Development of Escape Route System for Emergency Evacuation Management Based on Computer Simulation

Denis Shikhalev[1(✉)], Renat Khabibulin[1], Ulrich Kemloh[2], and Sergey Gudin[1]

[1] The State Fire Academy of EMERCOM of Russia, B. Galushkina str. 4, 129366 Moscow, Russia
evacsystem@gmail.com

[2] Jülich Supercomputing Center, Forschungszentrum Jülich GmbH, Wilhelm-Johnen-Straße, 52428 Jülich, Germany

Abstract. In this article we propose a safest path route choice algorithm which determines the safest path directions for pedestrians in case of fire. We also propose an escape route system for emergency evacuation management. The model and the algorithms are implemented in an open source framework (JuPedSim) which is a research platform to simulate pedestrian dynamics. The proposed algorithm allows the even distribution of the evacuees to all available emergency exits. We simulate the evacuation of a shopping centre and show that the application of the algorithm can reduce the total evacuation time up to 63% depending on the settings of the algorithm. Based on those results we elaborate an escape route system for emergency evacuation. The system includes three modules and can be operated in several modes. The designed system allow not only significantly to reduce the evacuation time but also to ensure people's safety during evacuation.

Keywords: Pedestrians dynamics · Evacuation strategies · Safest evacuation routes · Escape route system · Computer simulation

1 Introduction

In the last few decades, large fires in shopping malls were the reason of many people's death. A few of them are listed below:

- December 25, 2000. A fire occurred in a central shopping Centre (Luoyang, China). The fire killed 309 people;
- August 01, 2004. A fire occurred in a supermarket (Asunción, Paraguay). The fire killed 464 people;
- May 28, 2012. A fire occurred in a Villagio Mall (Doha, Qatar). The fire killed 19 people, including 13 children.

One of distinguishing features of shopping malls is the uneven distribution of people in the building. It can influence the evacuation process and lead to an unbalanced use of emergency and exits routes. Studies shows that a significant number of

S. Hammoudi et al. (Eds.): ICEIS 2016, LNBIP 291, pp. 122–139, 2017.
DOI: 10.1007/978-3-319-62386-3_6

people are usually gathered in supermarkets and shops of home appliances compared to other shops of a shopping mall.

An analysis of some existing escapes route systems from different countries [1] showed that only a third of the systems were able to determine the direction of the escape routes using a scientifically founded method. The studies of many authors [2–5] indicate the following problems in the area of evacuation management in shopping malls:

- Uneven distribution of people inside shopping malls;
- Management problems in the evacuation process, done by the staff of shopping malls;
- Lack of information about possible (available) evacuation directions.

Therefore, the lack of both models and algorithms of information and analytical support for evacuation management lead to the fact that a decision maker cannot objectively evaluate the whole range of hazards and determine the safest routes for people during an emergency evacuation. To solve these problems, a mathematical model of a safest path route algorithm was developed. The algorithm is used to calculate the safest path for people in a danger zone, and to direct them to a safer area [6]. In a first estimation the model showed a positive impact on the evacuation time and overall on the people's safety during evacuation simulations [6]. Nevertheless, it is needed to complete a full estimation of all features of the model as well as determine the best combination of models parameters for evacuation simulations.

In this paper we consider the results of evacuation simulations using the algorithm. Simulations were performed using the Jülich Pedestrian Simulator, JuPedSim [7] with various numbers of people and different objects. The results of simulations are used while a decision support system for emergency evacuation is being developed.

This work is structured as follow:

In the second section we introduce the model and the algorithm. In the third section, we present computer simulations and analyses. The development of the decision support system for emergency evacuation is shown in the fourth section. Some concluding remarks and directions of future work are given in the last section.

2 Description of the Safest Path Route Algorithm

The safest path route algorithm is applied for calculation of the safest path for people from different points of a building to the exterior of the building. Originally the safest path route algorithm was created for a shopping mall. The main tasks of the algorithm are to calculate a safest route and direct people to a goal (current or newly defined). The algorithm of Floyd-Warschall [8] was applied for calculating the safest path to the nearest gate. In its normal application the Floyd-Warschall's algorithm finds the shortest path between all pairs of edges in a graph. A physical distance is used as the weight of the edges. For our task, we used a complex criterion φ as the weight of the edges. φ is calculated using Eq. 1:

$$\varphi = \sqrt{\alpha \cdot (a_i)^2 + \beta \cdot (b_i)^2 + \gamma \cdot (l_i)^2} \tag{1}$$

at:

$a \rightarrow$ min, i = 1,…,n
$b \rightarrow$ min, i = 1,…,n
$l \rightarrow$ min, i = 1,…,n

where:

a – an obstruction criterion;
b – a timeliness criterion;
l – a length criterion.
α, β, γ – the weight coefficient at a, b, l.

The obstruction criterion is determined by the ratio of the people's density on a section of the escape route network, to the maximum people's density that does not cause adverse effects to humans. The timeliness criterion is directly linked to fire hazards (high temperature, a large amount of smoke, low visibility, toxic products of combustion etc.). The length criterion is the relative length of the current section. It is calculated as the ratio of current escape route length, to the maximal escape route length in a building. The coefficients (α, β, γ) are added to regulate the importance of the individual criteria. More details about the criterions and manners of its computing are found in previous work [6].

Under sections of escape route, we consider the crossing of two (or more) escape routes in the corridors of a shopping mall. Hence a section of an escape route corresponds to an edge in the graph of a shopping mall, and the crossing place of two (or more) escape routes corresponds to a vertex.

We used the JuPedSim simulator for computer implementation of the algorithm. The Generalized Centrifugal Force Model (GCFM) is applied into the simulator to simulate an evacuation process [9]. GCFM belongs to the class of forces based models [10] and describes the movement of people at the operational level [11] i.e. defines basic rules for the pedestrians such as acceleration, braking and stop. Motion of the pedestrians is determined by a so-called "social power" [10]. The calibration of the basic parameters of GCFM (attractive and repulsive forces, the size of the semi-axes of the ellipse depending on the density and velocity of the people flow etc.) were performed in [12, 13]. Verification and validation of the GCFM, as well as a more detailed description is given in [9, 14, 15].

