Evacuation modelling: Comparison of (FDS + Evac) with Simulex

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Abstract. Building evacuation in case of an emergency usually goes uncontrolled, human psychological, sociological and physical factors affect the evacuation. Simulation models of evacuations do not take these factors into account, while the consequence could be substantially. Also human reaction on atmosphere changes, like the production of toxic gasses or the decrease of visibility can contribute negative to the evacuation results. Therefore is would be useful if the evacuation models could deal with these factors. This contribution describes the influence of the mentioned factors on evacuations and compares a computer program (FDS+Evac) which processes these factors in a model to simulex, another evacuation simulation model.

Keywords: Smoke simulation, evacuation, simulation models, fire safety engineering. FDS, Fire Dynamics Simulator, Simulex, human behaviour

1 Introduction

When simulating evacuations from buildings, mostly only the building geometry and crowd characteristics are used as parameters. Some very important parameters, like smoke toxicity, visibility through smoke and psychological factors are usually not taken into account.

The influence of smoke on people on evacuation could be very high. Smoke from a fire comes together with heat, smoke contains toxic parts, smoke decreases the visibility. All these consequences could make people panic, or make them behave improvident.

This indicates it is important to know whether there is smoke on or near an evacuation route and what characteristics this smoke has. Therefore we investigated the fire simulator program FDS (Fire Dynamics Simulator) with the evacuation module Evac (from now on called FDS+Evac in this document) and compared the results of this program with Simulex, the most used human egress simulation in The Netherlands [1].

2 Smoke and fire

2.1 Fire

A fire is a chemical reaction from fuel and oxygen which releases heat. Three elements are necessary for combustion, fuel, oxygen and an ignition temperature. At a certain temperature a chemical process starts, which releases gasses from flammable surfaces. These gasses mix with oxygen in the room. When the ignition temperature is reached, de fire starts. From the point of the gas release, smoke is produced.

2.2 Smoke

Within a combustion, smoke is created as a residual. Smoke contains hot gasses, mostly CO_2 and H_2O, soot particles (risk of decrease of visibility) and half burnt residuals. These last component gives a risk for combustion of within the smoke when enough oxygen is interfered and the smoke temperature is above the ignition temperature.

Smoke is threatening for humans and can impede evacuations in different ways.

Temperature. The temperature raise can cause skin burning and lung burning. The time a human can stay in a hot setting is depending on the temperature of the atmosphere. The time a human can stand a specific temperature can be calculated with formula (1)

$$t = \frac{5{,}33 \cdot 10^6}{T_{smoke}^{3,66}} \; [s] \; . \tag{1}$$

Radiation. The impact of heat radiation on evacuating humans is depending on the degree of radiation, the time of exposure and the part of a body that is exposed to the radiation. The radiative flux on a human can be calculated with (2)

$$T_{smoke} = \left(\frac{Q}{\varepsilon \cdot F \cdot \sigma} + T_e^4 \right)^{1/4} \; [K] \; . \tag{2}$$

Visibility. Smoke production can decrease visibility. The existence of smoke particles in the results in light absorption and light scattering and has irritation influence on eyes. Both characteristics of smoke result in a disorientation for evacuating people.

$$Z = 1/RD \; [m] \; . \tag{2}$$

Toxicity. As states before, smoke contains residuals. With a complete combustion, the smoke is clean, but in most cases a fuel isn't completely burned. Local effects always results in incomplete combustions. These incomplete combustions create toxic residuals, like carbon mono oxide. In a fire, most people die because of the inhalation of toxic gases.

In The Netherlands, the critical temperature is 45°C, the critical heat radiation is 1 kW/m² for a safe egress [2]. If temperature and radiation is below these values, a safe exposure unlimited in time is acceptable.

3 Human behaviour with smoke and fire

In the Dutch building regulations the requirements for buildings to be save in case of a fire are set up with the human behaviour as foundation for these requirements. But scientific research showed that human behaviour is different in case of a fire as expected [3]. This means that widely used regulations are based on incorrect principles. When dealing with fire safety engineering, it is important to know the real physical behaviour of fire and smoke, but also the real behaviour of humans. Because all knowledge of fire and smoke is useless if people act different as expected and no human is saved.

