Model Situation of Behavior of a Person Endangered by Fire

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Marta Blahova
Faculty of applied informatics
Tomas Bata University in Zlín
Zlín, Czech Republic
m6_blahova@utb.cz

Martin Hromada
Faculty of applied informatics
Tomas Bata University in Zlín
Zlín, Czech Republic
hromada@utb.cz

***Abstract*—When assessing a safe object evacuation in case of fi redevelopment, there is an applicable alternative way of project design to simulate human egress using the mathematical modeling of fire. The article is therefore focused on the case simulations of people´s evacuation in a fire. Basic data about the simulation environment are addressed, as well as the conditions of fire, the characteristics of persons or development, and the assessment of two simulations. The introductory part of the article is devoted to the basics of the mathematical formulation of human movement and behavior during actual evacuation.**

***Index Terms*— evacuation, fire, mathematical modelling, human behaviour, toxicity.**

I. Introduction

We currently live in a time when the fire safety of buildings and fire prevention are significant concerns. Considerable development in this area occurred in the last several decades and the field is constantly developing. Enormous effort is put into the prevention of fire or its subsequent spreading, but there are still situations in real life when one can´t prevent these incidents completely. In most cases, several simultaneous factors may occur that one doesn't foresee and that can't be ruled out even by the best standards. Therefore, it is important to take these aspects into account and reckon with the worst possible scenario or, better still, prepare for it.

Computer simulation programs can provide a prospective way of achieving this goal. Many of them are available in the present time and the the choice depends predominantly on the specific fire or evacuation situation which should be analyzed. One can use them not just for critical scenario projection, but also for reverse simulation when these programs may help to discover the cause of the fire. However, we should know well the mechanisms and mathematical apparatus that the particular program uses to utilize all the available information and so that the simulation could approximate the real situation.

Human safety should be always the major concern, that's why such simulation programs are developed that focus on modeling human movement and behavior. Some of them address just human movement without the influence of fire, which may be useful for assessing the time that people need to escape from a building with a complex structure.

More flexible, though, are applications that make it possible to connect the model of fire with evacuation. The latter way can relate fire impact to human behavior that is naturally influenced by fire. It's not easy to implement these factors into simulation programs because every person reacts to impulses in his/her manner. Therefore, this field is constantly improving. To achieve new findings and data, experimental evacuations are performed that provide useful information.

II. Materials and Methods

Simulation programs for human egress can be divided into many groups according to various viewpoints. From the point of view of model procedures, the evacuation models can be sorted into three categories[1]:

- description of basic aspects of behaviour or movement using equation or equations,
- description of various aspects of human movements,
- connection between movement and behaviour.

The latter mentioned category, which is the main theme of this article, doesn't take into account just the characteristics of the spaces. It also views the individuals as active objects and takes into consideration their reactions to given impulses. These models are characterized mainly by a high level of complexity and elaboration. Basic data about the aspects of human behavior are constantly explored using trial evacuations, and the new findings offer a valuable basis for improving the simulation programs. The following partial sections provide the basics of mathematical modeling of human movement and behavior during evacuation. [1]

The given theoretical grounds are implemented in simulation software FDS+Evac, which served as a tool for simulations in exercises.

III. Movement of persons in simulation

Simultaneous egress of more persons from a room or building can cause life-endangering situations. For example, the problem occurs when the crowd is obstructed by a narrow passage or blocked exit (due to many persons), which inhibits the quickness of the persons in the front of the crowd. The rest of the crowd tends not to stop moving forward and it can block the exit completely. Even a slight pressure from the end of the crowd, which tries to move forward constantly, can cause fractures to people in the front. Another kind of trouble can be when some persons fall a make the evacuation harder for other people. The ability to identify these dangerous situations is very important in modeling.

To simulate the above mentioned situations in a realistic way, it's significant for simulation software to work with real physical forces which can result from situations like these. The main factors that should be taken into account are body's resistance to pressure and friction forces among persons or persons and obstacles. In the program FDS+Evac every person is directed by his or her movement (1). [2]

This procedure enables all simulated individuals to have their exit strategy.

$$m_i \frac{d^2 x_i(t)}{dt^2} = f_i(t) + \xi_i(t) \qquad (1)$$

Where

mi the weight of a person,
xi (t) the position of the person at given time,
fi (t) the force that impacts on a person at given conditions,
ξi (t) the small random fluctuation force,
dxi/dt the speed of a person's movement.