At each step of the simulation, the evacuees are guided with the shortest path, to the nearest emergency exit in the building i.e. a shortest path route algorithm (*ShPA*) is used to determine the shortest escape route (Fig. 1).

However, there is a need to change the *ShPA* with regards to the problem of determining the safest evacuation routes. For this purpose, a safest path route algorithm (*SaPA*) was developed (Fig. 2).

An update frequency (*UF*) was added into the *SaPA* for the possibility of regulating how often the algorithm will be refreshed. Thus, a *UF* value of 5 means that the safest

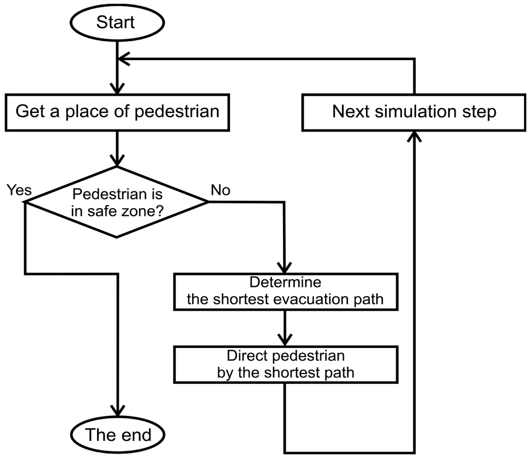

Fig. 1. The shortest path route algorithm (*ShPA*).

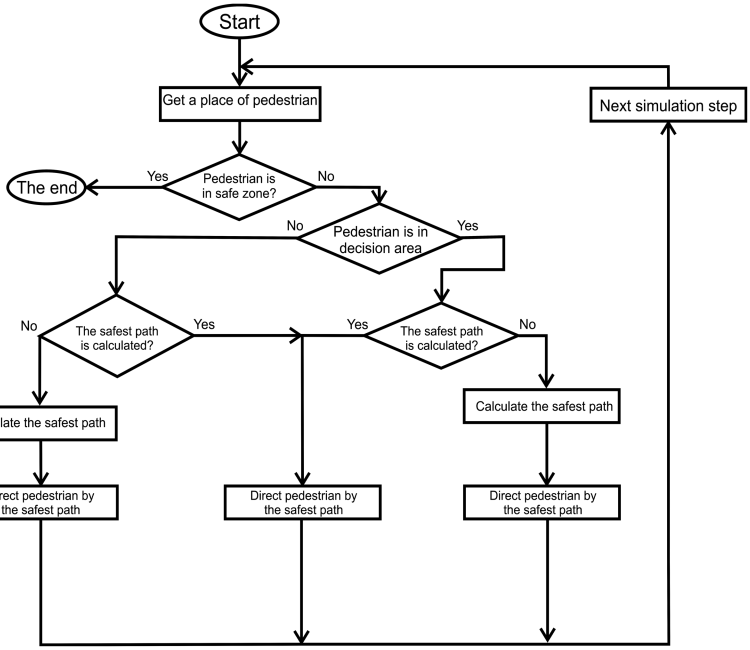

Fig. 2. The safest path route algorithm (SaPA).

path will be calculated once for every 5 s and the direction of movement will also be updated (in the decision areas) every 5 s.

The shortest path is given for all evacuees in an initial stage (pre-evacuation). Then the safest path is computed for each node (decision area) according to the *UF*. In other words, the decision area is a place where two or more routes crossed. It is possible from this place (decision area), to direct the pedestrians by a new path, for example, by using a dynamic indicator [16]. If a current path is not a safest path anymore, a re-routing will happen in the decision area. The safest path route algorithm was implemented into JuPedSim as a separate module and it can be chosen from other routing algorithms such as a quickest or shortest path algorithms.

The main purpose of simulation is to evaluate the effectiveness of the safest path route algorithm. This evaluation is done by comparing the performance of the shortest path route algorithm and the safest path route algorithm. Thus, the following research problems should be solved during simulation:

- How are the *a*-criteria and *b*-criteria changed in the process of evacuation and under what values does the process of re-routing happens?
- Which are the effects of re-routing pedestrians?
- How do weight coefficients affect the course of the evacuation process?
- How does the update frequency affect the course of the evacuation process?
- When is it advisable to apply the safest path route algorithm?

To answer these questions, it is necessary to conduct a preliminary assessment of the adequacy of the developed algorithm. From there, we perform a computer simulation of the evacuation process on the topology of an existing shopping mall, as an example.

3 Simulation and Analysis

In this section we provide simulation results and its analysis.

3.1 Preliminary Assessment

Several simulations at the *T*-junction of escape routes (Fig. 3) were carried out within a preliminary assessment of the *SaPA* as well as on the abstract model of the building (Fig. 4).

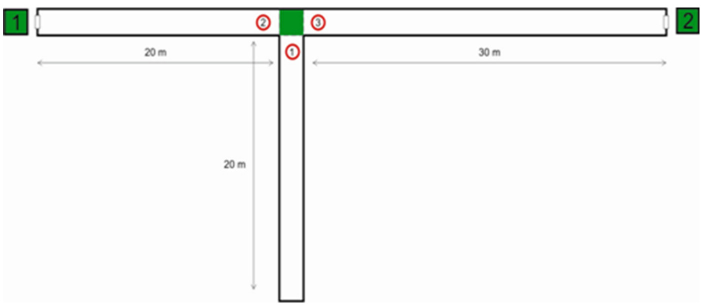

Fig. 3. Objects of simulation within a preliminary assessment – *T*-junction.

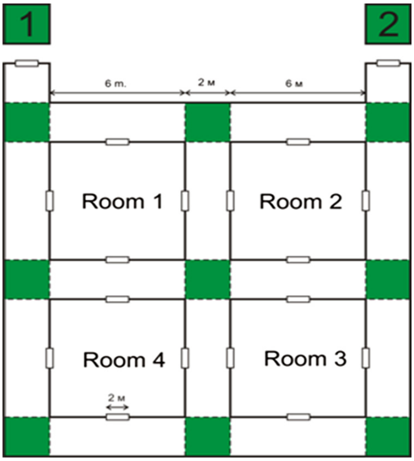

Fig. 4. Objects of simulation within a preliminary assessment – abstract model of the building.

