Simulations of Fire Evacuations in "Sigma FS" Software as a Fire Safety Training Instrument

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ABSTRACT

This paper deals with an up-to-date fire evacuation simulation technique and explores the possibilities which a simulation gives to solve fire safety training tasks in buildings. To model evacuation an individual discrete-continuous model is used. To model fire spread a CFD approach is realized in program code. Both modules work with one initial building file that provides the opportunity to make integrated simulations of both processes and make a time-spatial analysis automatically. Some case studies of fire evacuation simulation are presented.

KEYWORDS: Evacuation modeling, numerical simulation, fire safety training.

INTRODUCTION

Fire evacuation simulations are used in many fields from organization of mass events to fire safety of buildings, ships, and aircrafts. The main task of applying such simulations is to estimate the total evacuation time in different scenarios, duration of congestions, compare this time with time available for safe evacuation from a building and provide/find safe conditions for visitors, passengers in emergency situations. In a regime of every day operation of the building, a number of different scenarios may be used for virtual training systems to instruct staff on means of supporting evacuation. Under construction/reconstruction, simulations of fire spread and evacuation are applied for design of fire safety equipment (alarm systems, ventilation, smoke removing systems, fire extinguish systems), geometrical sizes of evacuation routes and the whole construction, safe delay of the evacuation start, people initial position, etc.

The software tools are based on different mathematical models. For instance, the dense flow model cannot consider bi-directional flow, assign individual projection areas and free movement speed with each person. Functionality of the software may or may not allow for the individual properties for the persons, and CFD prediction of smoke movement. The current trend is to simulate fire dynamics and people evacuation using the same software and the single building file. Temporal and spatial superposition of both fire dynamics and people evacuation provides more accurate prediction results represented in a user-friendly format, with joint visualization of fire products dynamics (distributions of smoke, toxic gases, heat fluxes, and temperatures) and evacuation dynamics.

The other main contribution in modern fire evacuation simulations are mathematical models. They determine the range of application and variety of conditions and characteristics which may be taken

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into account. As a result, using a mathematical model provides the opportunity to reproduce some conditions which are a matter of concern and which would not otherwise be investigated.

The accuracy of the model and numerical presentation of the model are important to allow a reliance on simulation under given conditions. Nevertheless, one should remember that a simulation not always estimate reality. When we deal with fire safety simulations, we should keep in mind the following specifics concerning interpretation of the whole fire evacuation scenario(s). Simulation does not give us an answer to the question “Which will an emergency situation be?” It is wrong to try to predict (estimate) by simulation real pre-evacuation time, for example. If we input some pre-evacuation time T_{start} in seconds it means that people will start to move to exits T_{start} seconds later then a fire started. Simulation gives an estimate of evacuation duration from rooms, floors, building and provides information on people exposure by dangerous fire factors if they started at T_{start}. And that is all. However, simulation helps us to answer another question: “What should pre-evacuation time be to provide safe evacuation conditions?” A collection of scenarios with different T_{start} and other conditions are a source of information to produce instructions for staff to manage evacuation depending on their location.

This paper is organized as follows. In the next section, mathematical models are presented. This is followed by the software section and then a case study section, where some fire evacuation examples are considered under different initial conditions. The paper ends with conclusions.

MATHEMATICAL MODELS

Evacuation

Different approaches from the social force model based on differential equations to stochastic CA models are developed; see [1] and references therein. They reproduce many collective properties including lane formation, oscillations of the direction at bottlenecks, the so-called “faster-is-slower” effect.

The most popular for practical applications is the agent-based approach when each person is considered as individual agent, and a model gives coordinates of each person in each time step. Each person may be assigned with individual properties: free movement velocity, pre-evacuation time, projection size, evacuation way. This approach enables solving a variety of pedestrian movement tasks, including fire evacuation tasks, and makes this model a powerful simulation tool.

At the present time there are two main approaches to simulate individual people movement: continuous and discrete. Combining the advantages of the continuity of a modeling space (as in continuous models) with the intuitive clarity of update rules (in discrete models) a discrete-continuous model Sigma.DC was developed [2, 3]. In this model, the agents move in a continuous space (in this sense the model is continuous), but the number of directions where agents may move is limited and predetermined by the user (in this sense the model is discrete). Real sizes are considered, which is very important to allow for narrow places such as doors. At the same time, the model is quite simple. The main concept is worth explaining here.

