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ANALYSIS OF HUMAN BEHAVIOR AND EVACUATION IN BUILDING FIRES USING COMPUTER EVACUATION MODELS

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Abstract

Human behavior in critical situations is at the core of all concerns about the fire safety of buildings, regardless of their destination. The way in which the human caught in the fire reacts to the risk factor to which he is exposed, his behavioral response to the direct action of the fire, or his psychological response to the effect of the fire (temperature, smoke opacity, reduced visibility, exposure to toxic combustion gases), are all factors that can drastically influence the required safe escape time. All these considerations underlie the modern evacuation models used both in the design phase of fire-safe buildings and during the post-event investigation of these undesirable situations. This paper analyzes the possibilities of using the computerized evacuation models and highlights the advantages of using the engineering approach in the field of fire safety.
A study was conducted using Pyrosim specialized software and one of the most popular evacuation model, namely FDS+Evac, in order to evaluate the numerical model's capability to predict the occupant evacuation in the case of a presumptive building fire scenario.

Key words: evacuation models, FDS+EVAC, fire safety engineering, fire simulation, human behavior

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1. Introduction

Human behavior research has shown that any action taken in a particular situation is the result of a complex, behavioral or decision-making process, rather than based on random reactions and choices resulting from environmental changes (i.e., stimulus-response relationships) (Carter, 2017; Hutchison, 2018; Kuligowski, 2009). The study of human behavior in fire has a multidisciplinary character, involving notions in the field of engineering, architecture, informatics, mathematics, law, sociology, psychology, communication and ergonomics etc., with the ultimate goal of minimizing the risk of fire exposure (Mawson, 2007; Stahlschmidt et al., 2015). In emergency situations, including fire exposure, the human behavior is characterized by *the response to this risk factor*, including awareness, beliefs, attitudes, motivations, decisions, comportments and strategies to combat this exposure.

The human response to fire is a very complex process and varies greatly so that theories developed over time have a rather partial than general nature. Often, the human response to fire is characterized in a simplified way through two main periods: the pre-evacuation stage and the reaction or evacuation stage, with a rather low emphasis on understanding the behavioral processes taking place in each of the periods (Kuligowsky, 2016, 2017).

The rapid development of the numerical computing capabilities and the reduction of IT technology costs have contributed to the extensive development of computerized models in all engineering fields, particularly in the field of

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evacuation. Engineers carrying out life-safety analyzes for building-type structures are having today a number of distinct tools, from which they can choose the optimal one for the selected task. Depending on the type and destination of the building and the time allocated to the analysis, engineers can opt for a range of techniques, including empirical calculations, engineering calculations, manual calculations, or computer modeling. Hand calculations usually follow the equations given in the Emergency Movement Chapter of the Society of Fire Protection Engineers (SFPE) Handbook to calculate mass flow evacuation from any height of building (Nelson and Mowrer, 2002).

Computerized evacuation models represent a diverse set of methods and techniques, starting from a relatively homogeneous flow of occupants, to autonomous agents, moving freely through a three-dimensional space. Some computerized models incorporate empirical engineering and manual computations, effectively automating the modeling process. It is important that these evacuation models take into account both the building characteristics and the occupant behavior. Furthermore, they are in a process of continuous improvement, adding new factors that prove, through research and statistics, that they influence the evacuation processes of occupants in building fires (Kasereka et al., 2018; Li et al., 2018).

Most current evacuation models use human behavioral aspects based mainly on theoretical assumptions and less on experimental data obtained by conducting evacuation drills that correspond to different possible situations and statistically processed (Gwynne et al., 2015). If over the years, in the development of evacuation models, the main focus was on the physical aspects that characterize the agent movement, on the choice of optimal evacuation pathways and on the avoidance of obstacles or dangerous areas, in the future, model validation will be one of the most important research directions in this field (Chen et al., 2019; Gwynne et al., 2015; Isobe et al., 2004; Ronchi and Kinsey, 2011).

Currently, there are more than 30 computer models that focus on providing evacuation data from buildings. Many of these models can also simulate evacuation from other types of structures. Of the most known evacuation software, we can mention the following: EXIT 89, EVACNET, ASERI, Building EXODUS, WAYOUT, Legion Studio Enhancement Pack, Myriad, EXITT, SIMULEX, EgressPro, FDS+Evac, Pathfinder.