Getting the mentioned coefficients leads to other relatively complex equations include important factors (reaction of the person to fire, contact with an obstacle or other person, etc.).

The shape of the human body is represented in simulation equations by three of mutually connected circles. [3] So, it implies some rotary degree of freedom, when every the person has his or her rotary equation.

IV. Choice of emergency escape

In a model situation, every person considers the position and activities of other escaping people and chooses, my guess, the emergency escape which would help him or her to evacuate fast. The expected time of evacuation consists of the estimation of movement time and the time of queue formation. The movement time is calculated as a quotient of distance to the door and the speed of movement. Calculated time, which depends on queue formation and queuing into them, is a function of activities of other escaping persons. There is also an assumption that people change their behavior only if they have a better option. [3]

Besides the location of escape exits and the other people's activities, more factors should be taken into account. The issues are the conditions related to fire and the person's awareness about location of escape exits and their visibility.

Based on all the mentioned factors, the escape exits can be divided into seven groups and certain preferences are assigned to them. [3] Knowledge of escape exits can be generated, randomly or every simulated person may get it arbitrarily. The visibility of escape exit depends on the density of smoke and also on the location of obstacles. The choice of preferences then depends on conditions related to the effects of fire, like temperature and smoke, which have adverse impact on escaping persons, but they aren't fatal.

Knowledge of escape exit location is the main factor that affects decision making. It's due to unknown conditions that could occur on unfamiliar emergency escape routes and thus increase the danger. Escaping persons prefer to use known emergency escape routes even if faster routes are available but unfamiliar to them.

V. Groups

The crowd consists of partial groups (e.g. families) which tend to act together. In model the situation, the groups' activities can be divided into two phases, one being the collecting phase in which the persons are gradually grouped, and the second phase, in which the group is already moving together along the chosen escape route. [3]

In the collecting phase, the persons try to move towards the center of the group. If the distances among the center of the group and all other moving persons are below the required limit, the group is considered to be complete and it starts to move towards the escape exit. While in the movie, the members of the group try to stick together in order not to disintegrate. This is simulated by the necessary correction of the person's walk speed and by adding the additional force which acts towards the center of the group. The force is called group force and its intensity determines how much the escaping persons try to hold the group together, which can differ from one group to another. For example, the group that consists of mother and child should have more group force than the one consisting of work friends.

VI. Simulation of evacuation in case of fire

This part of the article aims to put together exercises in which the evacuation is connected to the model of fire. This task was executed using the software Fire Dynamics Simulator (hereinafter referred as FDS) and auxiliary module Fire Dynamics Simulator with Evacuation (hereinafter referred as FDS+Evac), while FDS itself serves for creating the geometry of space and the conditions of fire. The auxiliary module enables the simulation the evacuation in the created environment. The main theme of this work is the situation of a fire originating in a nightclub. The subject of simulation is the development of heat with simultaneous emission of toxic fumes that represent the fire and the development of the night club guests evacuation. To give an illustrative example, two exercises were crated which differ in the intensity of given fire and its location in the room (see Fig. 1). This allows comparing the influence of fire on escaping persons that are located in the same room, but they are submitted to distinct effects of fire on different locations.

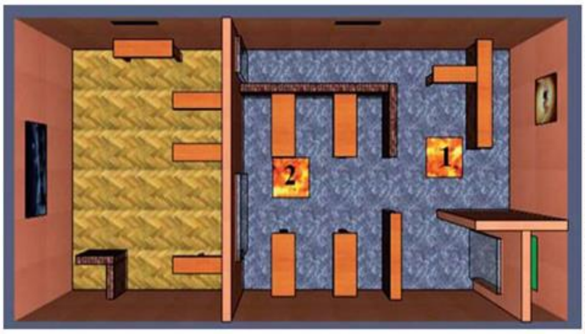


Fig. 1 Depiction of the room for simulation and location of the fire

VII. DESCRIPTION OF THE ROOM

The object chosen for the simulation is a night club with the size of 6 x 12 x 3 m. The inner layout of the object is derived from several existing night clubs. There is only one entrance into the object, which also represents the only escape exit. The club is divided into the room with dance floor and the bar- room. Both rooms are furnished and the furniture forms evacuation obstacles. The ventilation system for the simulation is adjusted commonly. It consists of just two airshafts under the ceiling with the size of 1 x 0.2 m. There is only one in every room. The floor of the dance room is classic parquet floor 1 cm thick, while in the bar-room there is a concrete floor with load carpet 6 mm thick.