A discrete-continuous evacuation model - Sigma.DC

The following assumptions and restrictions are considered in the model: people movement is a stochastic process; while moving people do not exceed their free movement velocity, every person maintains his/her velocity in accordance with local time-spatial density conditions (the tighter the crowd and the more urgency, the smaller this distance); the main driving force is approaching a destination point; people follow one of two strategies: the shortest path and the shortest time.

A continuous modeling space $\Omega \in R^2$ and including the infrastructure (obstacles) and the free space are prescribed in the unified coordinate system. Obstacles include walls and furniture. People are modeled as discrete agents, which move in free space. To navigate in the space, the agents use the static floor field S [4]. Each agent is assigned a certain target point (exit).

The shape of each agent is a hard disk with diameter d_i, $i = \overline{1, N}$, N – number of agents, $\vec{x}_i(0) = \left(x_i^1(0),\, x_i^2(0)\right)$, $i = \overline{1, N}$ – initial positions of each agent which are the coordinates of the disk's centers (it is supposed that they are the coordinates of body's mass center projection). Each agent is assigned with a free movement speed v_i^0, $i = \overline{1, N}$, and with the projection area. We assume that free movement speed is a random normally distributed value with a certain mathematical expectation and dispersion. It is supposed that, while moving, people do not exceed the maximum speed (free movement speed), and they control the speed according to the local density.

Each time step t particle i may move in one of predetermined directions $\vec{e}_i(t) \in \left\{\vec{e}_i^{\,\alpha}(t),\ \alpha = \overline{1, q}\right\}$, q is number of directions, a model parameter (here a set of directions uniformly distributed around the circle is considered). Agents which cross the target line leave the modeling space. For each time t, the coordinates of each particle i are:

$$\vec{x}_i(t) = \vec{x}_i(t - \Delta t) + v_i(t)\,\vec{e}_i(t)\,\Delta t, \quad i = \overline{1, N}, \tag{1}$$

where $\vec{x}_i(t - \Delta t)$ is the coordinates in the previous time step; $v_i(t)$, [m/s] is the agent's speed; $\vec{e}_i(t)$ is unit direction vector. The constant time step of Δt = 0.25 s is used.

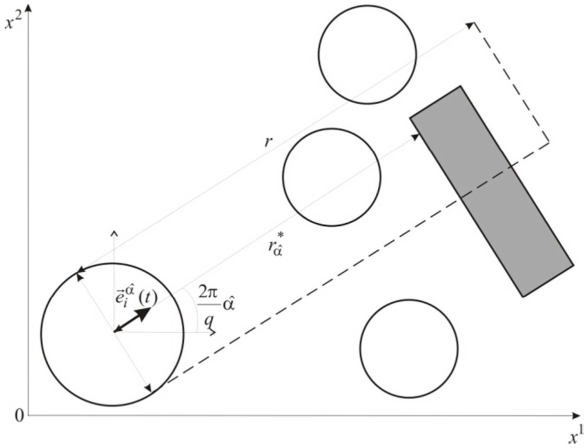

Fig. 1. Scheme of a visibility area of the particle in the direction $\vec{e}_i^{\,\alpha}(t)$.

The direction of the next step $\vec{e}_i(t)$ is proposed to be stochastic with probability distribution calculated from the discrete CA approach and inspired by the previously presented stochastic CA FF model [6, 7]. All predetermined directions for every agent to move at each time step are assigned with some probabilities, and a target direction is determined according to the probability distribution obtained. To reproduce directed movement, a static floor field S is used as a "map" that stores the information on the shortest distance to the nearest exit [4]. This field increases radially from the exit and it is zero in the exit(s) line(s) [6]. It does not change with time and is independent of the presence of the particles.

Personal probabilities to move in every direction at each time step are not static but vary dynamically and are affected by: (a) the main driving force (given by destination point), (b) interaction with other pedestrians, (c) interaction with the infrastructure (non-movable obstacles). The highest probability (mainly with a value > 0.9) is given to the direction that has the most preferable conditions for movement considering other particles and obstacles and the strategy of the peoples' movement (the shortest path and/or the shortest time).