Concurrently with the continuous development of the above-mentioned models, there are many new researches which are studying new numerical models, optimized for egress processes in a various field of applications. The evacuation models are able to deal not only with fire, but with any other imminent threat, an ongoing threat or a hazard. There are many case studies ranging from evacuation under non-emergency situations (Chen et al., 2018), small-scale evacuation of a building due to fire or storm (Rozo et al., 2019; Sheeba and Jayaparvathy, 2019), to large-scale evacuation planning in case of natural disasters, industrial accidents (Dulebenets et al., 2019, Phark et al., 2018; Pupăzan et al., 2017) or traffic accidents (bus evacuation – Liang et al., 2018; multimodal transportation network emergency evacuation - Yang et al., 2017).

In this paper, we will discuss the FDS+Evac model, due to the facilities offered and the possibilities of integration with the analysis of the fire dynamics and smoke spreading. The model presents a basic implementation of the behavioral characteristics that dictate the individual's response to the emergency situation, offering the possibility of defining multiple human profiles (depending on gender, age, physical ability / disability), as well as simulating the influence of fire, smoke visibility and toxic products combustion on the evacuation process, as stated in the following sections.

2. Material and methods

2.1. Theoretical aspects regarding the human behavior in building fires.

In the particular case of building fires, the stages and factors that influence each action are specific to occupants exposed to the risk, geometric and structural complexity of the building, and to the extent of the fire phenomenon. Generally speaking, the human response can be synthesized through two distinct stages, the pre-evacuation stage and the actual evacuation, each of these periods consisting of several phases with characteristic activities.

Thus, after the occurrence of the fire, occupants in the building are aware of the risk to which they are exposed, either by alarming or by observing specific indications (smoke, flames, information from others, etc.); in the literature, this stage is known as *the pre-alarm phase* or *the perception / reception of external physical and social clues phase* (Kuligowski, 2016). The perception phase thus involves the reception or observation by the occupant of the clues that lead him to become aware of the fact that there is a change in his neighborhood, namely a possible exposure to risk.

During this stage, occupants may also face complex states and situations, such as uncertainty, contrary or overloaded information, time pressure, or even their own emotions and memories of a previous particular event.

In the next phase, *the interpretation phase,* the occupant attempts to interpret the information received. Interpretation can be described as a process of organizing the received clues, building a meaningful scenario, based on clues, giving a mean to the situation, by risk awareness. Interpretation can be based on previous experiences, mental simulations, use of mental models, risk exposure analysis, etc. If the occupant recognizes the clue, correctly defines the situation and understands the risk, he will take protective actions in order to begin the evacuation process. In reality, however, at least initially, occupants tend to interpret the situation as if nothing is wrong, not considering themselves exposed to risk, this being a normal trend. To determine the rescue actions, people must interpret the situation as dangerous.

The third phase of the behavioral process, *the decision-making phase* or *the protective action phase*, involves occupants making decisions on the activities to follow, based on their interpretation of the clues, the situations and the risks. Typically, this phase consists of two parts: the occupants initially seek options about what to do, and then choose one of these options. The literature states that individuals or groups develop a limited number of options, often very small, or even insufficient, due to factors such as: time perceived as a pressure, limited mental resources, insufficient training and knowledge of emergency procedures. In the second part of the decision making phase, choosing the option to be executed, the rationality-based research claims that the occupants will make the optimal choice by taking into account all the options developed and choosing the best (strategy of rational choice). The choice of actions is based on heuristic diversity, simple rules in fact. Understanding these phases is very important because, in certain fires that take place inside buildings, the pre-evacuation stage can take significantly longer than the evacuation or action-taking period. Decisions may involve changes in time, under the action of new environmental indices, or the emergence of new risk situations. These decisional changes can also occur in the evacuation stage and involve mental simulations, followed by the identification of the new options to follow.

The evacuation stage generally consists of a single phase, also called *the action phase*. In this stage, the occupants implement the decisions taken in the previous phase. Action involves the execution of a physical act and takes place over a period of time. Actions may include, as the case may be, the following activities: searching for information, waiting for, investigating the incident, alerting the persons involved, preparing for personal evacuation or assisting others, fighting with fire, searching for victims and saving them. During the evacuation stage, a distinction must be made between the goals or purposes and the actions taken by the occupants. Thus, the goal is a general objective of the individual caught by the fire (e.g., fighting with fire, saving itself or others), a goal that translates into a series of actions.