3.1 Risks of smoke and fire

People usually know that smoke is dangerous because of de heat and toxic gasses of smoke. But most people don't know the degree of smoke production and the speed of spreading of a fire and smoke. People think they still have enough time to flee a few moments later before the smoke of fire has reached them. This phenomenon is known as the 'friendly fire syndrome' [4]. Examples show that a humans keep their role in a specific situation. When people are shopping, they continue shopping as long as they think it is possible [3]. It is hard for a layman to understand and estimate the speed of spreading of fire and smoke, so they wait to long before they flee. Because of their role in a situation they recognition of signals of danger is delayed and so is the processing of this information. Through this, the start of the evacuation is delayed.

3.2 Personal behaviour

The first scientific studies on human behaviour on fires in buildings started in the United States in the fifties. In the following years the personal reaction is classified in the categories, psychological, sociological, physical behaviour characteristic. A psychological reaction is the reaction based on the knowledge and experience of the human, a sociological reaction is a reaction based on the reaction of other in the vicinity, a physical reaction is a reaction based on a changing environment condition that influences the possibility to flee, like the inhalation of toxic gasses.

The are a lot of personal characteristics that influences the personal behaviour in case of a fire. Some of them are listed below.

Stress. Humans can process only limited information in a time period. When more information needs to be processed, one needs to make a selection. The more stressed a human is, the less information can be handled. So the more stressed a human is, the slower the reaction on danger is.

Mobility and condition. The mobility of humans ca be very different, children, elderly people and handicapped are less mobile. This are (semi) permanent conditions. People in hospitals and other sick people are also less mobile.

Ability to observe. This can be split up in visibility, the ability to hear and the ability to smell. If one of these is less developed, one will later notice a danger.

Group behaviour and social relations. People usually follow the behaviour of others, if one people start to flee, others will follow. Also people will help each other and stay with each other..

3.3 Reaction to fire alarm

In the building regulations we assume that people start evacuating when the fire alarm gives a signal. In reality this doesn't seem to be correct. The reason isn't clear, it is assumed that a fire alarm doesn't give enough assurance and clarity about the situation and the need to flee [5, 6]. This can mostly be declared by the high number of false alarms. The smell of smoke and the view on a fire are stronger indications that there is a faire en gives more reason to flee.

Also the behaviour of other people in the vicinity is important. If others don't show clear flight behaviour and continue their activities, others won't take action either.

Clear information about the situation seems to be important. A spoken fire alarm results in a faster response. A fire alarm without additional information is not immediately understood and results in a slower response and a later start of the evacuation.

3.4 Evacuations

Evacuation is a concatenation of events and can be described in three phases, awareness of danger, validation and reaction on danger signals, movement to a safe situation, the actual evacuation process.

Usually in a building the evacuation routes are indicated with emergency exit signals. In the Netherlands we use the sign as shown in figure 1.

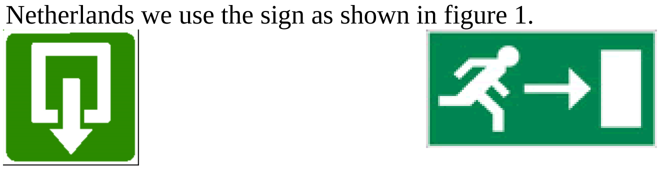

Fig. 1. The signs used in the Netherlands to indicate an exit of a building *on the left* and an evacuation route *on the right*.

Research showed that most people do not notice these signs [5, 7]. One person walked along eight evacuation route signs without noticing one of them and walked out of the building through the main entrance.

People usually use a known route when evacuating [5]. The knowledge of (part of) a building seem an important factor in the decision for the evacuation route. This means people try to escape through the main entrance, exactly how they came in the building. When calculating the necessary door width and evacuation routes the base rule is, that people distribute proportionally between all available evacuation doors and routes. In real life, people want to flee through the entrance they came in, even if this route isn't indicated as an evacuation route and when this route isn't equipped as an evacuation route.

