.2 Test case B

The second test geometry was an open floor office, whose floor plan is shown in Fig. 4. The floor has dimensions of 40×40 m^2 and there are initially 216 persons on this floor. The properties of these agents were assumed to be as the "Office Staff" category in the Simulex model and the reaction times of the agents were assumed to follow a normal distribution with mean of 90 s and standard deviation of 11 s. There are three stairs located at the central core of the building. The widths of the doors opening to the stairs are 1.2 m. In total seven different egress scenarios were simulated, covering the cases

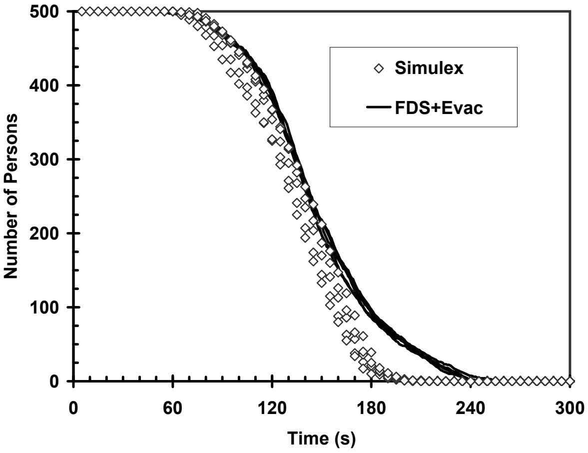

Fig. 3. The comparison of FDS+Evac to Simulex in a sport hall case. Results of five different simulations are shown for each case.

where all stairs are in use, one stair is blocked and a case where two stairs are blocked.

The results of FDS+Evac simulations are compared to Simulex simulations in Fig. 4. Only when two exit doors were blocked, queues were formed at the door. For two or three operational doors the main form of the evacuation curves arise from the reaction time distribution. The FDS+Evac and Simulex results are quite similar. It should be mentioned, that in the FDS+Evac simulations, the initial positions of agents do not change between different door scenarios (see Fig. 4), whereas in Simulex runs the random initial positions are used in each calculation. This explains why the Simulex results have larger scatter.

3.3 Test case C

The last test case is a large fictitious assembly space having dimensions of 50×60 m^2 and 1000 people initially inside. There is only one 7.2 m wide corridor leading to the exit. The geometry is shown in Fig. 5. The FDS+Evac results are compared to those of Simulex [5, 6] and buildingExodus [22] in Fig. 6. Note, that the FDS+Evac simulations were also done using parameters describing more relaxed egress (labels “FDS+EvacSlow”), where the value of the anisotropy parameter of the social force, λ_i, had a value of 0.3.

Considerable differences are seen between the results of FDS+Evac and the results of Simulex and buildingExodus codes. These differences can be traced back to the motion of the agents in the corridor. Simulex and buildingExodus are not using the whole width of the corridor efficiently, when the simulations are done using the default values and standard input [9]. (An

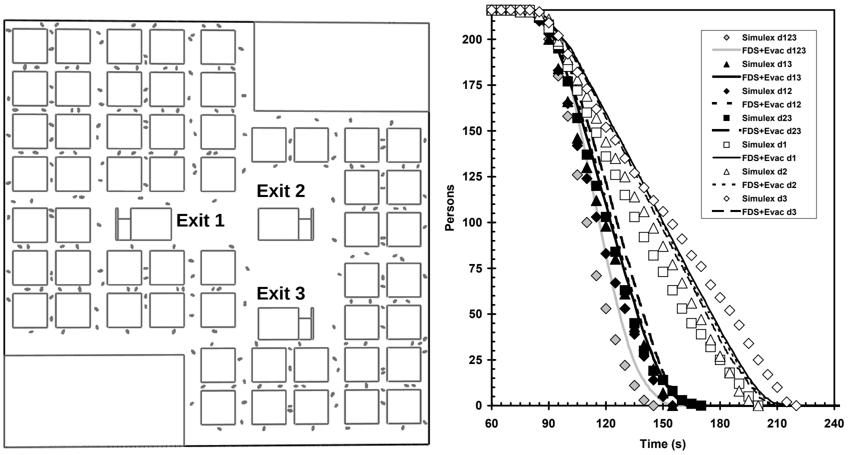

Fig. 4. The geometry of the open floor office test case and the comparison of FDS+Evac to Simulex.

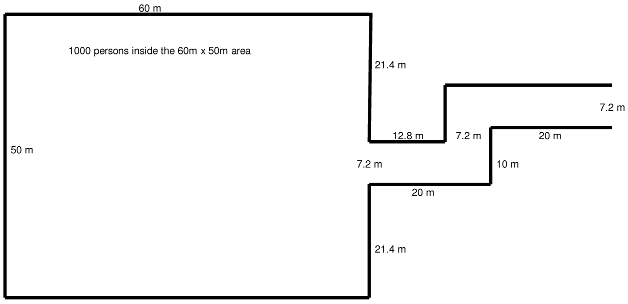

Fig. 5. The geometry of the assembly space test case.

advanced user of these codes might be able to get different results by using some additional features.)

In Figure 6 also shown are the results of the simulations for a case, where there is no corridor at all, *i.e.*, there is just one 7.2m wide exit door located at the wall of the room. In this case, the agreement between the different evacuation programmes is much better. The calculated specific human flows (1/p/m) are: Simulex 1.44, Exodus 1.95, FDS+Evac 2.14 ($\lambda_i = 0.5$) and 1.74 ($\lambda_i = 0.3$).

4 Summary

This paper presents a recently developed evacuation modelling programme FDS+Evac that allows the simulation of fire and evacuation at the same time. FDS+Evac was found to run satisfactorily, and fast enough for practical

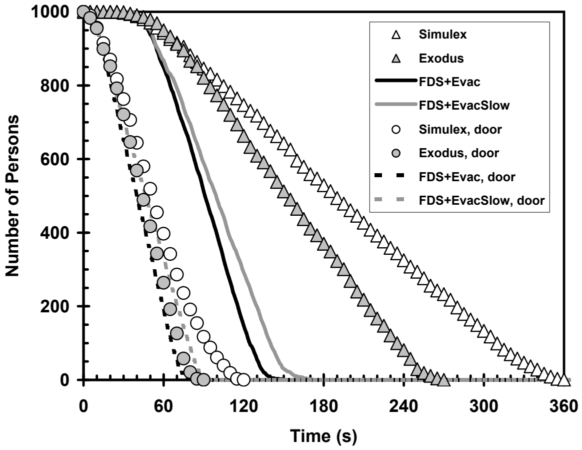

Fig. 6. The comparison of FDS+Evac to buildingExodus and Simulex in an assembly space.

purposes. The comparison of the FDS+Evac simulations 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, where the models perform differently in the bended corridor.

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