Schematically, the response of the occupants to an emergency situation inside a building can be represented as shown in Fig. 1 (Kuligowsky, 2016).

The particular mode in which each individual acts to the risk factor is very much dependent on his behavioral responses to alarm signals, to direct fire action, and to psychological response to fire effects (Bahrepour et al., 2010; Diaconu-Sotropa, 2014).

2.2. The behavioral response to alarm signals

The behavioral response to alarm signals is conditioned by people's ability to hear or see an alarm (audibility and visibility). The ability to hear and recognize an acoustic signal may depend on the frequency of the signal (generally, people hear the low frequencies better than high frequencies), the ambiental noise level (influenced by traffic noise, or by the noise of the air conditioning or other various industrial equipment), or the physical condition of the occupant.

The physiological ability of an occupant to withstand the conditions created by the fire - heat, smoke and gases - depends on a combination of factors: age, size, weight, pre-existing physical or medical problems, the presence of medication, drugs, alcohol. According to statistics, at least 10% of those who die in residential fires were affected by alcohol or other types of drugs at the time of death. In the case of people with hearing problems or people on sleeping pills, the alarm signal should have an ambient sound level of more than 100 dBA, so that it can be heard. Unfortunately, people do not respond well enough to non-voice signals, because they do not know for sure the meaning of those alarm signals. They cannot always distinguish between a fire alarm, a test of the building's signaling system, or a training exercise.

2.3. The behavioral response to the fire direct action

Behavioral response to direct fire action is based on human behavioral categories, defined as being the core components of the decision-making process by affected personnel: recognition, validation, defining, evaluation, engagement and re-evaluation.

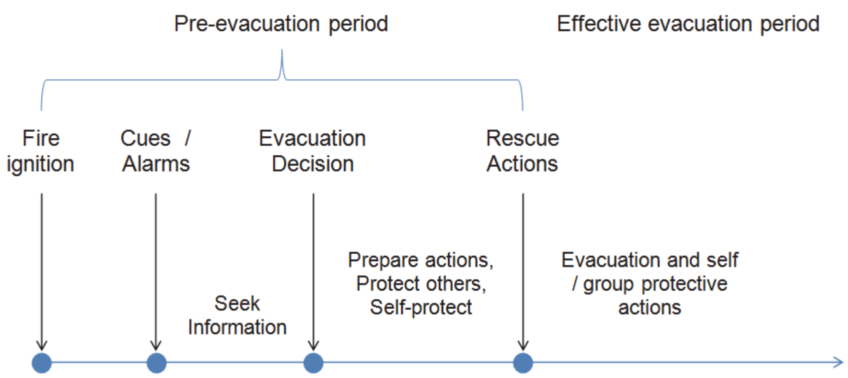


Fig. 1. Timeline of a human response to a building fire emergency

Another way to explain people's actions in the event of a fire is to use four socio-psychological concepts: avoidance, engagement, affiliation, cooperative behavior and role (Cheng and Zheng, 2019; Yang et al., 2017).

2.4. The psychological response of the occupant to the effects of fire

The process of selecting the resistance and survival criteria (important in determining the success or failure of a proposed project) is a critical component of life risk assessment. This process is based on conditions that have a psychological impact on people: temperature, heat flow, smoke opacity, oxygen deficiency, exposure to exhaust gases and constitute *the psychological response of the individual to the effects of fire*.

Temperature. The effects of temperature vary with the amount of heat exposure time, the relative humidity (air humidity increases the effects of heat), the breathability degree. Temperatures above 44° C may begin to cause burns on the skin; at above 50° C severe breathlessness (mouth, nose and esophagus) occurs. Over 100°C, death occurs due to hyperthermia. To estimate the severity of burns, the combination of temperature and exposure time required to cause burns, should be taken into account. The higher the temperature, the faster the burn will occur. For example, a second grade burn occurs in 60 seconds with a temperature at skin surface of 71°C, in 30 seconds with a temperature at skin surface of 82°C, or in 15 seconds with a temperature at skin surface of 100°C.

Heat flow. Describes the availability for the heat transfer form specific to any surface, including human skin (generally, the upper limit of the heat flux without severe pain is 2.5 kW/m^2 for 3 minutes, equivalent to holding a hand at 100 mm distance from a 100 W bulb, for 3 min).