A problem when evacuating is the 'follow the crowd' principle. People react the same as other people, the follow each other in behaviour and in the direction of the evacuation. Because of that, large groups of people use the same exit and there is no spreading of the population proportionally between the doors. This creates a jam on the most used exits [8].

Because of the smoke in a room, the visibility decreases. Because of the loss of visibility the walking speed of people is lowed down too. This could be compared by walking in a dark room. Fleeing will also fail when the smoke contains too high concentrations of toxic particles or contains too less oxygen [5, 7]. Decreasing the walking speed is a way to increase the observation of emergency exits, but is only possible when the smoke layer contains only non-irritating particles.

Despite the known and unknown dangers of smoke, people are willingly to flee through the smoke layer, especially when they are familiar with the building they are in [5].

3.5 Panic

Several research projects concluded that people stayed self-controlled and logical thinking in a fire situation. In many cases where video materials was studied from incident evaluations, the conclusion was that one doe not react at all on a fire. They walk away slowly or keep watching on the physical process. Only when the situation become threatening they start to flee [5]. Sometimes people panic in a situation like this. It is important to use a correct definition for panic. We speak of panic when people react irrational, illogical and uncontrolled [5, 9]. What or when a panic reaction occurs is hard to define and is depending on human behaviour, experiences of a human in the past and the environment [10]. Panic during an evacuation is among other related to the following aspects [9]. When there is limited time for evacuation, people become more aggressive when their life is in danger, when behaviour becomes irrational or illogical and when others panic. Panic seems to be infectious.

When panic occurs, people start running, start pushing and mainly taking care for their own lives. Trying to go faster, creates jams en accidents. Helbing called this phenomenon " ….such as the 'fasteris-slower phenomenon in which people in a rush end op going slower." [8].

4 Evacuation simulation models

Evacuation safety in a building is defined using two variables, the Required Safe Egress Time (RSET), and the Available Safety Egress Time (ASET). If the RSET is shorter than the ASET, the building is defined as a safe building for an evacuation.

The available safe egress time can be defined by different factors like a limited time fixed in the building regulations (in the Netherlands this could be 15, 20, 25 or 30 minutes, depending on the facilities for evacuation), the time a smoke layer is on a height it is obstructive for people. All these limitations do not look at local effects like smoke spreading and accumulation.

When using fire safety engineering an engineer thinks in risk and uses different scenario’s to evaluate situations. And when using a physically correct burning model when running a simulation, it is possible to see whether local effects have a positive or a negative influence on evacuations.

The Dutch building regulations use a deterministic approach. The base rule is that a human must not walk through smoke for more than 1 minute, describes as a specific distance a human can walk through a smoke compartment1. Depending on the expected number of people in a room, the distance to an exit, the sum of the width of all exits and the maximum number of people is defined. A lot of these calculation rules are based on agreements and not on scientific experiments [5]. Therefore in the Netherlands it is hard to judge a solution when it does not fit in these rules.

Some other countries use a performance based system. These systems describe the target of e.g. an evacuation and not the time an evacuation must be completed. These systems use a scientific bases and is also called Fire Safety Science. When using this knowledge for designing, it is called fire safety engineering (FSE).

The number of available models is increasing. All models have limitations. In the Netherlands we already have some models and calculation rules (semi-dynamic) for smoke-spreading and evacuation, but these are usually not useful in complex situations. This means the building does not fit the model principles, or the results are too conservative / negative, which results in an disapproved building planning permission. Therefore more complex models needs to be available.

4.1 Simulating and modelling

Simulations are an approach of reality, but are not reality. To simulate, you have to create models. Modelling technique can be described as ‘The scientific art to translate reality through physical formulas and mathematical equations in a predicting model’ [5]. It are arithmetic models which only give an limited view of reality. One would expect that a more detailed simulation gives a result that is nearer to the reality, but more details give a higher chance to make mistakes. Every time it is a search for the degree of details entered in a model to create a reliable model which gives enough certainty that an evacuation will succeed. Therefore, ideally, we use the following steps [5]:

[1] A smoke compartment is a room or a combination of rooms, with a size and with a number of exits so that on can leave this compartment in less than a minute.