VIII. MATERIALS USED AND THEIR PHYSICAL PROPERTIES

All the walls, room dividers, floor (before surface treatment), and ceiling are made of concrete panels, while their surface finish isn't taken into consideration, except for floors. The low dividing wall in the bar-room, the base of the bar, and space for music band service are made of bricks. Table, bar, and parquet blocks are made of the same wood material. For all the mentioned materials, regular physical properties were used. [4]

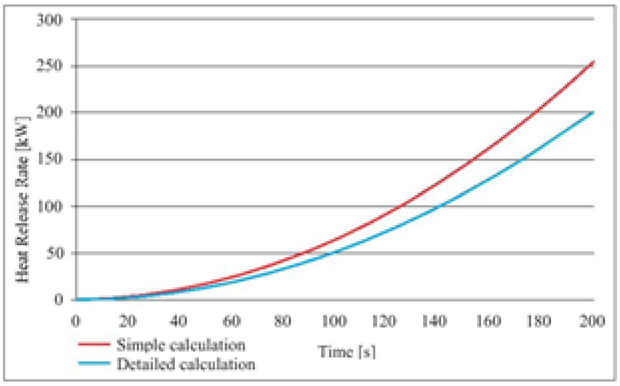
IX. SIMULATED FIRE

To simulate the evacuation after the fire developed, the most important part is the development and spread of the toxic emissions of fire, to which simulated persons react. In the following practical simulations, the designed fire does not spread gradually in the given space and does not take progressively more area. Fire is simulated in the area of 1 m2 and, dependently on time, its intensity grows, and with it the development of toxic emissions. [5]

The rate of heat release during time Q was Unique simple quadratic equations in different time steps and changes into the source code of the program that was able to calculate all values for the next time intervals. The result was a time-dependent parabolic curve in which they affect the rate of heat release the second force of time. The growth of t was calculated α using fire load and carbonation rate coefficient.

The values of A and P were taken into account for the simulation. They refer to the ballroom where a = 1.2 and p = 15 kg.m-2. To determine the value of p, Table 1 was changed, the coefficient as having a constant value of 0.9. Maybe This is not strictly the case with the ballroom space for that it was also necessary to calculate the values of A, P, P, and the final degree of carbonization more efficiently exactly. After a complicated calculation, it is the final one the Q value was lower than using the standard values. However, a higher Q value is important for a single-use calculation and the default value were used to simulate fire. The final fire does not reach too high temperatures, less toxic emissions to which escaping persons react primarily, they are present. It is why the higher Q value resulting from these two possible calculation methods was chosen.

The following graph for expected simulation time of 200 seconds enables to compare the rates of released heat. [4]



Graph 1 Speed of heat release in time

X. SIMULATED PERSONS

General data on simulated persons usually occur in the practice exercises listed in this cast. Behavior, movements, and reactions to the external the program assesses the impact individually for each person, even if they belong to him specific data group according to set parameters. Perform simulations in space nightclub, it is assumed that only adults are present. It is also assumed that people are aware of escape points because it is the only entry to the building that is possible.

Number of persons and their detection and reaction time.

The total number of people in the simulated space The nightclub is 69. The location of var re varies differently in practical exercises (see Fig. 2). That's how it can be assumed that people would start responding to fire in different ways - time intervals due to their location in a space nightclub. The people in the simulations are always divided into three different groups (see Fig. 2) depending on time intervals of noticing the starting fire and their response to it. So their time of movement begins in the time given by equation (2) [3] or even sooner if they notice the occurrence of smoke in their surroundings and specific height level (the height of 1.6 m from floor level was chosen for practical simulations).

$$t_{motion} = t_{start} + t_{noticing} + t_{reaction} \ [s] \qquad (2)$$

The term "start time" means the time from the start of the fire simulation. If there is no delay, the value is standardly 0.

Fig. 2 Division of persons into groups according to different time of the start of evacuation

Reaction of persons to toxicity

The effect of fire gas emission toxicity in software FDS+Evac is determined using the concept of fractional effective dose called FED. The current version of the program uses only the concentrations of CO, CO, and O for the computation of total FED. The concentration of CO is taken into account only due to accelerated breathing (hyperventilation), owing to which big amount of dangerous toxic fire emissions gets into the human organism. There is no substantiated supposition, though, that the concentration of CO_2 would be so high that it would have any toxic effect (over 5 vol. %). [6]

Simulation I.

