PROCEEDINGS, Fire and Evacuation Modeling Technical Conference 2011
Baltimore, Maryland, August 15-16, 2011

FDS+EVAC EVACUATION MODEL: RECENT DEVELOPMENTS

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ABSTRACT

This paper lists the recent developments in the FDS+Evac evacuation model. FDS+Evac is an agent based emergency egress simulation model which is embedded in the fire simulation program FDS, thus, enabling simultaneous simulation of the fire and egress processes. The main new feature of the evacuation module is better treatment of different behavioral types of the evacuees using herding type algorithms. The four implemented types are conservative, active, follower, and herding agents and they differ in the way they select their target exits. Conservative agents prefer familiar routes, active agents actively observe their environment to find the fastest exit route, and herding and follower agents tend to follow others. The other developments of the evacuation model are a much easier and simpler user input, better way-finding towards visible exits, a counter flow model, and a better treatment of geometries like theatres and auditoriums, where the obstacles blocking visibility and movement differ. Some verification and validation cases are discussed in the paper and the basics of the new sub models are presented.

INTRODUCTION

In emergency evacuations, occupants' behavior in given situations may vary largely depending on their individual characteristics. One key factor is the available information; all evacuees may not know all possible exit routes, and thus may end up using inferior options. Also, even if everybody were aware of all possible exits, individual characteristics may lead them to selecting different routes. Some people may prefer exit routes that they are familiar with even if faster options were apparent (Proulx, 1993; Sime, 1980).

A common observation from real life evacuations has been that many occupants tend to select the exit where the majority of the others are heading. Such behavior seems to occur even if shorter and faster routes were available and clearly visible (Helbing et al., 2002; Pan, 2006; Rinne et al., 2010). This behavior is usually called herding. Many prescriptive fire codes implicitly assume that the total exit width of buildings is used in egress. Herding behavior, as well as people's tendency to favor the familiar routes, may easily lead to outcomes that contradict with these assumptions.

The impact of individual differences, like tendencies to favor familiar routes or to follow others, should be taken into account in evacuation simulation models. The occupants of an office building may have a different distribution of behavioral types than the people in a shopping mall or a rock concert. The modeling of different agent types has been considered in many previous studies. Many times the differences relate to the physical properties of the agents, e.g., the body size and walking speed may differ between males, females, and children (Korhonen and Hostikka, 2009; IES, 2009). Also agents with different behavioral types have been considered, for instance, the different characteristics of staff members and regular crowd members (Pelechano et al., 2005) or senior and junior occupants (Gwynne et al., 2006).

In this paper, it is presented how different behavioral types have been added to the FDS+Evac evacuation model (Korhonen and Hostikka, 2009). FDS+Evac is an agent-based egress calculation module that is designed to work on the platform of Fire Dynamics Simulator (FDS) (McGrattan et al., 2007). Four different agent types are considered: a conservative type, an active type, a follower type, and a herding type. Also other recent developments of FDS+Evac are presented in this paper. These include, e.g., a much simpler user input, better way-finding towards visible exits, a counter flow model including a better model for staircases, and better treatment of geometries like theatres and auditoriums, where the obstacles blocking visibility and movement differ.

FDS+EVAC EVACUATION MODEL

The evacuation process of a building floor is modeled as a 2D system, where autonomous agents simulating the escaping humans are moving according to equations of motion and decision making processes. The different floors of the building can be connected through stairs. FDS+Evac follows the trajectories of the agents in continuous space and time. The agents choose their target exits using an algorithm, where the familiarity and visibility of the exits are considered together with the queues at the exits. Because FDS+Evac is coupled with the fire simulation program FDS, the smoke and toxic gas information is used to reduce the movement speeds, calculate intoxication effects, and modify the exit choice of the agents.

The method of Helbing et al. (1995, 2000, 2002) is used as the starting point for the pedestrian movement method used in FDS+Evac. The method introduces so-called "social force", which is used to keep reasonable distances between pedestrians and between pedestrians and walls. For a description of the method, see the papers by Helbing et al. and references therein. For the modification of a one-circle representation of the elliptical cross sectional shape of a human body to a three-circle one, where one large circle describes the torso and two smaller ones the shoulders, see the papers by Langston et al. (2007) and Korhonen and Hostikka (2009). The original agent movement model introduced by Helbing et al. and its three circle equivalent are not well suited for situations where agents are going to different directions and their paths are crossing or opposite to each other. To overcome this deficiency, a counter flow model was implemented in FDS+Evac.