Simulation results at the T-junction identified one of the features of the *SaPA*: the safest path route algorithm behaves as the shortest path route algorithm when there are no congestions or high-density of pedestrians.

It was also found that the usage of weight coefficients has an impact on the time of re-routing during evacuation. Weight coefficients (0,9-0-0,1) lead to the re-routing that occurs both with few and many pedestrians. In addition, weight coefficients of 0,6-0-0,4 allow to re-route flows when we have a high number of pedestrians. Moreover, re-routing occurs only at the maximum configured number of people in simulation (250 per., 6.25 pers./m^2 in a case when the weights are not applied).

Re-routing moments and duration of re-routing become longer when the value of *a*-criterion is increased.

The results obtained in the T-junction simulations led us to several conclusions:

- The safest path route algorithm behaves as the shortest path route algorithm in the case where there are no congestions or high-density of pedestrians;
- The application of weight coefficients influences the course of the evacuation process where the escape routes sections are of different geometrical size.
- In order to achieve the minimal evacuation time and prevent pedestrians' congestions, it is necessary to increase the importance of the *a*-criteria. Reducing the importance of *a*-criteria leads to an increase in evacuation time;
- It is possible to control a moment of re-routing of evacuation flows by applying different weight coefficients.

After simulations at the T-junction we continue in the abstract model (Fig. 4). Simulation results in the abstract model allow us to formulate the following facts.

Firstly, for uneven distribution of people during evacuation, the *SaPA* can immediately distribute pedestrians evenly to the emergency exits. This in turn significantly affects the evacuations time. Efficiency of the *SaPA* (Fig. 5) reduces when there is an uneven distribution of people. Efficiency is the ratio of evacuation time with the *SaPA* to evacuation time with the *ShPA*.

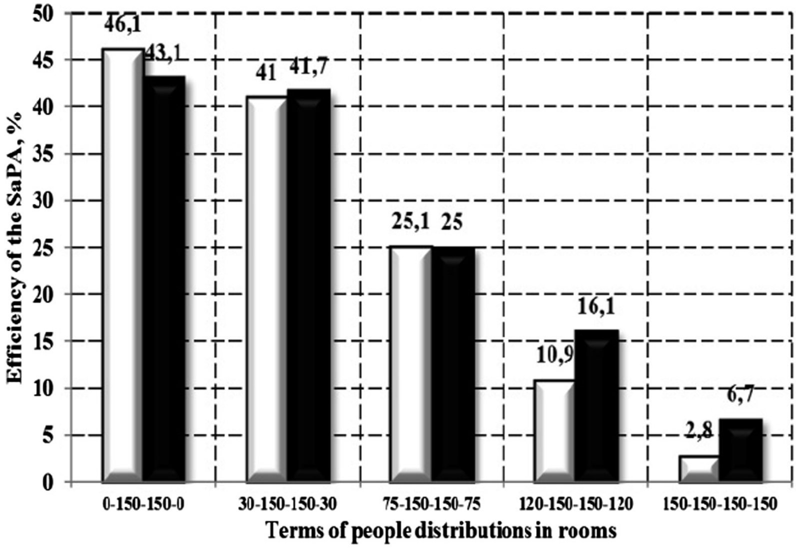

Fig. 5. Efficiency distribution of the *SaPA* depending on terms of people distributions. (0-150-150-0 value corresponds to the people distribution in rooms 1, 2, 3 and 4, respectively (Fig. 4)). White - scenario 1, black - scenario 2.

Secondly, there is a negative efficiency of the *SaPA* at 4%. This happened in the case where we had an uneven distribution of a small number of people (up to 50 people). Having reviewed the evacuation process in decision area, a reason of the negative efficiency of the *SaPA* was found. This is due to the update frequency of the *SaPA* which was equal to 1. There were many re-routing of pedestrians while they followed the decision areas (geometric size of decision area is 2 m by 2 m). Pedestrians were sometimes directed to different exits. This in turn, had to slow down the speed of pedestrians and as a result, increase the evacuation time.

Thus, an optimal value of the update frequency should be investigated and determined. The simulation results in the abstract model led us to conclude these facts:

- Weight coefficients do not play any role when there are two identical routes (by both geometric characteristics and number) from the decision area to the exit;
- The *SaPA* update frequency of 1 has a negative impact on evacuation process given a small number of pedestrians;
- The *SaPA* directs pedestrians by routes which are not using during evacuation but are available.

3.2 Simulation of a Shopping Mall

After preliminary assessment we performed simulations in a shopping mall. The plan is shown in Fig. 6. The color represents the decision areas. Some geometric characteristics of the evacuation exits and evacuation route sections in the front of evacuation exits are shown in Table 1.

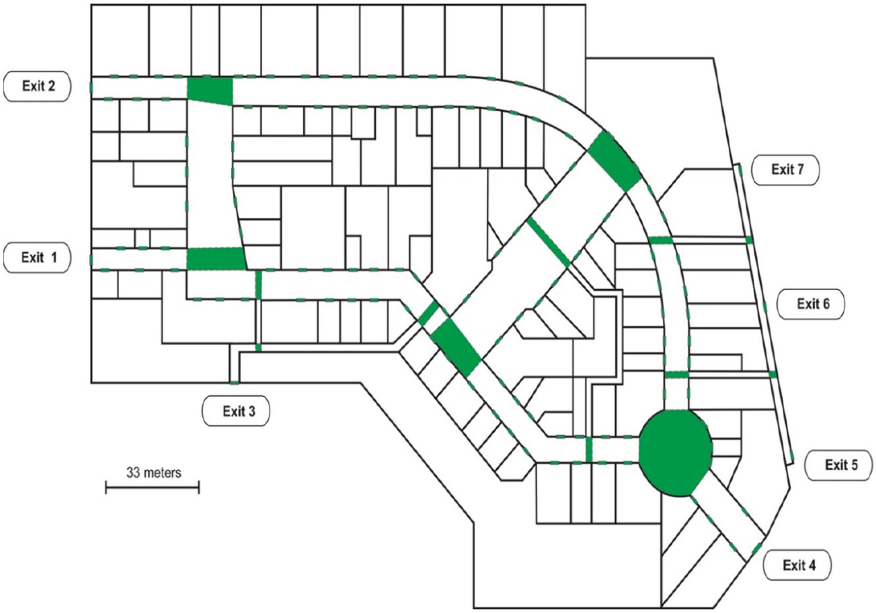

Fig. 6. Layout of shopping mall.