We omit here exact formulas to calculate probabilities for particle i to move from present position to directions $\vec{e}_i(t) \in \left\{ \vec{e}_i^{\,\alpha}(t), \alpha = \overline{1,q} \right\}$, decision rules to choose direction $\vec{e}_i^{\,\hat{\alpha}}(t)$, and the final conflict resolution procedure. All this information has been provided previously in [2]. The speed $v_i(t)$ of each agent is determined from the experimental data (the fundamental diagram, for example, see [5]), taking into account the local density $F(\overset{*}{r}_{\hat{\alpha}})$ in the direction chosen $\vec{e}_i(t) = \vec{e}_i^{\,\hat{\alpha}}(t)$:

$$v_i(t) = v_i^{\hat{\alpha}}(t) = v_i^0 \begin{cases} 1 - a_l \ln\left(F\left(r_{\hat{\alpha}}^*\right) / F^0 \right), & F\left(r_{\hat{\alpha}}^*\right) > F^0 \\ 1, \quad F\left(r_{\hat{\alpha}}^*\right) \le F^0 \end{cases} \tag{2}$$

where F^0 – limit on people density up to which free people movement is possible (density does not influence the speed of people movement); $a_1 = 0.295$ is for horizontal travel; $a_2 = 0.4$, for stair descent; $a_3 = 0.305$, for stair ascent.

Numerical procedures that are used to estimate the local density are presented in [2]. The density is only determined in the region consistent with the direction of movement and visibility, see Fig. 1.

In this discrete-continuous model, in contrast with pure continuous force-based models [8, 9], the task of finding the velocity vector is divided in two parts. Firstly, the direction is determined; secondly, the speed is calculated according to local density in the direction chosen. Using this strategy we omit the step of describing any forces that act on persons, thereby avoiding the numerical solution of N differential equations. As a result, the computational cost of the model is reduced compared to the force-based models, and the relaxation parameter Δt is allowed to be at least 10 times larger. At the same time, the modeling space is considered to be continuous, which is valuable in terms of practical applications.

Validation of the discrete-continuous evacuation model

The model presented here was realized in the computer program module SigmaEva©. A validation of the module was performed under basic conditions which take place in a normal evacuation process and which are provided with empirical data. The following tests were considered: movement in a straight corridor under open and periodic boundary conditions; movement in bottlenecks. A specific flow versus the density was investigated.

The investigation showed good dynamic properties, i.e., maintaining the speed in accordance with the local density under periodic and open boundary conditions. An initial density and a free movement speed were unchanged until the density of about 0.5 [persons/m^2] (in open boundary conditions), [5]; a flow diffusion realizes if it is possible (open boundary conditions for an experiment with 50 m and 100 m corridor); the model total flow increases as the bottleneck width increases, specific flow is approximately constant, except for small widths when an arch effect is often pronounced [2, 3, 10]. A comparison with corresponding data ([1], [5], [11] and others) suggests that the model works within the context of empirical data on speed versus density.

Fire simulation

Modern computers allow everyday use of powerful simulation tools such as CFD (computational fluid dynamics) for fire simulations. CFD provides an approximate three-dimensional solution to the equations governing fluid motion. The modeling area is spanned by a very large number of grid cells. Complex geometries, and time-dependent flows, are readily handled. The solution provides distributions of velocity, pressure and gas concentrations, calculated at each grid cell. It provides a three-dimensional, time-dependent picture of complex fluid flows.

The use of CFD modeling techniques is widespread and well investigated already. There are many available sources related to it, for example [12], and a good guideline is provided in [13] and the references therein. Here we only mention algorithms that are used in our CFD code and implemented in the SigmaFire© fire simulation computer module: numerical method - finite-volume methods; calculation of cell-center gradient - least-squares method; convective terms – UDS (Upwind Differencing Scheme [14]), QUICK [15], UMIST (The Upstream Monotonic Interpolation for Scalar Transport [16]), TVD (Total variation diminishing [17]), Superbee TVD; pressure-velocity coupling - SIMPLE-like (Semi-Implicit Method for Pressure Linked Equations [14]) algorithm with Rhie-Chow interpolation (collocated grid arrangement) [18]; solution of algebraic equation systems - conjugate-gradient method, conjugate-residuals method, Algebraic Multigrid (AMG) Method [19]; approximation of unsteady terms - implicit 2nd order method; parallelization - domain decomposition, MPI.