Problem analysis. Demarcation of the problem;

Scheduling. Choosing the borders of the model;

Modelling formulation. Capture the relations between the relevant variables in mathematical equations;

Solution method. Choosing a method to solve these equations;

Validation. Check if the model essentials fit the purpose;

Sensitivity analysis. Check how calculated variables react on assumptions changes;

Calibration. Estimate the unknown model coefficients based on known and validated values and results;

Verification. Check the suitability of the calibrated model based on known results, other than used for calibration.

The validation of a model is used tot see whether this model fits reality. This can be done through using similar models, through theoretical tests, through test in practice and incident evaluation.

One of the main problems in simulations is the degree of detail in simulations. Through the years a lot of programs are developed for evacuation simulation, all use different input parameters and generate different output parameters. Some software tools have their own specific situation of use, some are more general.

5 Human behaviour in evacuation simulation models

In this paper the most used program in The Netherlands is compared to a new player on this 'market', the Evacuation plug-in for FDS, also called FDS+Evac.
Because of the difficulty of simulating real human behaviour this comparison focuses on the modelling of humans and only refers to relevant other features like usability, costs, presentation e.g.

In both programs the persons are modelled as three circles, one for the body, and two for the shoulders/arms (see figure 2). In both programs some default person characteristics are defined, for elderly, human male, human female, child, average, the NFPA and the SFPE human, both average size and average speed with standard deviation are defined. Both programs use a definition of some common groups, for use in shopping malls, offices and stations. Both programs have the possibility to change the persons characteristics and to define group formats. In both programs humans change their walking speed depending on the inter-person distance. A smaller distance between people results in a lower walking speed.

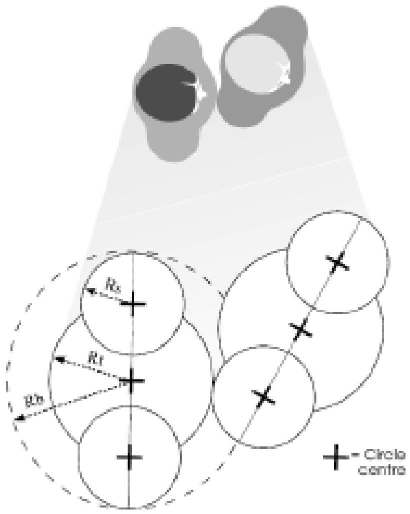

Fig. 2. The modelling of humans and the possible distance between humans.

On evacuations it is possible to use a pre-evacuation time, which is the time it takes before a person reacts on a fire alarm. Also there is a deviation possible on this parameter.

For this chapter the following sources are used: Simulex manual [11] and the FDS and FDS+Evac manuals and reference guides [12-18],

5.1 Simulex

Simulex uses two-dimensional figures to model a building. It can import Cad-drawings and can not model floors with a slope. It can not simulate fire and/or smoke. In Simulex persons will not walk through exits of gaps smaller than 0,55 m, because of the deviation in groups, the minimum gap width must be 0,60 m. The humans evacuate through the nearest exit, even if other exits are completely unused. The program calculates a distance map for every person. They can be forces to use another exit than the nearest.

Simulex is validated through evacuation practice and analysis of human motion.

5.2 FDS+Evac

FDS is a CFD-tool (Computational Fluid Dynamics), generally developed to simulate fires, fire development and smoke development and smoke spreading in time. It is developed by NIST (National Institute of Standards and Technology). The evacuation plug-in is developed by the VTT (VTT Technical Research Centre of Finland). Because of the main program possibilities fire and smoke can be simulated together with evacuations of humans. It has a three dimensional result view with possibilities to look from all different kinds of angles. Some psychological, physical and sociological behaviour of humans is used in the simulations. Examples are decrease of walking speed when walking through smoke, looking for faster evacuation routes, interaction between humans mutually and between humans and walls, which results in pushing and decreasing speed. The influence of heat radiation on evacuations isn't used yet. The minimum width of openings is 0,70 m. It is possible to model stairs and sloped floors in FDS+Evac.