In the new FDS+Evac version an agent aims directly towards the chosen target exit if there are no obstacles blocking direct movement and the local agent density is not too high. In other cases, it is guided to the chosen exit by a preferred walking direction vector field, which is obtained using FDS and its flow solver similarly as in the earlier versions of FDS+Evac. This vector field is obtained as a solution to a flow problem of a two-dimensional incompressible fluid, where the chosen exit 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. The actual path of the agent will deviate from this fictive flow field or direct aiming due to the interactions with the other agents and walls and due to inertia.

The exit selection algorithm of FDS+Evac is based on a game theoretic model described and analyzed in detail by Korhonen and Hostikka (2009), Ehtamo et al. (2010), and Heliövaara et al. (2010). The agents observe the actions of the others and select the target exit through which the evacuation is estimated to be the fastest. The evacuation time of each agent to each exit is calculated from the distances to the exits and the congestion in front of the exits. The estimated evacuation time is not the only criterion considered in the model; also the visibility of the exits and the fire related conditions at the exits affect the decision, as well as the familiarity with the different exits, which can be defined for each agent by the user. These three criteria define five different exit groups as presented in Table 1. An agent regards a visible exit as a "no smoke" exit if there is less smoke than a user given amount along the bee line to the exit. For non-visible exits the smoke concentration at the position of the agent is used to estimate the presence of smoke or not. If there is no sign of smoke then it is assumed that there is no reason for the agents to prefer other routes than the familiar ones. If there is clues of smoke then the agents are more willing to use visible exits, familiar or not, than non-visible ones to get out safely. The agents select an exit with the smallest preference number, and only if two or more exits share the smallest preference, the decision between these is made by minimizing the estimated evacuation time. Previously, all agents of FDS+Evac selected their target exits using this algorithm. In this paper, we present three new agent types besides this original type. The original type agents are from now on called "conservative" agents.

Table 1: Preference order of the exits.

Preference number	Visible	Familiar	No Smoke
1	yes	yes	yes
2	no	yes	yes
3	yes	no	yes
4	yes	yes/no	no
5	no	yes	no

NEW FEATURES OF FDS+EVAC

Herding Behavior and Exit Selection

A common observation from real life evacuations has been that many occupants tend to select the exit where the majority of the others are heading. Such behavior seems to occur even if shorter and faster routes were available and clearly visible. This behavior is usually called herding. Recent observations on different egress situations (Rinne et al., 2010) give many examples where the exit usage during egress is not optimal. In almost all cases studied in that work, occupants used the exits of the buildings inefficiently. In some cases just one leaf of double leaf doors was used even though the other leaf could be opened just by pushing it. People decide to follow others using the part of the door that had the leaf already opened or held open by someone in front. This was seen to happen also when there was congestion in front of the doors, i.e., people had to slow down and wait a little bit to go through the door that had the leaf already opened. A related example is a fire drill in a vocational high school that had a staircase ending at ground level, where the usual way out was through the entrance hall. But there was also an emergency exit on a side wall at the bottom of the stairs. During the fire drill, it was observed that it took two and a half minutes before the emergency exit was opened, apparently by a safety organization member, and the evacuees started to use this way out. Just one person was enough to trigger the use of an emergency exit.

Many prescriptive fire codes implicitly assume that the total exit width of buildings is used in egress. Herding behavior, as well as people's tendency to favor the familiar routes, may easily lead to outcomes that contradict with these assumptions. The exit selection algorithm of FDS+Evac was modified so that these kinds of phenomena could be modeled. Four different agent types were introduced in FDS+Evac: conservative type, active type, follower type, and herding type.

The first new agent type is "active" agents, who use a different preference order for the exits than the "conservative" type. Active agents regard all visible exits also to be in the same preference group as familiar exits. The second new agent type is "herding" agents. Herding agents use only the familiar exits, if any given by the user. If there is no familiar exit at the current floor of the building then a herding agent looks its nearest neighbor agents and tries to follow them. The third new agent type is "follower" agents. A follower agent looks its nearest neighbors in front of it and check if exit where the neighboring agents are going is better than the current exit choice of the follower agent, i.e., the follower agent treats its neighbors' target exit doors as familiar doors.