To model turbulence, the shear-stress transport k-ω model (Reynolds-Averaged Approach - RANS) is used [20]. To resolve near-wall regions, blending of the viscous sublayer formulation and logarithmic layer formulation is implemented. For highly unsteady flow, unsteady RANS is used.

An iterative procedure is used to obtain a solution which stops if a satisfying solution is reached. There are two criteria: number of iterations and value of residuals.

To model fire the following combustion model for solid fuels is used: $\Psi = \psi_s \pi v^2 t^2$, where Ψ is rate of burning, kg/s; ψ_s is specific rate burning, kg/(s·m^2); v is speed of fire spread, m/s; t is time, s. The speed of volatile is $\phi_{volatile} = \alpha\Psi$, kg/s.

Validation procedures, which showed appropriate convergence with real and experimental data [23, 24, 25], were made.

In Table 1, some features of SigmaFire© versus the well-known CFD code FDS are presented.

Table 1. SigmaFire© components compared to those in FDS

Feature	SigmaFire	FDS
Turbulence	URANS	LES
Grid	Unstructured nonorthogonal	Orthogonal
Pyrolysis reaction rate	Constant	Arrhenius
Radiation	P_1-aproximation [21]	Finite-volume method [22]
Liquid spray	No	Yes

Fire and evacuation integrated simulations

There are at least two levels of integration of fire and evacuation models. The first one means that the software provides an opportunity to work with one building file for both fire spread and evacuation modules. In this case, time and spatial superposition of both results is more accurate and comfortable for the user, the 3D-visualization of fire products dynamic (smoke, toxic gases, heat flow, temperature) and evacuation dynamics gives a more illustrative understanding of processes (for example, total and/or detailed time-spatial distributed information on that the time during which individuals were affected by extreme fire conditions, corresponding concentrations (life compatible/incompatible) of toxic gases and other).

The next level of integration means that fire products (smoke, toxic gases, heat flow, etc.) may have an influence on people and/or people can influence fire spread. Such an approach may be used to improve the reliability of the simulation, extend information about a simulated scenario, or extend the application area.

From a computational point of view, such a statement of the simulation problem implies several subpoints including a formalization of people's reaction to fire, a formalization and implementation of a calculation scheme and influence of people on fire spread, time and spatial compatibility of calculation schemes for evacuation and fire spread models and 3D-visualization.

The simplest part is to realize the influence of people on fire dynamics, for example when people may open and close doors while moving. From a CFD computational point of view, it means that a modeling area is changing at certain moments. To remain stable in computing terms, these changes should be smoothed in time. This task is rather technical and needs accurate numerical realization. Note that there is also a time factor. The CFD simulation is very slow compared to the evacuation simulation. To overcome this, an iterative procedure is proposed. First, we calculate evacuation under a given scenario and estimate intervals when flow (or individuals) passes doors. Then we input this information into the CFD module and the simulation is made. Such an algorithm is already realized in the software SigmaFS©.

Another way that people may influence the fire development is when using a hand-held fire extinguisher. The simplest way to model this is to reduce the area of the fire in accordance with the extinguisher characteristics.

Simulation of people's reaction to fire products requires a new task that is a (mathematical) formalization of people's reaction to fire and influence of fire products on movement activity. An agent-based approach to simulate people movement is very convenient in this case, since each person is considered individually, and the model can give the coordinates of every person.

There are some data in the literature on the psychological reaction to fire (smoke, smell) and there are also data on the physiological reaction of the human body to toxic gases, heat, temperature, lack of oxygen, for example [5, 26-30]. Almost all sources contain descriptive information on people's reaction to fire and fire products. Among the variety of human responses, it seems reasonable to extract the most common behavioral features which are: human velocity decreasing due to smoke and the influence of toxic gases; individuals may not change their evacuation route if smoke concentration is low; however, a human may change an evacuation path if the nearest way is blocked by fire factors. Note that we do not consider the impact of the fire/smoke on the pre-evacuation period.