The number of people in evacuation simulation was chosen in the rate of 1 person per 1 m^2 of retail premises (the total number of evacuees is 2609). The influence of the update frequency on the evacuation process was considered in the first series of simulation. The simulation results are shown in Fig. 7.

Analysis of Fig. 7 shows that for many people, the closest emergency exit is №7, but based on its geometrical characteristics, it is not preferable because of its small width (See Table 1). However, most of the pedestrians were distributed between exits 1, 2, 4 which are preferable due to their geometrical dimensions (exit width).

Table 1. Geometric characteristics of the evacuation exits.

№	Parameter	Evacuation exit						
		1	2	3	4	5	6	7
1	Width, m	3,0	3,0	1,5	4,0	2,0	2,0	2,0
2	Width of evacuation route section in the front of evacuation exit, m	6,4	6,4	2,0	10,1	2,2	2,2	2,2

It is more clearly shown in Figs. 8 and 9. Almost all pedestrians were evacuated by using the *SaPA* after 300 s (Fig. 8). At the same time there are people's jams when using the *ShPA* (Fig. 9).

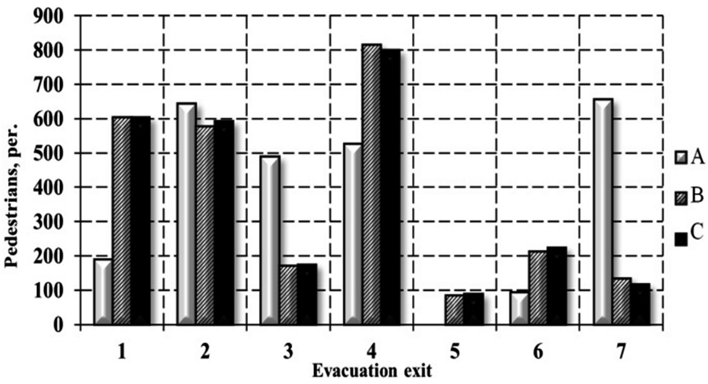

Fig. 7. People distribution to emergency exits. A - *ShPA*; B - *SaPA* with update frequency equal 5 (result of minimal evacuation time); C - *SaPA* with update frequency equal 13 (result of maximal evacuation time).

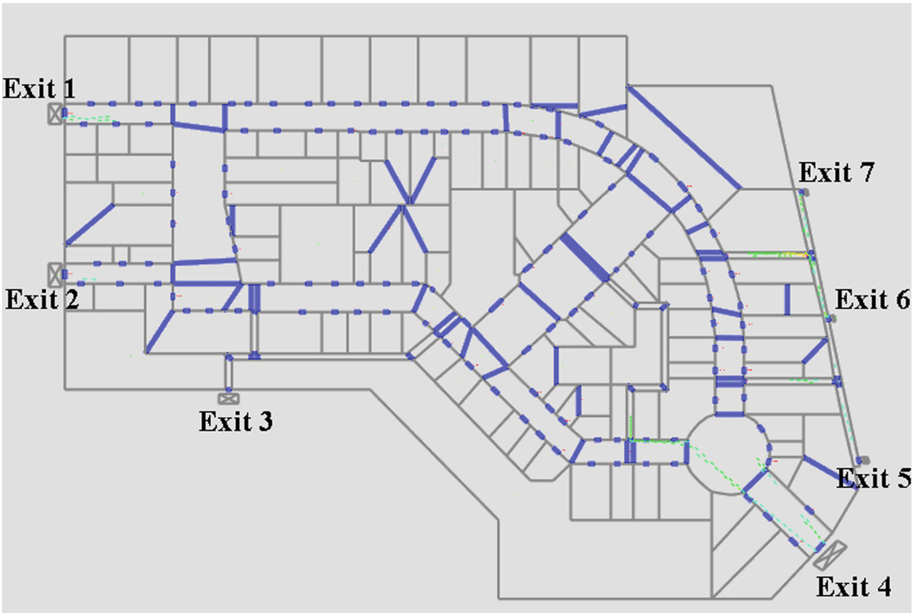

Fig. 8. Evacuation process stage in 300 s. when using the *SaPA*.

Thus, the direction of all pedestrians to the shortest emergency exits is not always justified and often leads to a significant increase of total evacuation time. Application of the *SaPA* allows to reduce evacuation time up to 63% depending on the update frequency of the algorithm.

The assessment of the update frequency of the algorithm showed that the preferred frequency is 5. That is why the frequency used for further studies will be 5. The

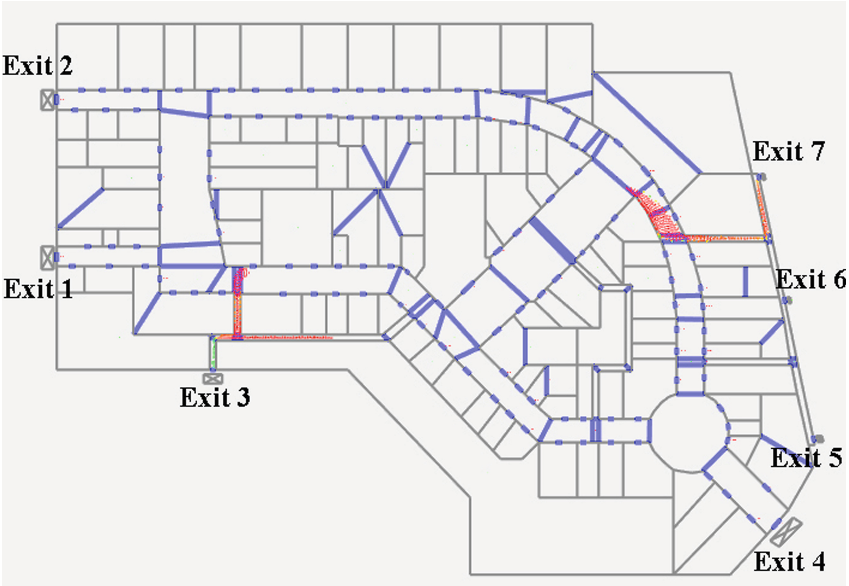

Fig. 9. Evacuation process stage in 300 s. when *ShPA* is used.

simulation results in the *T*-junction suggest that using different weight coefficients can reduce the evacuation time. An analysis of the effect of weight coefficients on the pedestrian's distribution to emergency exits was conducted in the next stage of the simulation. The results are shown in Fig. 10.