Conservative agents

The conservative agent type in the present version of FDS+Evac (2.3.0 onwards) is modified from the older versions (prior 2.3.0). If there is some smoke at the exit routes then the preference order is modified a little bit. All visible exits are put to the same preference group regardless of their familiarity when there is smoke on the exit routes. It is assumed that the agents have higher stress and are willing to change their behavior such that any exit that leads out of the smoke is used. The other modification in the present program version is that L1 distance is used to describe the walking distance to the non-visible exits and L2 distance is used only for the visible ones. L2 distance is the straight Euclidean distance between two points, while L1 distance is the sum of absolute differences in the coordinates of the points. The L1 distance is also called Manhattan metric. The name alludes to the grid layout of the streets of Manhattan, which causes the shortest path between two points to be equal to the L1 distance. We use the Manhattan metric to approximate the walking distance to non-visible exits because corridors and obstacles often make buildings resemble grid geometries. This approximation is used because the current version of FDS+Evac does not include calculation of the actual shortest path. While the shortest path calculation is likely to be implemented in the future, L1 distance gives rather accurate approximations in most building geometries.

The movement of the conservative agent type is triggered by the user given detection time and reaction time distributions. The detection time can be shorter than the user given distribution if there is enough smoke to trigger the detection. The smoke can be detected either by the local smoke concentration at position of the agent (detection by senses) or detection by a device (usually a smoke or a heat detector). If a conservative agent gets lost then it starts to behave like a herding agent for a while until it is able to locate an exit by its own reasoning. An agent is lost when it cannot see any exit and does not have any familiar exit in that part of the building. This might happen if an agent is using some visible but not familiar internal door to go to some other floor or connected space within the building. It might also happen that some of the familiar routes are blocked by smoke and the agent ends up using an unfamiliar route. Conservative type agents could be used in many building evacuation situations, e.g., the customers in a shopping mall, who know the main exits but are not so willing to use special emergency exits.

Active agents

The active agent type is very similar to the conservative agent type. The difference is that active agents observe their environment actively to find the fastest exit route. Hence, active agents prefer all visible exits similarly regardless if the exits are familiar or not. Detection and reaction times are like those of conservative agents and lost active agents are treated similarly to lost conservative agents. Heterogeneous crowds contain more and less observant occupants. The less observant will head to their familiar exits or follow others, while the more observant ones actively look for possible faster egress routes. The active agent type can be used to model these more observant crowd members. The existence of active agents may be very significant to the outcome of evacuations as, in addition to themselves, they may also lead herding agents to some normally unused exits. This kind of behavior was observed quite often in the evacuation drills and real fire alarms in Finland analyzed by Rinne et al. (2010) as discussed in the introduction.

Herding agents

The second new agent type is "herding" agents. These are assumed to be unfamiliar with the geometry and they will not use any exit, unless it is regarded as a familiar exit. Usually just the doors that they used to enter the building could be regarded as familiar exits. This agent type represents also lost agents, who can not figure out any available exit. Herding agents are looking around and seeing what the other agents are doing and, if some of the others are heading towards an exit, they start to follow these other agents. A herding agent will remain still even after detecting the fire and its reaction time has passed if it has not been able to select any exit either by being familiar with it or by observing other agents. If the nearest neighbors of a herding agent are heading towards some exit then the herding agent starts to follow these agents almost immediately regardless of its detection and reaction times. If there are available familiar exits at a given floor for a herding agent then it behaves like a conservative agent, i.e., the familiar route behavior overrides the herding behavior.

A herding agent looks always around and checks where its nearest neighbors are heading. By default five nearest neighbors that are within a radius of 5 meters are included. The herding agent will follow the majority of its nearest neighbors. Only those nearest neighbors are considered that are heading away from the herding agent (cosine of the angle less than -0.2). This mimics the fact that the herding agent wants to follow other agents, not to lead them. The default distance is 5 m but the user may change this if it is not appropriate for the application in question. The default value was selected after some test simulations as it was seen to operate reasonably well for the verification cases. In principle, the distance should depend on the agent density and the typical room size of the building. But it was seen that this distance had no effect with reasonable design densities, because most of the agents have at least one neighbor within 5 m distance.