Smoke opacity is closely related to visible smoke, which adversely affects the human psyche through two components: reduced visibility and irritation and intoxication caused by the inhalation of smoke particles. At the same time, smoke can also have an emotional effect, causing fear installing (Isobe et al., 2004; Sheeba and Jayaparvathy, 2019; Zheng et al., 2017). Although recent studies have shown that smoke does not stop, in most cases, the movement, even in increasingly bad conditions, however, the reduction in visibility leads to decreased evacuation ability.

Lack of oxygen. The respiratory and nervous systems have adapted their operation to an oxygen concentration in the air of about 21%. When there is a slight decrease in oxygen in the air, psychological effects occur. The effects of lack of oxygen on each individual vary, sometimes within very high limits, depending on age and general state, but fall within the limits of the table below (see Table 1).

Exposure to combustion gases. Carbon monoxide poisoning, according to reports, caused about 50% of the victims of fires; carbon monoxide combined with other factors is responsible for another 30% of the dead. Carbon monoxide is very easy to combine with hemoglobin, lowering the ability of the blood to carry oxygen; it is so dangerous that, even in small quantities, it can cause disability or even be fatal. A measure of toxicity is the *concentration of exposure*, *C*, in parts per million (ppm) × exposure time in minutes (min), namely C × T (ppm × min); any carbon monoxide concentration exceeding 35,000 ppm × min is dangerous (Table 2).

Carbon monoxide levels are frequently expressed as the percentage of carboxyhemoglobin (COHb) saturation in the blood. In general, carboxihemoglobin levels below 30% will not affect a person's ability to save himself from a fire; however, from 40%, rescue process becomes more difficult.

Table 1. Effects of oxygen deficiency on human individuals

Oxygen percent in air (%)	*Exposure time*	*Effects*
17 ÷ 21	Undefined	Decrease in breath volume, loss of coordination, difficulty in thinking.
14 ÷ 17	2 h	Rapid pulse, dizziness
10 ÷ 14	30 min.	Nausea, paralysis, insensitivity to pain, rapid tiredness, trouble of judgment
9	5 min.	Loss of consciousness
6	1 ÷ 2 min.	Death

Table 2. Effects of carbon monoxide on people

C_{CO} (ppm)	*Exposure time (min)*	*CxT (ppm x min)*	*Effects*
200	120 ÷ 180	24000 ÷ 36000	Mild headache
800	45	36000	Mild headache
3200	10 ÷ 15	32000 ÷ 48000	Dizziness
3200	30	96000	Possible death
6900	1 ÷ 2	6900 ÷ 13800	Dizziness
12800	0.1 (2 ÷ 3 breaths)	1280	Unconsciousness
12800	1 ÷ 3	12800 ÷ 38400	Death

At saturation levels of 50% ÷ 60%, severe symptoms and even death occur. It is important to note that although the carboxyhemoglobin levels are useful in measuring the toxicity, the size of the exposure is not taken into account. The CxT measurement also takes into account the exposure time of the victim to the hazard.

3. FDS+EVAC Computerized evacuation model

Mathematical models designed to analyze the evacuation of persons in a building fire situation can be used to assess the security provided by buildings during evacuation process. The computational algorithm for agent moving, for the case of FDS + Evac model, developed and maintained by the Technical Research Center of Finland (VTT), is based on the Helbing method. The model input data required for the evacuation module to describe a particular scenario are transposed as a text file, with the same structure as those used for FDS (Fire Dynamics Simulator) simulations (Korhonen, 2018).

FDS + Evac module calculates the position, velocity and doses of toxic gases for each individual (agent) within the computing domain, at each time step. People are modeled as agents, moving in 2D geometries, representing the floors or levels of the building. The movement of each agent is described by a motion equation; this approach allows each occupant to have his / her own evacuation moves or strategies. Agents encounter forces and moments of contact, their own psychologies, motivational forces and moments. The resulting equations of motion for translational and rotational degrees of freedom are solved using the methods specific to the dynamics of the dissipative particles. Thus, the model uses time and space to characterize the trajectory of the agents. FDS + Evac allows modeling of situations characterized by large masses of occupants, as well as the interaction between evacuation and fire development simulations.

The size of each agent is represented by three circles, approximating the elliptical cross section of the human body (Fig. 2).