Decision-making is based on sensitivity and visibility of dangerous fire factors. Smoke is visible at a distance. Temperature and heat flow may be sensed by touch. High concentrations of some gases (CO_2, CO) cannot be sensed by humans but they influence activity with time. Smoke spreads faster than other fire factors. We rely on literature data which indicate that the front region can be defined by the threshold values of smoke density 0.0001-0.0006 kg/m^3, visibility 6-12 m, O_2 concentration 16%.

We formalize smoke recognition as follows:

- max r^{fire} (model parameter) is a distance from a person when smoke zone may be sensed,
- a person recognizes a fire (fire attributes) in the direction chosen in the distance, max r^{fire} if optical density μ is greater than 0.238 ($\mu > 0.238$ means that visibility is less than 10 m);
- γ_0 (model parameter) is the initial probability to move in the smoke region;
- a person decides to maintain the chosen direction with the probability of $0.16\gamma_0 / \mu$ ($1 - 0.16\gamma_0 / \mu$ is the probability of changing the direction).

We assume that a person may take another way because of fire only one time per scenario. A decision to move towards a smoke zone could not be reconsidered.

In reality, when people move along a corridor, and a changing of the route takes place because of fire detection, an inertia effect takes place. Some people (from the front line) decide to change the direction, whilst others still move in the same direction. Such an inertia effect is to be implemented as follows. Once the direction is changed, there are M steps when the fire recognition procedure is applied, then it is stopped and all people are redirected to another exit. Computationally, the redirection means changing the static field, S.

Information from the literature allows an estimation of intervals for concentration of dangerous fire factors and range them according to reaction on the human body.

Simulation case studies by “Sigma FS” software

Simulation computer modules SigmaEva© and SigmaFire© are parts of the Russian software “Sigma FS” ©. One can create a 3D-model of a building using the 3D-building editor, input initial and boundary conditions, simulate fire dynamics by CFD code (that is pure Russian code), simulate evacuation by the Sigma.DC model, visualize results in 3D and get automatically the super-positioned and analyzed outcome on the contact of people with dangerous fire conditions, evacuation and blocking times for the evacuation paths.

The first level of integrated simulations is already realized in the software. The influence of people on fire spread is also possible, albeit only the influence of fire on people is considered here.

“Sigma FS” is a tool for simulations that may be used in many fields from organization of mass events to fire safety of buildings, ships, aircrafts under operation and construction conditions. One may vary construction of a building, a combustible material and its mass, place of fire, systems of smoke removal, pressurization systems, using hand extinguisher, doors’ conditions, number of people, their initial positions, individual properties (free movement speed, pre-evacuation time, projection size, evacuation way), and furniture location.

The main task of applying such simulations is to estimate evacuation time (including duration of congestions) in different scenarios in order to provide safe conditions for visitors in emergency situations.

Let us consider and compare fire *evacuation scenarios 1 and 2* from a school under fire conditions. According to both scenarios, people evacuate from a 3-storey building using the nearest stairways (Stw) numbers 1 and 2 and exits 4 and 2 respectively. A fire started in a marked room, Fig. 2.

During the simulation it was assumed that doors in the corridors were open (one may interpret this condition as doors' closers are missing or non-operational). The regions of interest are denoted by circles in the figure.

In this analysis, two scenarios were considered – one where the pre-evacuation time of the occupants was 30 s and the other where the pre-evacuation time was 120 s from ignition. Here the pre-evacuation time is not modelled explicitly but rather is assumed to be a constant value. This is because the primary goal is to investigate differences in evacuation results. One can interpret the 30 s delay as an example of a fast reaction to an alarm system. The delay of 120 s may be interpreted as representing low discipline or an alarm system fault.