A evacuee chooses an exit depending on the estimated evacuation time and the reaction of other evacuees. Also a person can be indicated as familiar in a building or not, you can choose whether or not an emergency exit is visible for a person and if there are disturbing conditions.

Currently the FED-function is under development. FED stands for Fractional Effective Doses. FDS used chemical reactions to calculate the chemical elements in the air, depending of the burning process. With this function it is possible to calculate whether an atmosphere composition is toxic on a long or short stay and whether this has influence on the evacuation process. Also the social factors on evacuation, like fleeing in groups and communication between persons are improved to be more realistic

5.3 IMO cases

The IMO (International Maritime Organisation) describes safety rules for shipping for crew and passengers. It has done several researches on evacuation, especially related to human movement. The resultants of this research is described in 'Interim Guidelines for Evacuation Analysis for New and Existing Passenger Ships' [19]. This document describes eleven cases tot verify simulation models. Both Simulex and FDS+Evac passed these IMO-cases.

6 Validating cases

The following cases are done with Simulex version 11 and FDS+Evac version 2.1.0 (SVN revision no. 2645). In all cases the characteristics of the population and the evacuees are the same for both programs. The possibility IN FDS+Evac for humans to start evacuating when smoke is detected by the person is not used, to make a fair comparison between all simulations.

6.1 Simple case, walking speed

In the first case the model contains a 30 meter (98.4 feet) long corridor with one human. The Dutch building regulations describe a walking speed of 1 m/s for an evacuee. This should result in a RSET of 30 seconds. In this model we used a adult male.

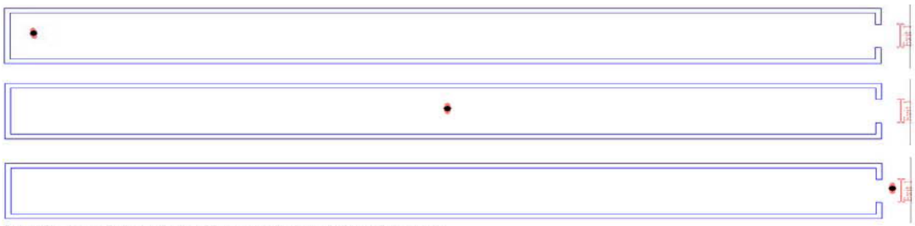

Fig. 3. Graphic view of simulex after *0, 15* and *30* seconds (from top to bottom). The *black/red figure* is the evacuee.

In 30,6 seconds the evacuee leaves the corridor, which corresponds to the base point in the Dutch building regulations.

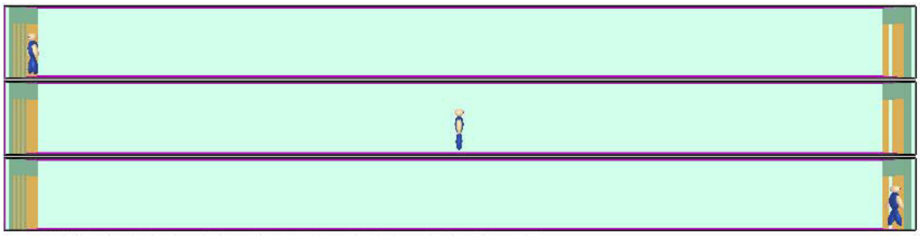

Fig. 4. Graphic view of FDS+Evac after *0*, *15* and *30* seconds, no smoke production simulated.

In 30,1 seconds the evacuee leaves the corridor when using FDS+Evac with no smoke production simulated. The result corresponds to the result with simulex. There is no significant difference.

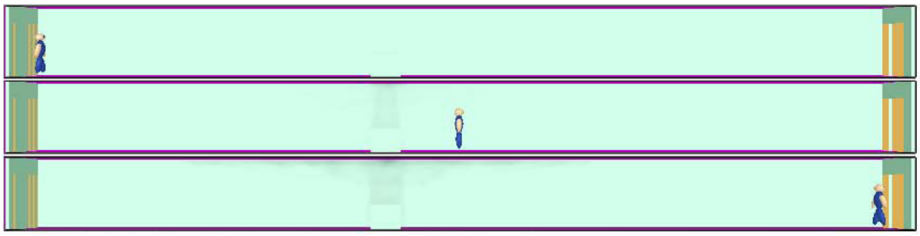

Fig. 5. Graphic view of FDS+Evac after *0*, *15* and *30* seconds, with little smoke production simulated.