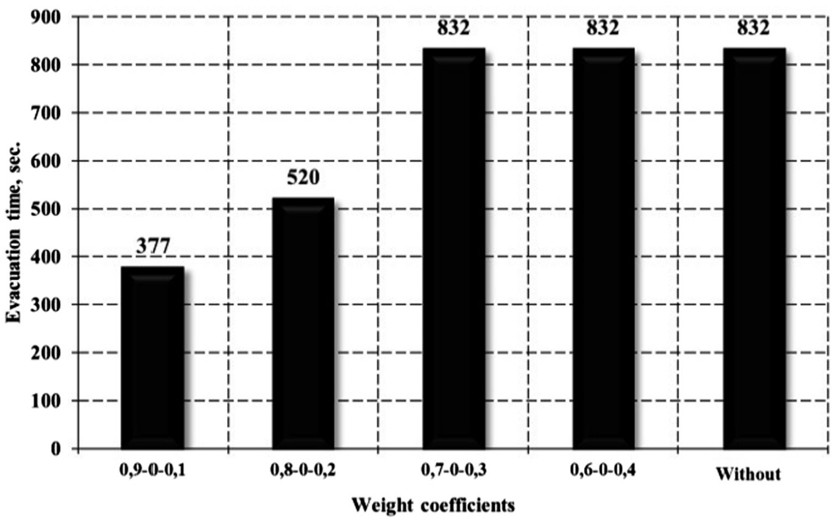

Fig. 10. Weight coefficients vs. evacuation time.

The results confirmed previous findings about the effect of the weight coefficients on evacuation process. It should be noted that using weight coefficients of 0.7-0-0.3 or 0,6-0-0,4 leads to the same results as not using weight coefficients at all. Nevertheless, these conditions (weights: 0,7-0-0,3; 0,6-0-0,4; without weight coefficients) contribute to reducing evacuation time in comparison with *ShPA* by 21%. The main difference between the weights of 0,7-0-0,3 or 0,6-0-0,4, however, as between all the weight coefficients is the people's distribution according to emergency exits.

Figure 11 presents the data with more details on the distribution of people to emergency exits. It shows that the largest reduction of the evacuation time was achieved when pedestrians were directed to wider exits and in contrast the maximum evacuation time was achieved by overloading narrow exits.

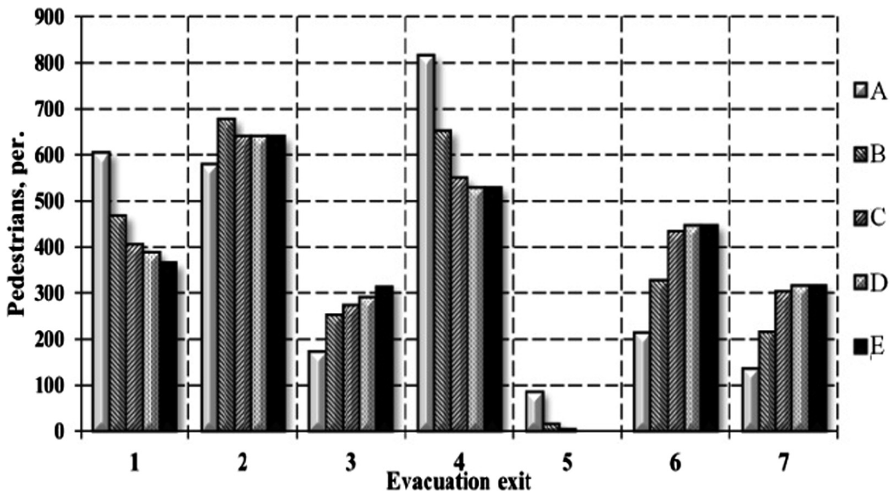

Fig. 11. The pedestrian distribution to emergency exits depending on the weights. A - weight coefficients are 0,9-0-0,1. B - weight coefficients are 0,8-0-0,2. C - weight coefficients are 0,7-0-0,3. D - weight coefficients are 0,6-0-0,4. E - without weight coefficients.

It was also interesting to consider the fairly frequent assertion of researchers in the field of human behavior, that people in case of a fire will follow the escape routes they used to get into the building [3–5]. It is likely that visitors enter a building on the gate leading from the metro stations, parking places, etc. Corresponding exits are 1, 2 and 4 in Fig. 6.

To carry out the simulation exits (3, 5, 6 and 7) are blocked, because it is unlikely that they can be used by most pedestrians entering the building. Different cases were simulated and investigated particularly when all of the exits (1, 2 and 4) are opened and then when one of the exits is blocked. The simulation results for different positions of the emergency exits are shown in Fig. 12.

The simulation results show that the direction of all pedestrians through the main evacuation exits can significantly reduce the evacuation time. For the last part of the simulation we elaborated four evacuation strategies:

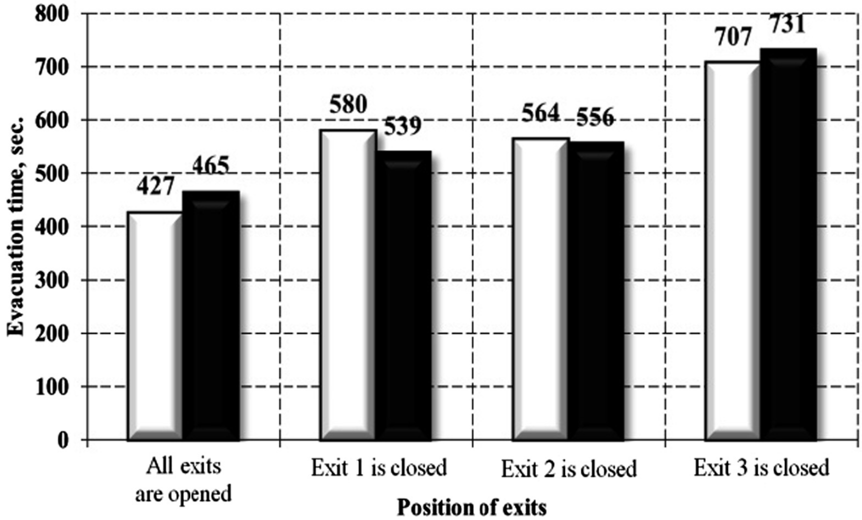

Fig. 12. Dependence of the evacuation time to an algorithm (*SaPA* vs. *ShPA*). White – *SaPA*. Black – *ShPA*.