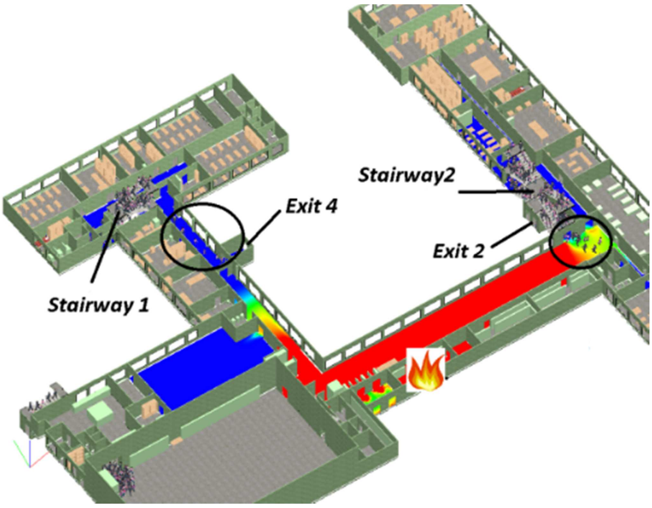

Fig. 2. Location of fire, exits and stairways in 3-storey buildings.

Fire conditions in the picture are presented as a 2D-slice at a height of 1.7 m above the floor. This slice is extracted from the 3D-fire-simulation results. In the figure, the blue color smoke slice is for safe areas for people health, red color is for dangerous areas (boundary values are from the Russian fire safety legislation).

Integrated simulation of the evacuation and the fire spread helps to show and estimate potentially dangerous consequences of some initial conditions. Here the evacuation start delay is considered. The most important areas are marked in Figs. 3 and 4.

For the case of a 120 s pre-evacuation delay (scenario 1) one can see that people moving in a corridor to Exit 2 are in a risk area at 142 s, Fig. 3a (right circled area). Combustion products need more time to reach Exit 4. Nevertheless, the pre-evacuation time was very long, and people moving to Exit 4 are in a dangerous area at 215 s, Fig. 3b. In both cases, evacuation is not finished by these times. The analysis suggests that over 100 people evacuate in unsafe conditions if they start moving with a 120 s delay after ignition. Exposure time was calculated to be greater than 60 s, and this information may be used to estimate possible health damage.

If the pre-evacuation period is 30 seconds only (scenario 2), people evacuate in comfortable conditions, Fig. 4 (remember that we changed only the duration of the pre-evacuation period and consider the same fire scenario). One can see in Fig. 4a that evacuation is already finishing; only some people are on Stairway 2, and conditions at that time (142 s from ignition) are still comfortable in that region. Figure 4b shows that only some people have to leave the building using

Exit 4 but smoke is only coming to the corridor. In Table 1 evacuation result data for both scenarios are presented.

To understand the influence of using door closers, let us consider another scenario (*scenario 3*) when the doors that are marked in Fig. 5 worked with a door closer during the simulation: pre-evacuation time is 30 s; fire position and all other conditions are as in scenarios 1, 2. Note that, from a computational point of view, the valid closer means that 10% of the doorway cross-section is open. Figure 6 presents the same point of interest in a building as in the previous scenarios. It was estimated that door closers postponed dangerous smoke conditions by up to 360 s.

Table 1. Evacuation result data for scenarios 1, 2

Pre-evacuation delay, s	Number of people in risk zone	Exposure time, s
120 (Scenario 1)	~100	>60
30 (Scenario 2)	~5-10	1-5

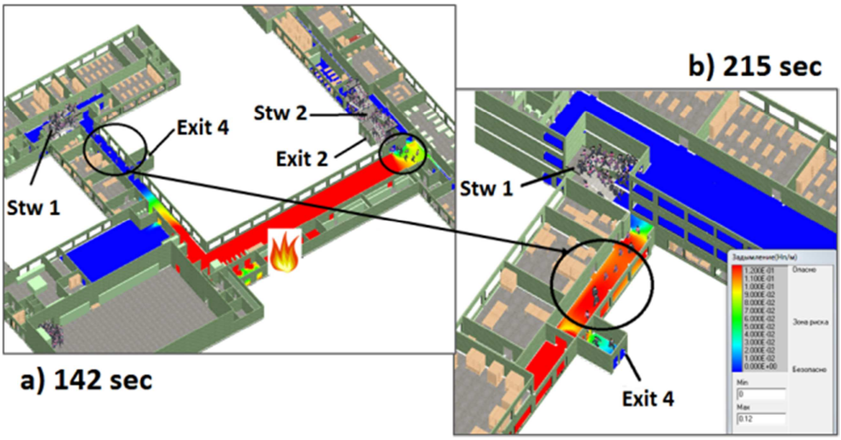

Fig 3. Evacuation from the building under fire conditions, evacuation started 120 s after ignition.