The influence of smoke is visible, but because of the low degree of smoke production the walking speeds decreases barely. This results in a RSET of 30,7 seconds. The person reacts on the smoke when the smoke layer height is below 1,6 meter. This can be changed in the input file.

Fig. 6. Graphic view of FDS+Evac after *0*, *15* and *30* seconds, with lot of smoke production simulated.

The smoke production is raised to an un realistic degree to see the influence on the walking speed. The influence is clearly visible, after 30 seconds, the smoke layer is significant and the walking speed decreases to approximately 0,1 m/s. The person keeps walking, the RSET is 87,8 seconds. In normal circumstances a person would not survive this smoke concentration for a long time like this.

6.2 Large number of people through a door

In the second case 90 and 135 evacuees (50% adult male and 50% adult female) are placed on a floor of 10x11 meter, there is one door with a 1 meter width. The same situations as used in 6.1 are simulated. The results are shown in table 1.

Table. 1. Results of evacuation simulation through a door. Comparison of simulex and FDS-Evac and the influence of smoke.

Program	# persons	Smoke production	RSET [s]
Simulex	90	Not possible	61.5
Simulex	135	Not possible	92.8
FDS+Evac	90	None	61.0
FDS+Evac	135	None	90.1
FDS+Evac	90	Little	63.5
FDS+Evac	135	Little	89.7
FDS+Evac	90	High	69.6
FDS+Evac	135	High	118.5

Again Simulex and FDS+Evac have the same RSET value when there is no smoke in the simulation. The influence of smoke is small when the smoke production is low. This can be explained by the low walking speed because of the obstructed exit when the smoke reaches the evacuees. The walking speed can hardly decrease anymore. When the smoke production is high, the visibility decreases a lot. This does result in a significant longer egress time.

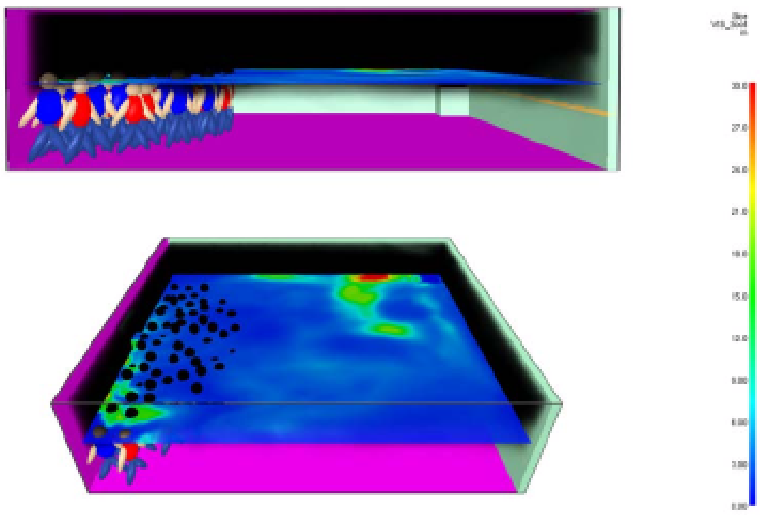

Fig. 7. This figure shows the evacuees in the room obstructing the door. Also the smoke layer is visible and the *visibility* is shown on 1.50 meter height. *Dark blue* means, *no visibility* at all (0 meter) *red* means a visibility of *30 meter*.

6.3 Evacuation from a building with high rooms

The last case discussed here is a church with only 2 exits far too small to evacuate all present people in one minute, as the Dutch building regulations prescribe. This project was simulated by Adviesburo Nieman in two steps. First the smoke free height was calculated using the TNO vultijden model, a dynamic smoke production model to calculate smoke production and smoke conditions. This results in an ASET of 631 seconds, taking 180 seconds as start time for the evacuation. At this time the smoke free height is at 2,5 meter from floor level. With this information a evacuation simulation is done with simulex. The figure is shown below (fig. 8.). De RSET of this room was 321 seconds.