If a herding agent has not been able to get any exit information from its nearest neighbors nor has it any familiar exit route available, then it looks for all visible agents and tries to find the nearest agent that is heading to some exit. It constantly updates this information as long as there are some visible agents heading towards exits. Note that also here the walking directions of the other agents have a similar effect as the effect of the moving directions of the nearest neighbors: If the other agent is heading towards the herding agent the direction is recorded when the moving agent has passed the herding agent. If all moving agents have disappeared then the herding agent will remember where the last visible moving agent went. If the herding agent has detected the fire and the reaction time has passed then the agent starts to move towards this previously recorded exit direction.

If an agent is not able to find an exit after entering a floor through a door, it starts the herding behavior by checking the nearest neighbors and other visible agents. If the agent is not able to find any information of exits, it moves away from the entering door a couple of meters, stops there, and continues to observe other agents. At this point, the herding agent has already started to evacuate the building so the detection times and reaction times are not used anymore, i.e., the agent will continue to move immediately when it gets information on a new target exit to be used.

The herding behavior could be easily modified to take into account effects like patron vs. personnel, child vs. adult, etc., where some agents are more likely to be followed than others. This could be modeled by giving different weights to the influence of different agent types. For now, the only effect that the user can specify is the distance dependence of the effect of the nearest neighbors on the decision of the herding agent. The user can specify that the nearer neighbors have larger weights than the more distant ones using a linear function.

Follower agents

The third new agent type is the follower agents, which are somewhere between conservative agents and herding agents. Follower agents use the same door selection procedure than the conservative agents, but they also see where the nearest neighbor agents in front of them are heading and include those exit doors in their list of possible exit doors. A follower agent will add the target exit door of its nearest neighbors to the familiar door list in the door selection algorithm. Thus, the follower agent will change its target door if the nearest neighbors seem to go to a “better” door, where “better” means shorter exit time constrained by the preference order table. Otherwise the follower agents behave like the conservative agents.

Simplified User Input: An Example

The most observable new development of FDS+Evac is the much simpler user input. Simple example geometry and the corresponding user input (excluding coloring information and output file options) are shown in Figs. 1 and 2, respectively. Figure 1 shows also the other new development which makes it possible to distinguish between obstacles that block both the movement and visibility (the walls of the room) and obstacles that only block movement (the black obstacle in the middle of the room), e.g., seats in an auditorium. In principle, it is also possible to define obstacles that block visibility, but not movement (the gray obstacle in the figure), but in reality these kind of things are not probably present. It can also be seen that the agents aim directly towards the target exit door if there are no obstacles blocking direct movement and the agent density is not too high. In other cases, the agents follow the fictitious flow fields towards the exit doors like in earlier versions of FDS+Evac.

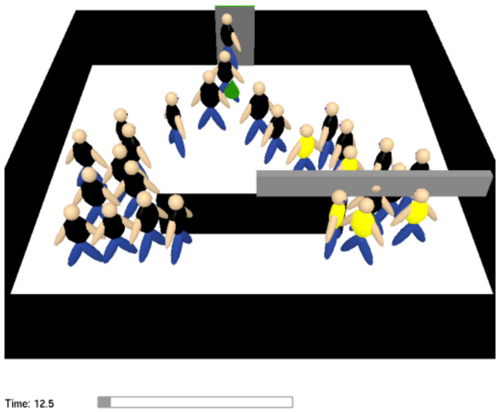
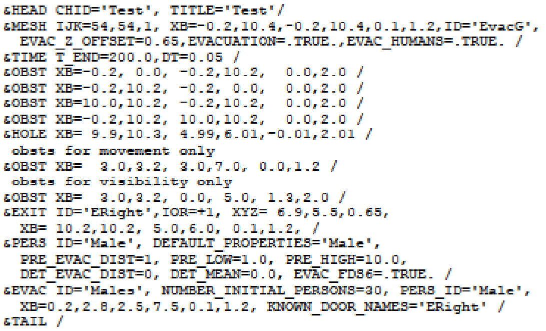