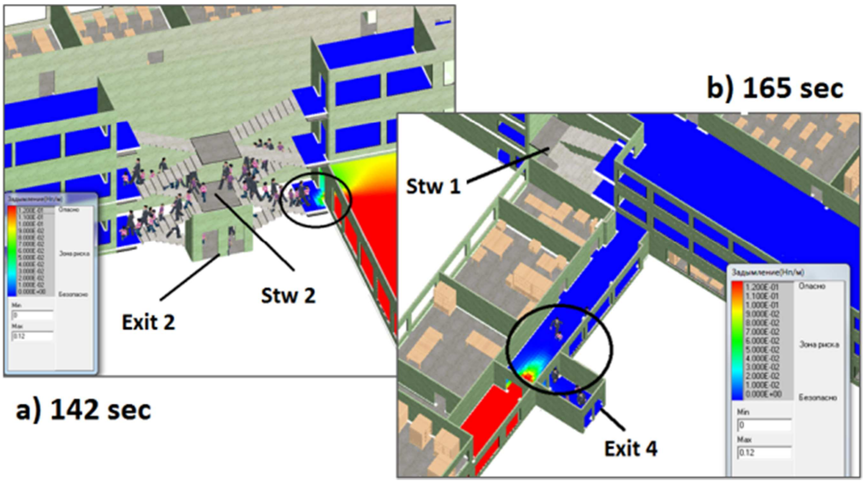

Fig 4. Evacuation from the building under fire conditions, evacuation started 30 s after ignition.

CONCLUSIONS

The paper has demonstrated how real conditions could be taken into account in modern fire evacuation simulations. The scenarios considered show the influence of different initial conditions on evacuation results. This information could be used to estimate possible time gaps to react on fire alarm, start evacuation, available routes and form the basis for instructing staff on how to manage the evacuation process.

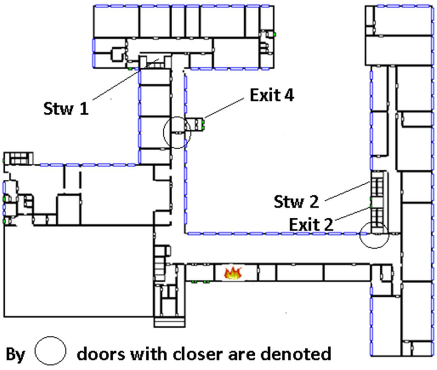

Fig. 5. Doors which were considered with closers while simulation in scenario 3.

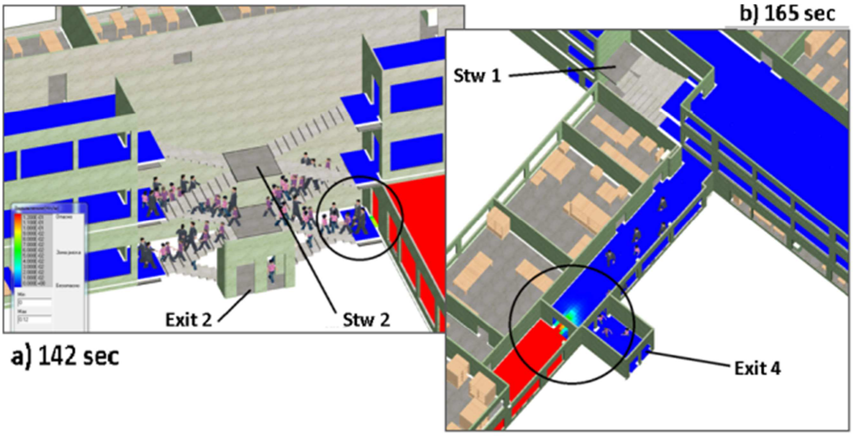

Fig. 6. Evacuation from the building under fire conditions, an evacuation started 30 s after ignition, doors closers are valid.

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