The same calculations were done with FDS+Evac, FDS for the smoke production, Evac for calculating the ASET, both in the same model. This resulted in an ASET of 297 seconds, taking 180 seconds as start time for the evacuation. The smoke layer height is different in both methods. The TNO vultijdenmodel uses a stratified model as a base, FDS also looks at local turbulence and smoke accumulation. This means that FDS is also usable in more complex room shapes and that local positive or negative effects are shown and don’t need to be eliminated by assumptions in the model.

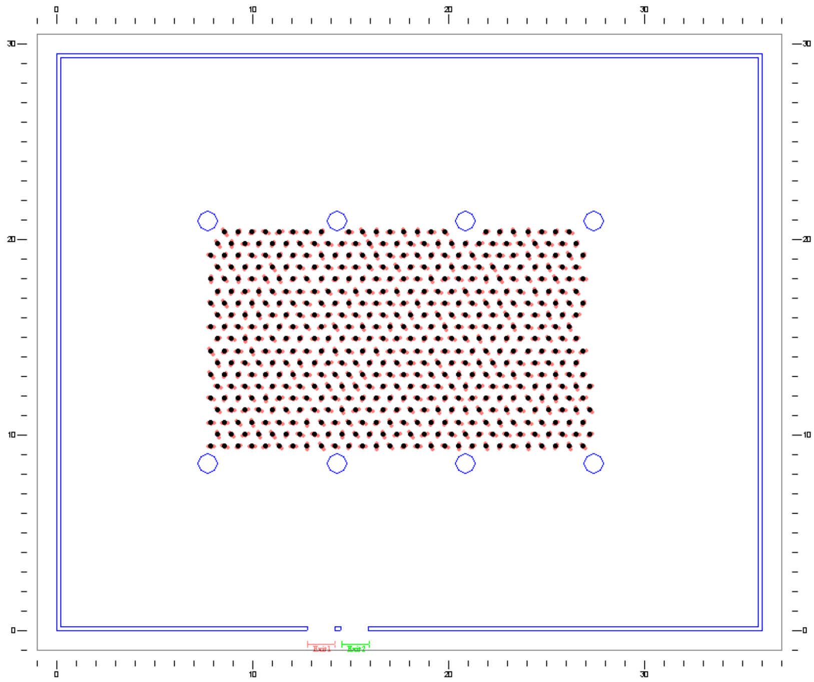

Fig. 8. Simulex presentation of *520 persons* in a church with *two exits* close to each other.

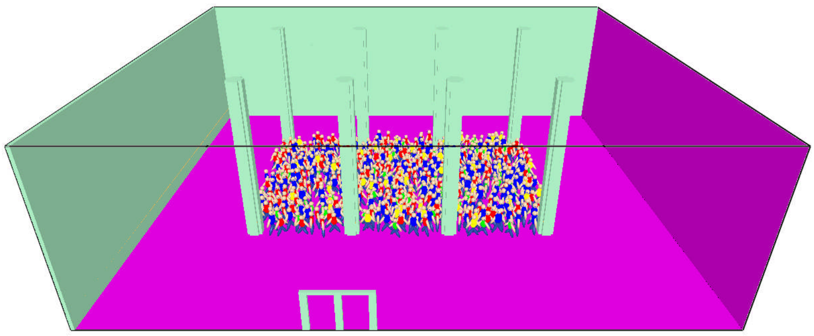

Fig. 9. FDS+Evac presentation of *520 persons* in a church with *two exits* close to each other.

The smoke layer does not influence the egress time, because all people left the building before the smoke is at 1.6 meter height. But there is a difference in egress time between FDS+Evac en Simulex. When taking a closer look at the simulations there is a difference in both models in the distribution of evacuees between the exits. In simulex all evacuees take the nearest exit, in FDS+Evac the evacuees choose the fastest way out, see figure 10.