Figure 1: A snapshot of a simple example case that illustrates how the obstacles could block the movement of the agents, the visibility or both. In previous versions of FDS+Evac, obstacles blocked always both the visibility and movement.



```
&HEAD CHID='Test', TITLE='Test'/
&MESH IJK=54,54,1, XB=-0.2,10.4,-0.2,10.4,0.1,1.2,ID='EvacG',
  EVAC_Z_OFFSET=0.65,EVACUATION=.TRUE.,EVAC_HUMANS=.TRUE. /
&TIME T_END=200.0,DT=0.05 /
&OBST XB=-0.2, 0.0, -0.2,10.2,  0.0,2.0 /
&OBST XB=-0.2,10.2, -0.2, 0.0,  0.0,2.0 /
&OBST XB=10.0,10.2, -0.2,10.2,  0.0,2.0 /
&OBST XB=-0.2,10.2, 10.0,10.2,  0.0,2.0 /
&HOLE XB= 9.9,10.3, 4.99,6.01,-0.01,2.01 /
 obsts for movement only
&OBST XB=  3.0,3.2, 3.0,7.0, 0.0,1.2 /
 obsts for visibility only
&OBST XB=  3.0,3.2, 0.0, 5.0, 1.3,2.0 /
&EXIT ID='ERight',IOR=+1, XYZ= 6.9,5.5,0.65,
  XB= 10.2,10.2, 5.0,6.0, 0.1,1.2, /
&PERS ID='Male', DEFAULT_PROPERTIES='Male',
  PRE_EVAC_DIST=1, PRE_LOW=1.0, PRE_HIGH=10.0,
  DET_EVAC_DIST=0, DET_MEAN=0.0, EVAC_FDS6=.TRUE. /
&EVAC ID='Males', NUMBER_INITIAL_PERSONS=30, PERS_ID='Male',
  XB=0.2,2.8,2.5,7.5,0.1,1.2, KNOWN_DOOR_NAMES='ERight' /
&TAIL /
```

Figure 2: The user input of the simple example case shown in Fig. 1.

Counter Flow Model

The original model of Helbing et al. is not well suited for situations where agents are going to different directions and their paths are crossing or opposite to each other. The agents do not react to the oncoming agents explicitly. There is just a small implicit action by the social forces, but this is not large enough to hinder the agents from colliding. To overcome this deficiency, a short range counter flow model was implemented in FDS+Evac.

In the counter flow model, the area in front of an agent is divided into three overlapping sectors, which are pointing to the left, straight ahead, and to the right. Straight ahead means always the preferred walking direction, where the agent would go without the effect of the counter flow model, e.g., the direction towards an exit door. The basic idea of the counter flow model is to choose the sector with least counter flow. This is formulated as an optimization problem, where each agent lying within a sector either increases or decreases the score of the sector depending on its location and moving velocity. There are terms in the optimization problem that prefer the right (and straight ahead) to the left to produce observed right handed traffic (Kretz et al., 2006).

The implemented counter flow model is designed for dense crowds and thus, the extents of the sectors are not very large. The range of the sectors extends maximally to three meters ahead of an agent and on the sides the sectors extend up to 1.5 m. If the speed of the agent is low then the maximal range straight ahead is approaching 1.5 m and the sectors form a semi circle.

V&V RESULTS

Verification: An Auditorium

Some of the new features of the FDS+Evac program are verified using auditorium geometry, where the seats form barriers for movement but not for visibility. The auditorium is 20 m × 20 m in size and it has seventeen 17.2 m wide seat rows. There are initially 280 agents randomly located at the seat rows and there are two 1.0 m wide exit doors in front of the auditorium.

Snapshots of two of the five different FDS+Evac simulation cases are shown in Figs. 3 and 4. These verification cases are used to test the door selection algorithm with low obstacles that do not block the visibility of the exits nor the other agents and to test also the four different agent types introduced in FDS+Evac. In the case shown in Fig. 3, there are 250 conservative agents and 30 rational agents in the simulation. The bottom right door is marked as a familiar door for both agent types in simulations. The conservative agents prefer familiar, known, doors over visible doors, whereas the rational agents use evenly all doors they can see or they know. In the case shown in Fig. 4, there are 250 herding agents and 30 rational agents. The herding agents are selecting their exit door constantly by looking where their neighbors are going. These herding agents are shown in black. From the results it can be seen that the door selection algorithm is working like it is supposed to. The egress is fast in the case where there are only rational agents that are using both exits. The egress is also fast in the case where the few rational agents present are heading towards both exit doors and the herding agents are following rational agents towards these two doors, see Fig. 4. The egress is almost twice as slow in the cases, where mainly the familiar door on the bottom right is used.