- Strategy 1. Applying the *SaPA* with weight coefficients equal 0,9-0-0,1 provided that all exits are opened;
- Strategy 2. Applying the *SaPA* with weight coefficients equal 0,9-0-0,1 provided that only the main exits are opened;
- Strategy 3. Applying the *ShPA* provided that all exits are opened;
- Strategy 4. Applying the *ShPA* provided that only the main exits are opened.

Figure 13 shows the simulation results with the aforementioned strategies. Minimal evacuation time was achieved when the strategy 1 was chosen. The SaPA is still preferable than the ShPA only if main emergency exits are available. However, for

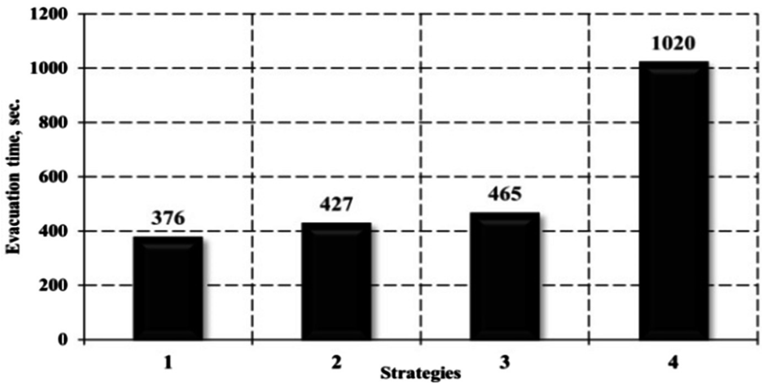

Fig. 13. Ratio of evacuation time to an evacuation strategy.

cases where the only possibility is to direct people through the shortest path, it is necessary to use strategy 4.

Obtained results shown an effectiveness of proposed algorithm. However an experimental assessment is required for its application in a real evacuation process.

4 Development of Escape Route System

The need for the development of Escape Route System for Emergency Evacuation Management (ERS) is defined by the several reasons. First of all, existing escape route systems are more oriented on voice alarm than evacuation management. Secondly, decision makers cannot objectively evaluate evolving situation during emergency evacuation in case of a fire due to a deficit of information (about the course of evacuation, people distribution in building, fire spreads etc.) and physiological features (including stress, time pressure).

4.1 Aim, Task and Structure

The aim of *ERS* is to ensure people's safety during emergency evacuation in case of a fire. To reach this aim, at least, implementation the following tasks are required:

- Definition of all available safest evacuation routes:
  - getting necessary information for calculating;
  - safest routes calculation in a building;
- Indication of the safest routs to all participants (staff and evacuees):
  - positioning of dynamic indicator in a safe direction;
  - update a safe direction when a newly safest route is identified;
- Evacuation process control:
  - evacuation process and fire spreading control by special devices;
  - take a decision if necessary.

A structure of the escape route system is based on the tasks assigned to it. The structure is presented in Fig. 14.

The diagram shows the basic modules of escape route system. The modules are discussed below.

Computing Module. This module is designed for calculation the safest evacuation routes. The *SaPA* has been developed [6] for this task. This model allows the assessment of the safety path evacuation of people in case of fire, and in real time to evenly distribute the flow of evacuation in a safe direction to evacuation exits. This model was presented in Sect. 2. Results of evaluation have shown that the use of the proposed algorithm can reduce the evacuation time up to 63% depending on the chosen frequency of the algorithm. The calculated routes are transferred to a management module.

Management Module. The objective of the module is to inform pedestrians and staff about the safe directions and direct to it. Analysis of existing dynamic indicators has

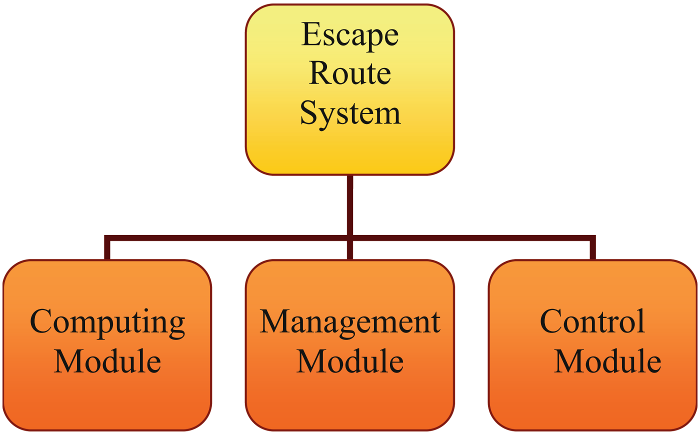

Fig. 14. Structure of escape route system.

showed its shortcomings [1]. A dynamic indicator was developed based on conducted analysis. The dynamic indicator allows updating a safe direction in real time based on information from computing module. A patent for utility model was received on the dynamic indicator. This way, the dynamic indicator can be used in the management module.

Control Module. Nowadays widely spread means of control are video cameras which are mainly intended for the control of public order. Assuming the video cameras as a means of control of evacuation process, the prerequisite is the installation of video cameras in each section of an escape route, which carried out the computation of the parameters in the mathematical model. Applying the video cameras, decision maker would always have information on emerging situations which could happen on escape routes. Decision makers can immediately "block" a section of escape route in the case of some critical situations that can be seen with video cameras. It will lead to re-routing of pedestrians flows and consequently avoid such place.

4.2 Functions and Algorithms

A functional process of *ERS* was elaborated according to the aim and the tasks of this system. The process is shown in Fig. 15.