The computed rate of heat release in time was used in this situation. For the simulation time of 200 s, the highest value of Q = 253 kW was reached, while fire was located in location 1 (see Fig. 1). The number of persons in the particular group and their different detection and reaction time are stated in Tab. 1. About fire location, the longest reaction and detection time was assigned to group 1 and, vice versa, the shortest one to group 3. The time intervals are meant from the start of the simulation.

Tab. 1 Description of persons in the simulation I

Persons	Number of persons	Interval of detection [s]	Interval of reaction [s]	Start of evacuation [s]
Group 1	46	50 - 55	50 - 55	100 - 110
Group 2	19	40 - 50	40 - 50	80 - 100
Group 3	4	35 - 40	35 - 40	70 - 80

During the simulation, persons react in accordance with expected evacuation start times and there were no visible instances when the evacuation would have started sooner in connection with the detection of smoke. Groups 2 and 3 left the space quite smoothly and even in the narrowed parts of the room no congestions of the escape exit occurred. The evacuation of group 1, which started its leave lastly, led to the creation of two evacuation streams.

The bigger stream consisted of 36 persons, who went from the dance floor towards the exit through the main bar room, i.e. through the aisle among tables. Smaller stream consisted of 10 remaining persons, who went towards the exit through the back aisle. These two streams were encountered at the 112th second of the simulation. Subsequently, a delay in the evacuation process occurred due to the great number of persons in the narrow space. At the 154th second of the simulation, there were no persons left in the room. No effect of fire emissions toxicity on escaping persons was recorded during the exercise. Not even in the case when the two mentioned evacuation streams encountered and collide right beside the fire site and were situated next to it for about 30 seconds. Due to the intensity of the designed fire, space was significantly filled with smoke until all the people escaped. The simulation started at the ambient temperature of 20 °C. During the evacuation, it gradually rose to values of 20 - 45 °C in the head level of escaping persons. During the exercise, the fire reached a maximum of 120 °C. [6]

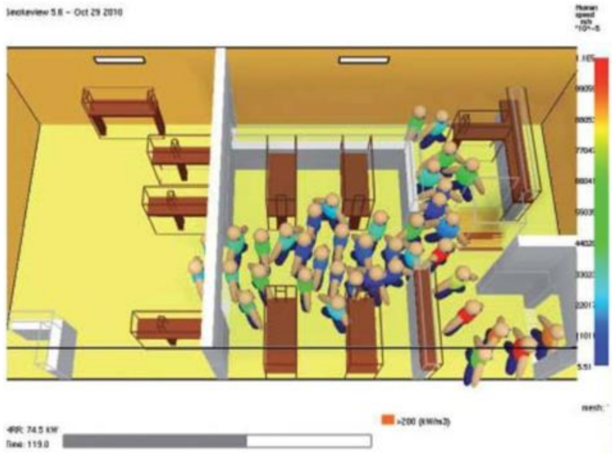


Fig. 3 Speed of motion after the encounter of evacuation streams

Fig. 3 depicts the decrease of escaping people's speed at the time when the two streams of group 1 encountered. The time progress of the simulation and amount of the released heat [kW] at the given time is visible in the lower part of the picture. Colour scale to the right represents the speed of escaping persons' motion which is coloured according to these values. The scale starts with the value of 5.51 · 10-5 m.s-1 (blue colour) and ends with the value of 1.1 m.s-1 (redcolour). [6]

Simulation II

Almost three times higher rate of heat release than in simulation 1 was chosen for this simulation. The reason was to manifest the effect of fire emissions toxicity on escaping persons. If the duration of the simulation was 200 s, then the highest value of Q = 731 kW, while the fire was located in position 2 (see Fig. 1). Numbers of persons in the particular groups and their different detection and reaction times are stated in Tab. 2. Due to fire location, the shortest reaction and detection time was set to group 2 and slightly longer one to groups 1 and 3.

Tab. 2 Description of persons in simulation II

Persons	Number of persons	Interval of detection [s]	Interval of reaction [s]	Start of evacuation [s]
Group 1	46	50 - 55	50 - 55	100 - 110
Group 2	19	35 - 40	35 - 40	70 - 80
Group 3	4	40 - 50	40 - 50	80 - 100

To start with, it's necessary to mention that the use of evacuation obstacle in the fire room was abandoned in this simulation exercise, which of course had some impact on the whole evacuation process. The reason of doing so was that it can serve as an illustrative example of the fact that escaping persons aren't discouraged by higher temperature of fire and they escape through the fire site as well.