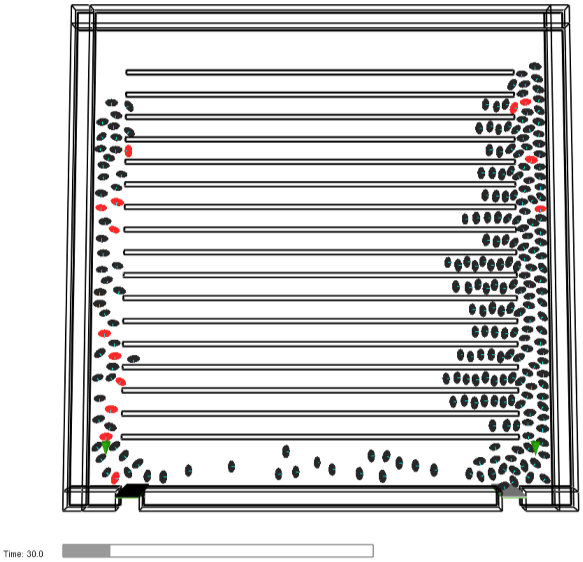


Figure 3: A snapshot of an auditorium simulation with 250 conservative agents (black) and 30 active agents (red). The right door is set to be the familiar door for the conservative agents.

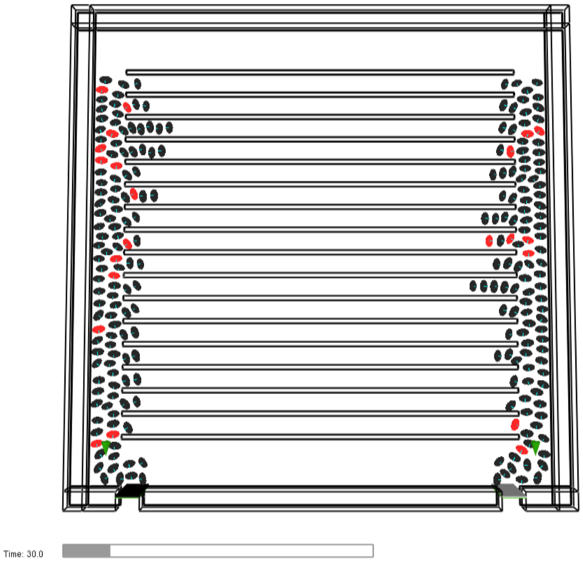


Figure 4: A snapshot of an auditorium simulation with 250 herding agents (black) and 30 active agents (red).

Validation: Counter Flow Model

A number of theoretical analyses have been published on pedestrian counter flow (Helbing and Molnar, 1995; Schadschneider et al., 2001; Tajima et al., 2002; Blue and Adler, 2001), but only a few sets of data of actual experiments are available (Isobe et al., 2004; Kretz et al., 2006). Isobe et al. (2004) ran experiments with university students in a 12 m by 2 m corridor. Initially, 50% of the students were randomly located in the left half of the corridor and the other 50% in the right half. As the experiment started, the students in the right half tried to walk to the left end of the corridor and vice versa. The same experiment was ran with different numbers of students to analyze the effect of population density on the flow rates.

Figure 5 presents the results of the experiment and the simulation results of FDS+Evac with the counter flow model. In the simulations, the body dimensions and walking speeds of the agents were selected to match the properties of the students participating in the experiment. Hence, 50% of the agents were generated from FDS+Evac default type “Female”, but the type ”Female under 30 years” walking speeds according to IMO (2007) were used. Similarly, the other 50% of the agents were the default type “Male” with ”Male under 30 years” walking speeds. Figure 5 shows that the simulation results match the experimental observations very well in all population densities.