The *ERS* is in constant contact with the external environment (fire detectors, CCTV etc.) through communication channels and permanently update information. The *ERS* begin to perform its functions in case of a fire and the beginning of an evacuation process. An algorithm of interaction between decision-makers and *ERS* is shown in Fig. 16.

The information about the location of the fire and about people's distribution inside of building are entered to the computing module in case of a failure of one or more fire detectors. The computing module calculates the complex criterion φ and defined safe escape routes from each room in the building to outside based on *SaPA*.

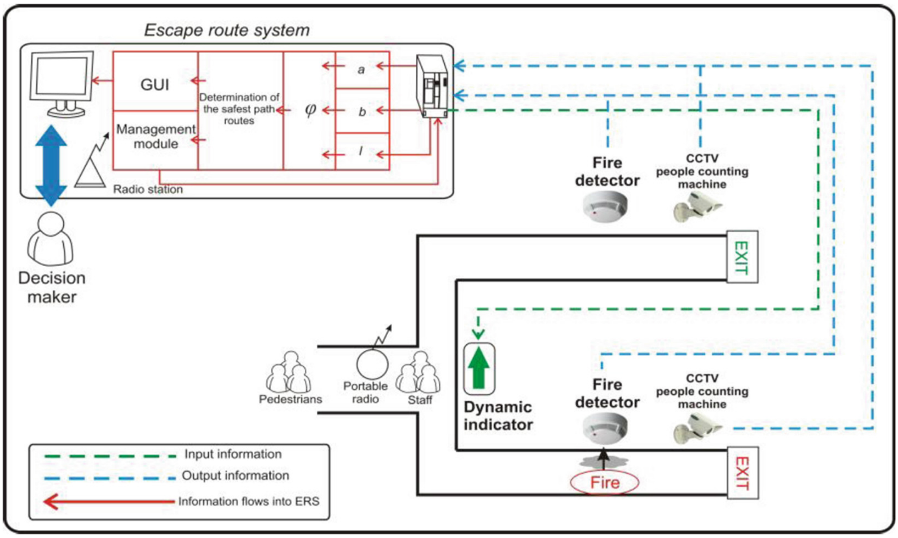

Fig. 15. Functional process of escape route system operations.

Information about safe escape routes is displayed on the decision makers PC and also supplied to the management module which switches each dynamic indicator to point to the safest direction.

Information is also transmitted to the staffs (on radio channels) who are involved in the evacuation. The information transmission process is represented in Fig. 17. Operation of the system is carried out till the end of the evacuation process and information about the features of the evacuation process is transmitted to a remote source. This information can later be used for assessment of staff and evacuees actions and for studies.

The designed system can be operated in several modes: daily activities mode (for getting information about the parameters of pedestrians in the building etc.) and emergency mode (for emergency evacuation management as well as for direct fire-fighter brigade to a fire place and/or to a place where pedestrians are blocked). The *ERS* can also be used for people's training for action during evacuation process.

The possibilities of decision maker are expanding with a such a system. The information load is also greatly reduced when making decisions during the evacuation process.

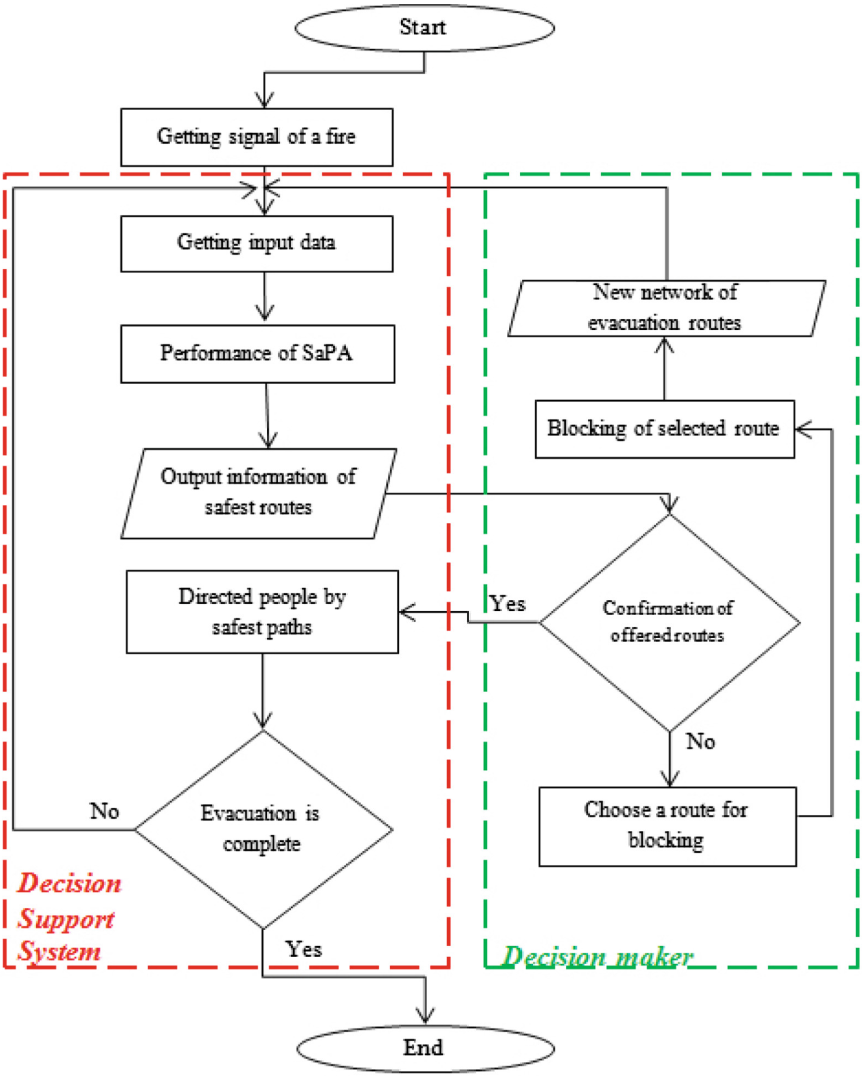

Fig. 16. Algorithm of interaction between decision-makers and ERS.