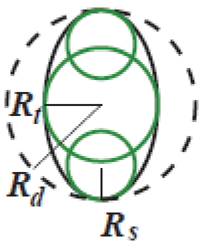


Fig. 2. Human body shape (basic representation) in FDS + Evac

The agent's movement algorithm in FDS + Evac has as its starting point the method developed by Helbing's group, introducing the so-called social force to allow agents to maintain reasonable distance from walls or other agents. FDS + Evac uses the laws of mechanics to track agent trajectories while making calculations. Each agent follows his own equation of motion (Diaconu-Sotropa, 2014; Kuligowski, 2016):

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

where: $x_i(t)$ – location of agent i at time t, $f_i(t)$ – the force exerted on the agent by the outside environment, m_i - agent mass, constant during the analysis, and $\xi_i(t)$, casual fluctuation of force, having generally a low value. The agent's speed is given by the relationship $v_i(t) = dx_i / dt$.

The force acting on the agent i has several components:

$$f_i = \frac{m_i}{\tau_i}(v_i^0 - v_i) + \sum_{j \neq i}\left(f_{ij}^{soc} + f_{ij}^{c} + f_{ij}^{att}\right) + \sum_w \left(f_{iw}^{soc} + f_{iw}^{c}\right) + \sum_k f_{ik}^{att}, \quad (2)$$

where: the first sum describes the agent-agent interactions; the second sum describes the agent-wall interactions; the third sum may be used for other agent-medium interactions (e.g., agent repulsion against fire).

The rotational degrees of freedom are treated similarly, i.e., each agent has its own rotational equation of motion (Korhonen, 2018) (Eq. 3):

$$I_i^z \frac{d^2 \varphi_i(t)}{dt^2} = M_i^z(t) + \eta_i^z(t) \quad (3)$$

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

By interfacing with the FDS program as a modeling platform, easy access to all parameters of local fire development, such as gas temperature, smoke density, visibility, etc., is ensured. As a result, it can be simulated the influence of fire effects on the evacuation process as well as the influence of people on the fire. The toxic effects of combustion reaction products are treated using the *Fractional Effective Dose* (FED) concept, taking into account only the concentrations of CO, CO_2 and O_2 (Eq. 4):

$$FED_{tot} = FED_{CO} \, x \, HV_{CO2} + FED_{O2} \quad (4)$$

It is noted that the Eq. (4) does not contain the effect of HCN, which is also a dangerous gas, and the CO_2 effect is only caused by hyperventilation, assuming that CO_2 is so low in concentration that it does not have narcotic effects.

The FDS+Evac was validated by its developers, by comparing the obtained results to experimental data on human flows, especially on horizontal paths and stairs. The specific flows for the different default agent types (adult, male female, elderly or child) were compared to experimental values, in various scenarios: specific flows through corridors, staircase of an office building or evacuation in a public library, showing in general a good prediction with the experiments (Korhonen, 2018). There are also some parallel validations of FDS+Evac with other evacuation models like Simulex, MASSEgress or Pathfinder.

4. Results and discussions

The stages of human evacuation from a building fire, using FDS+Evac model and Pyrosim software, can be summarized as follow:

- Activation of the FDS+EVAC module from the PyroSim application;
- Defining the evacuation mesh for the analyzed geometry;
- Defining the analyzed building geometry;
- Defining the specific parameters for human evacuation (detection time, reaction time, egress speed, etc.)
- The placement of agents in the analyzed model;
- Placement of virtual measuring and recording devices, useful for the analysis (FED detectors, thermocouples, gas-phase devices for CO, CO_2 and O_2 concentration detection, temperature and visibility slices, etc.);
- Defining the boundaries between the multiple meshes (e.g., for multi-level buildings);
- Defining the exit / exits;
- Defining the running time for the analysis;
- Running the analysis;
- Reading and viewing the results, using Smokeview application, or in graphical form (see Figs. 3-4).

It should be noted that in case of evacuation of personnel from a building, there are factors that make difficult or even limit the movement of the occupants to the safety zone. These factors are related to the geometry of the building, and are in the form of the access doors, elevators, corridors or stairs. Ramps or stairs require further analysis, as they do not present sufficient validation in the FDS + Evac model so far. Smoke visibility has a major effect on the ability of occupants to evacuate safely from a fire. The factors that influence visibility are the amount of smoke particles in sight and the physiological effect on the eyes, which could affect decision making. Some researchers propose the rule that occupants must have, during exit, a visibility of at least 3 meters in the primary fire compartment and 10 m for the fire escape routes. For demonstration purposes, Fig. 3 illustrates the modeling capabilities offered by the FDS+Evac module, in the case of an evacuation study of people evacuation for a two-level building with library and conference room destination. The specific feature of this building is the presence of the two 180° ramps with an intermediate stairway, which connect the two floors of the building.