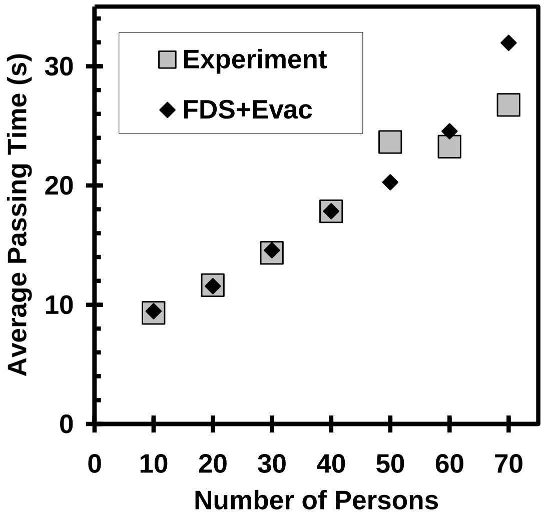


Figure 5: The experimental results of Isobe et al. (2004) and simulation results of FDS+Evac with the counter flow model. The values of the FDS+Evac simulation results are averages of ten simulation runs.

Validation: Flows through Doors

The geometry shown in Fig. 6 is used to study the flows through doors. There were 100 agents randomly located in the 5 m × 5 m square in front of the door. The width of the door was varied between 0.8 m and 3.0 m. The dimensions of the room are 15 m × 10 m

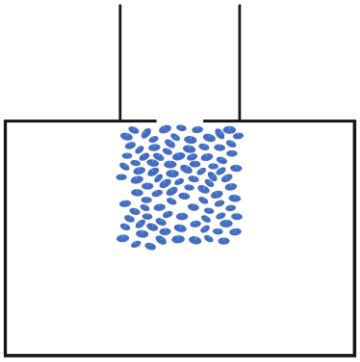


Figure 6: A snapshot of the beginning of a door flow simulation showing the geometry used.

The predictions of FDS+Evac model for specific flows through doors are compared to other simulation programs Simulex (IES, 2009; Thompson and Marchant, 1995a,b; Thompson et al., 2003) and MASSEgress (Pan, 2006) in Fig. 7. The results of MASSEgress ("MASSEgress") and Simulex ("Simulex, Pan") are extracted from Pan's thesis (2006), where Simulex version 11.1.3 from year 1998 was used. Shown are also results calculated by the author using Simulex version 2009.1.0.3 ("Simulex, VTT"), where the standard Simulex person type "Office Staff" was used and the exit was about 2.5 m behind the hole describing the door. This way the agents are not taken away from the calculation at the door line and the agents queuing at the door will feel these agents. If the agents are removed right at the door then the (specific) flows could be much larger as stated in the Simulex User Guide (IES, 2009). The labels "Male", "Female", "Adult", and "Elderly" refer to the corresponding default agent types of FDS+Evac. It is seen that FDS+Evac is able to produce reasonable flows through doors.

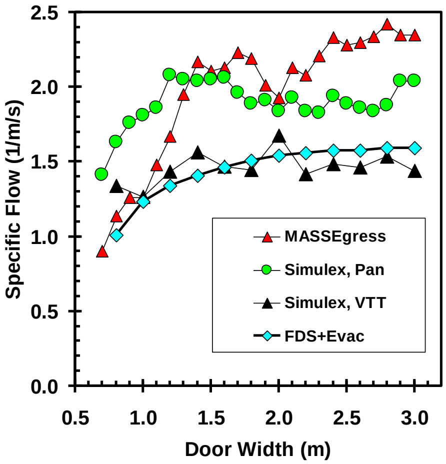


Figure 7: FDS+Evac simulation results for specific flows through doors compared to the results of some other evacuation simulation programs.

SUMMARY

This paper summarizes the main new features of the evacuation program FDS+Evac. These additions and modifications are released in the next official release of the computational fluid dynamics based fire simulation software FDS, which will be the FDS6, version 6.0.0. The verification and validation example cases presented in this paper illustrate some of the new features of the program.

There are many improvements in the algorithms of FDS+Evac, but the most noticeable change for the users is the much easier and shorter user input, which makes the use of FDS+Evac more robust. The main new feature of the evacuation module is better treatment of different behavioral types of the evacuees using herding type algorithms. The four implemented types are conservative, active, follower, and herding agents and they differ in the way they select their target exits. Conservative agents prefer familiar routes, active agents actively observe their environment to find the fastest exit route, and herding and follower agents tend to follow others. The other improvements in the algorithms include a better way-finding towards visible exits, a counter flow model, and a better treatment of geometries like theatres and auditoriums, where the obstacles can be blocking the movement but not the visibility.

ACKNOWLEDGEMENTS

This research was supported by the Academy of Finland.

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