In the course of the simulation, people reacted in the samewayasinsimulation1,accordingtoexpected evacuation start times, with only one exception. The mentioned exception was one person from group 2, who was located right inside the fire site. That's why this person reacted just on the occurrence of fire and started to escape the room on the 52th second of the simulation, which was 18 seconds sooner than their minimal evacuation start time.

The rest of group 2 and group 3 started to escape the room in accordance with their set evacuation start times. In the course of the evacuation of group 2, a reaction to toxic fire emissions was observed in the case of two persons. Evacuation of group 1 went almost identically as in simulation 1, but with the difference that 25 persons reacted to fire emission toxicity.

This was the case of persons who escaped through the main bar room and thus close to the fire or directly over it. There were no persons in the room on the 157^{th} second of simulation. Simulation started at ambient temperature 20 °C. During the evacuation, the temperature gradually rose to values of 20 - 90 °C in the head level of evacuating persons. In the course of the exercise, the temperature of fire reached maximum 470 °C. [7]

Fig. 4 illustrates the impact of toxicity on escaping persons. Also it helps to notice added smoke filling in comparison with simulation 1 due to higher rate of heat release. Colour scale on the right side illustrates the values of FED. It starts on the value of 0 (blue colour) and ends with the value of 2 · 10-5 (red colour).

Fig. 4 Response of persons to the toxicity of fire emissions

XI. Conclusion

There is one positive aspect - all the persons left given space in expected time and their movement wasn't stuck due to some obstacles. Group 1 divided itself into two evacuation streams according to algorithms of simulated persons who tend to seek the shortest way to the escape exit from their specific locations. Given the intensity of the set fire, there wasn't any demonstration of impacts of the fire emissions toxicity on escaping persons.

The course of the simulation was then generally trouble-free. On the other hand, one should mention that so called evacuation obstacle that escaping persons needed to avoid had to be placed in the space of the fire site. Otherwise the persons could move over the space of fire, which would be unrealistic. According to practical examples provided by the authors of FDS+Evac it's clear that the problem can be provisionally solved by placing the fire on elevated site that would be avoided by the persons anyway.

We can expect that the imperfection will be eliminated in the future, but we should provide for that when forming the simulation problems for now. In the course of this simulation, all the persons also left the room in expected time and their movement wasn't stuck due to obstacles of fire. Group 1 again divided itself into two evacuation streams which moved identically as in simulationI . In the course of the simulation, the toxicity had some influence on escaping persons, but the level of toxicity wasn't so high to paralyse in any way the persons on one place (which would happen in the case of exceeding the specific limit of FED in relation with current algorithms of FDS+Evac).

As mentioned earlier, evacuation obstacle in the fire site wasn't used in the course of this simulation. Evacuating persons thus passed smoothly over the fire site, even though there was quite a high temperature, as is well evident from Fig. 4. It can be expected that in real situation at such a high temperatures, people would turn towards a side aisle. But algorithms like FDS+Evac don't operate in this way. Simulated persons mainly react to smoke-filled space, which can affect the choice of escape exit (if there is such an option), and to the value of FED, which they consider as acceptable and continue to evacuate, or the value is so high that people are paralyzed and freeze in place - die.

Fire can influence the conditions of evacuation considerably. Thanks to the connection between FDS and evacuation module FDS+Evac, it is possible to take into consideration the effects of fire, like, for example, fire temperature, smoke density and its toxicity or the amount of heat radiation. The smoke has an impact on the speed of escaping people's motion. It can also affect the algorithm of choosing the escape exit by its density.

The article was devoted to characteristics, development and objective evaluation of virtual simulations of people's evacuation in fire conditions. The assessment of simulations revealed the positive and negative aspects of the whole evacuation process which partly follow from the algorithms of simulation module FDS+Evac. Making the computer simulations using this software should involve considering the positive and negative findings and taking them into consideration. Simulation can approximate the real situation more closely in this way, which should be its main objective.

Mathematical modelling of evacuating people's behaviour is permanently improving and developing. Newfindings,resultingfromexperimentalevacuations, are still being discovered. This knowledge is gradually implemented into mathematical equations.

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