The presented virtual model allows the acquisition of data obtained through the fire simulation, in the same time with the visualisation of the smoke generation and migration through the two access stairs. There are 50 occupants with adult profiles who will be evacuated from the first floor, and another 50 occupants at the ground floor.

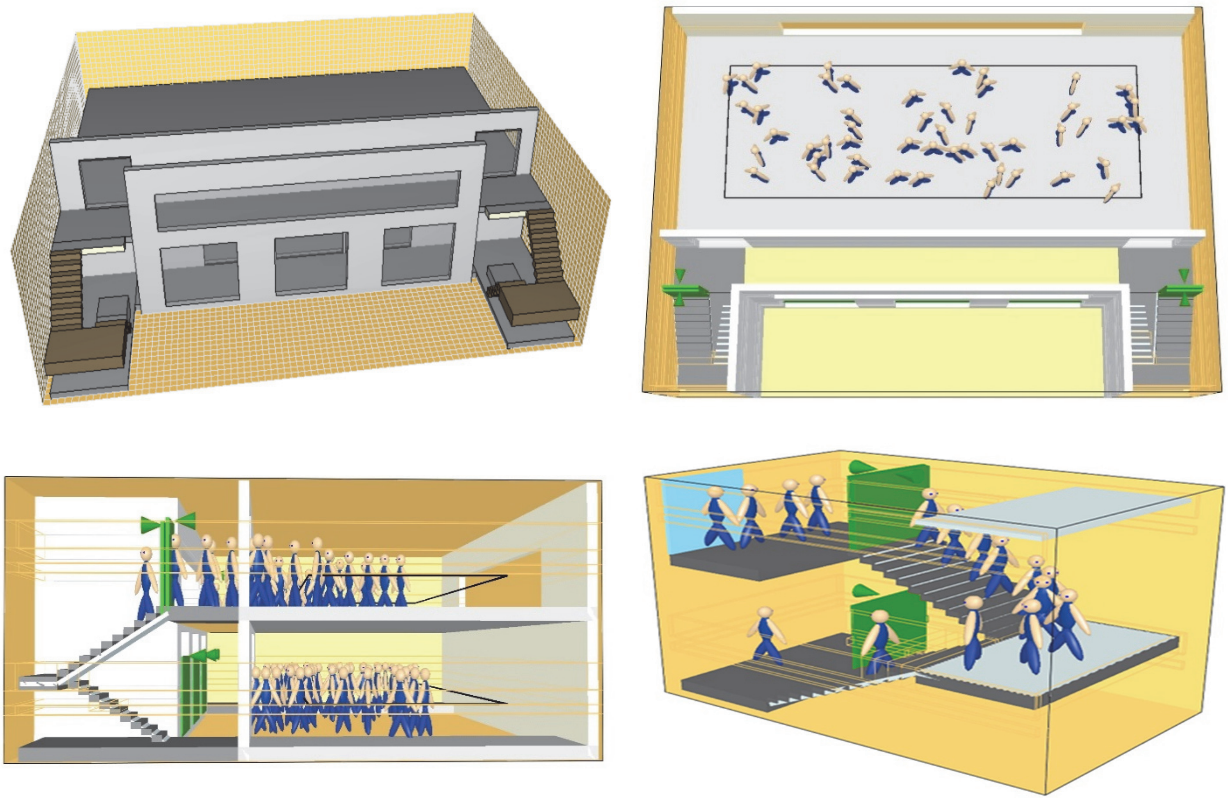
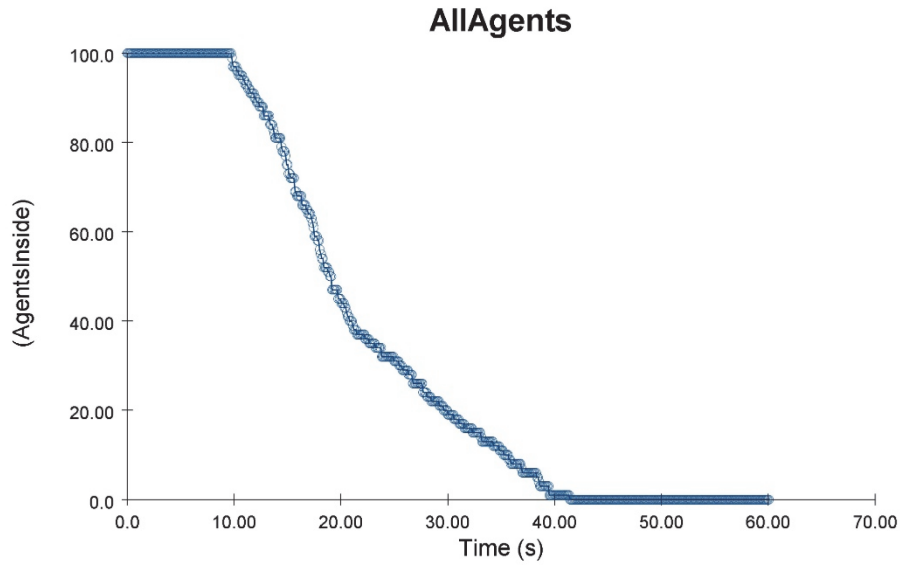
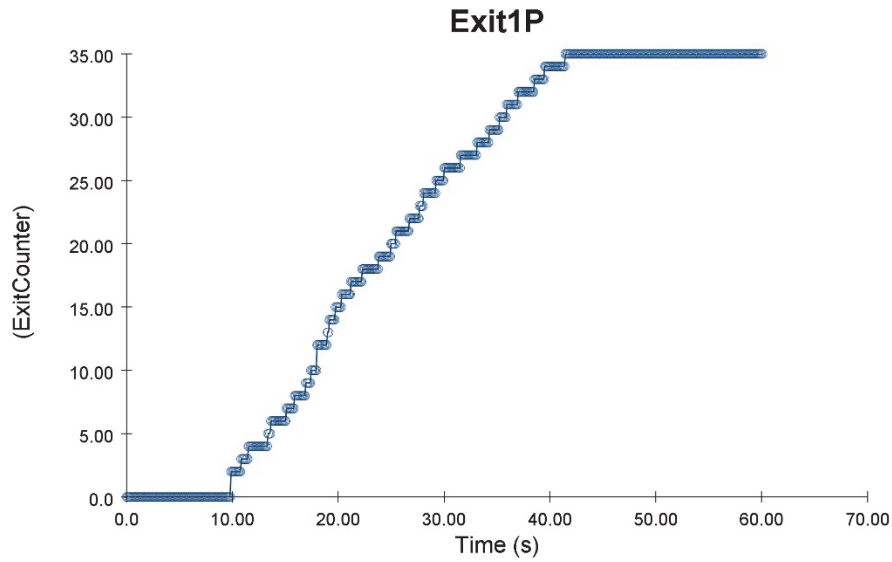