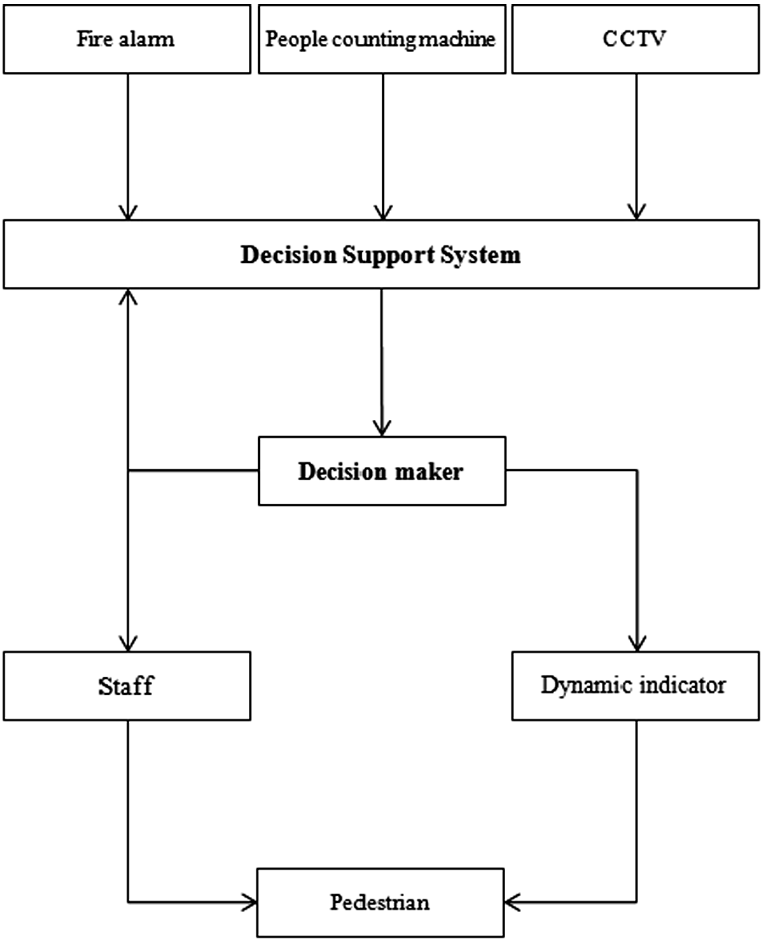

Fig. 17. Information transmission process.

5 Conclusions and Future Work

In this paper we presented the results of full assessment of the safest path route algorithm in the framework of evacuation simulations. It was found that the weights of 0,9-0-0,1 should be applied to prevent congestions during evacuations, when the density is high. For the algorithm, an update frequency of 5 should be chosen to timely direct the pedestrians to safe evacuation paths. The algorithm is suitable for cases when there are no widely dispersed emergency exits, uneven distribution of evacuation flows to the exits as well as to prevent congestions of high density during the evacuation.

In this contribution we designed an escape route system which will allow not only significantly to reduce the evacuation time but also to ensure people's safety during evacuation. It should be noted that the developed system can be used as a source of relevant information about the patterns and characteristics of people's movement. The results show the effectiveness of the proposed algorithm. However an experimental assessment is required for its application in a real evacuation process. The following phenomena should be investigated within the frame of an experimental assessment:

- people's reaction to dynamic indicators;
- do pedestrians follow the routes which would be offered;
- how staff responsible for evacuation organization will operate with dynamic indicators.

References

1. Shikhalev, D., Khabibulin, R.: Escape route systems at shopping malls. Fire Explos. Saf. J. **22**, 61–65 (2013)
2. Carattin, E.: Wayfinding architectural criteria for the design of complex environments in emergency scenarios. In: Advanced Research Workshop Proceedings, pp. 209–222. Universitad de Cantabria, Spain (2011)
3. Kobes, M., Helsloot, I., Vriesc, B., Posta, J.: Building safety and human behavior in fire: a literature review. Fire Saf. J. **45**, 1–11 (2010)
4. Samochine, D.A.: Towards an understanding of the concept of occupancy in relation to staff behaviour in fire emergency evacuation of retail store. Ph.D. thesis. University of Ulster, Belfast (1995)
5. Sandberg, A.: Unannounced evacuation of large retail-stores. An evaluation of human behavior and the computer model Simulex. Technical report, Lund University (1997)
6. Shikhalev, D., Khabibulin, R., Kemloh U.: Development of a safest path algorithm for evacuation simulation in case of fire. In: Proceedings of IV International Conferences on Agents and Artificial Intelligence, pp. 685–690 (2014)
7. Kemloh Wagoum, A.U., Chraibi, M., Zhang, J.: JuPedSim: an open framework for simulating and analyzing the dynamics of pedestrians. In: 3rd Conference of Transportation Research Group of India (2015)
8. Floyd, R.: Algorithm 97: shortest path. Commun. ACM **5**, 345 (1962)
9. Chraibi, M., Seyfrid, A., Schadschneider, A.: Generalized centrifugal force model for pedestrian dynamics. Phys. Rev. E **82**, 046111 (2010)
10. Helbing, D., Molnar, P.: Social force model for pedestrian dynamics. Phys. Rev. E **51**, 4282–4286 (1995)
11. Hoogendorn, S.P., Bovy, P., Daamen, W.: Microscopic pedestrian wayfinding and dynamics modelling. In: Pedestrian and Evacuation Dynamics, pp. 123–154 (2002)
12. Burghardt, S.: Analyse und vergleichende Untersuchung zum Fundamentaldiagramm a Treppen. Masterthesis. Bergische Universität Wuppertal (2009)
13. Meunders, A.: Kalibrierung eines Mikroskopischen Models für Personenströme zur Anwendung im Project Hermes. Masterthesis. Bergische Universität Wuppertal, Wuppertal (2011)
14. Chraibi, M.: Validated force-based modeling of pedestrian dynamics. Ph.D. thesis. Forschungszentrum Jülich, Jülich (2012)
15. Kemloh, U.: Route choice modeling and runtime optimization for simulation of building evacuation. Ph.D. thesis. Forschungszentrum Jülich, Jülich (2013)
16. Shikhalev, D., Khabibulin R.: Patent (in Russia) on December 27, 2013 № 136212 «Dynamic indicator» (2013)