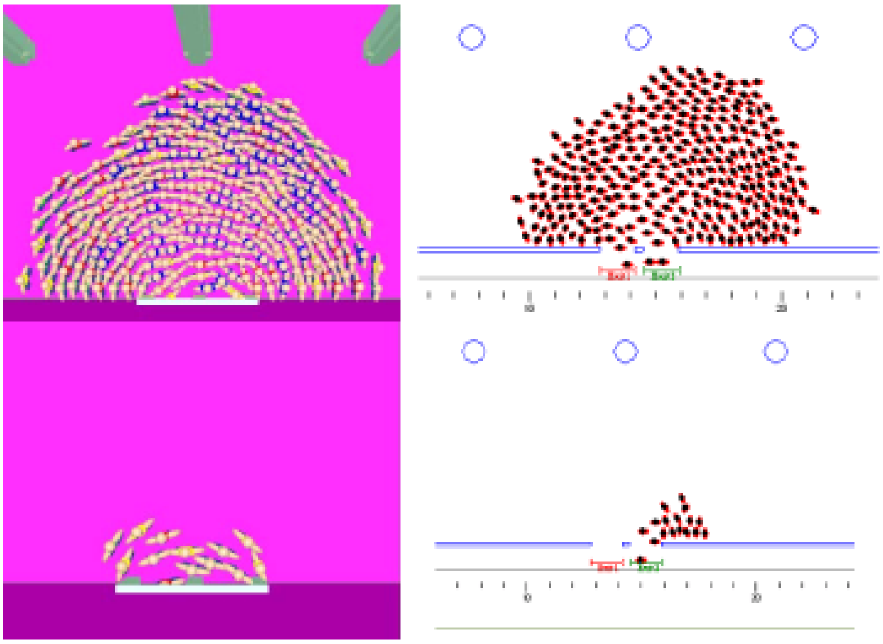

Fig. 10. Difference in evacuee distribution between exits in *FDS+Evac (left)* and *Simulex (right)* on two different time steps. In FDS+Evac the evacuees choose the fastest way out, in Simulex the evacuees take the shortest way out.

Figure 10 shows that the own choice of evacuees is implemented and works It gives a better (in his case more realistic) result. In Simulex evacuees can be forces to use another exit. This must be defined before the start of a simulation. For more complex situations this is hard to estimate.

6.4 Complex multi stage case

Another simulated scenario in a staircase with doors on each floor showed that in FDS+Evac evacuees actually obstructed the exits when they had to intercalate into a moving flow of evacuees. In some situations, the flow stopped because several persons tried to pass the exit together and stuck in the doorway. This is shown in figure 11. This obstruction was only existing in FDS+Evac. The obstructions are a known and realistic phenomenon on evacuations. A closer look at the evacuees I FDS+Evac passing the doorway showed that evacuees also look for small gaps to exit, even if they have to turn their body 90 degrees to fit the gap. Both characteristic are more realistic.

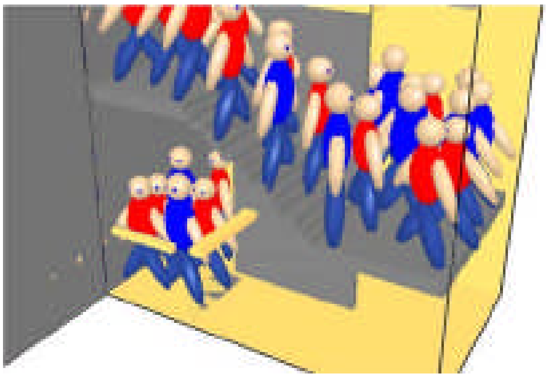

Fig. 11. When two different rows of evacuees had to intercalate, the door became obstructed several times for several seconds in FDS+Evac.

6.5 Conclusion

The cases show that human interaction and human behaviour can be simulated. FDS+Evac showed that the influence of visibility decrease, the intelligence of evacuees to look for a faster way to get to a safer place and the urge to get out of the building while disadvantaging others by pushing and looking for gaps can be calculated. If the influence of these phenomenon is well implemented is hard to say. More study on this subject is necessary.

The FED function in FDS+Evac could be a good addition. Mainly because most victims arises because of toxic gases.

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