Fig. 3. Tridimensional model of a 2 floor building and the egress process modeling, using FDS+Evac



(a)



(b)

Fig. 4. The evolution of evacuation process (a) and the occupants flow through one of the exit doors (b)

The graphs of occupant evacuation, for the entire building and the agent flow through the exit doors situated on the ground floor are presented in Fig. 4.

5. Conclusions

The main goal of human behavioral research and its implementation in practice is to minimize the risk of exposure to fire. This can be done by generating and collecting quantitative and qualitative data on human responses that can be used to develop the theory of the individual's reaction to fire. The areas of fire safety and design of fire-safe buildings do not always take sufficient account of this behavior, often resorting to simplifications and generalizations.

Current evacuation models, including evolved numerical modeling tools, are used to calculate the time needed to evacuate the buildings, which can later be used in fire safety engineering analyzes. Although there is a wide range of evacuation models internationally, the need to integrate the theory of human behavior into these models as well as their experimental validation remains challenges that specialists have to respond to.

Using the FDS + Evac module, the interaction between the evacuation process and the fire development phenomenon can be modeled for crowd of people, located in enclosed spaces. FDS + Evac can also be used to analyze the issue of evacuation without having to do calculations related to the presence of fire.

In this paper, we treated the human response to emergency situations as a complex behavioral process, determined by a series of physical, social and psychological factors. In our future work, we plan to achieve a validation of the FDS+Evac evacuation model, both by comparing the results with own experimental data sets and with those obtained using other computerized models (e.g., Pathfinder).

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