Evacuation Simulation under Different Conditions using a Safest Path Routing Algorithm

Denis Shikhalev[1], Renat Khabibulin[1], Ulrich Kemloh[2] and Sergey Gudin[3]
[1]*The State Fire Academy of EMERCOM of Russia, Moscow, Russia*
[2]*Jülich Supercomputing Center, Forschungszentrum Jülich GmbH, Jülich, Germany*
[3]*Ghent University, Ghent, Belgium*

Keywords: Pedestrians Dynamics, Evacuation Strategies, Safest Evacuation Route.

Abstract: In this contribution we propose a safest path route algorithm for determination of the safest path directions of pedestrians in case of fire. The model and the algorithms are implemented in an open source framework (JuPedSim) which is a research platform to simulate pedestrian dynamics. We found that increasing the importance of the obstruction criteria (responsible for people's density) leads to a reduction of the total evacuation time. The proposed algorithm allows the even distribution of the evacuees to all available emergency exits, when there is an uneven distribution of people on the escape routes while avoiding a place with fire hazards. We simulate the evacuation of a shopping centre and showed that the application of the algorithm can reduce the total evacuation time up to 63% depending on the settings of the algorithm.

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 an organization's evacuation process and leads to an unbalanced use of emergency and exits routes. A significant number of people are accumulated 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 (Shikhalev and Khabibulin, 2013) 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 (Carattin, 2011; Kobes, Helsloot et al., 2010; Samochine, 2004; Sandberg, 1997) indicate the following problems in the area of evacuation management in shopping malls:

- Uneven distribution of people inside shopping malls ;
- Organisation 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 managements leads to the fact that a decision maker cannot objectively evaluate the whole range of hazards and determine safe routes for people during an emergency evacuation.

To solve these problems, a mathematical model of a safest path route algorithm was developed. The algorithms are used to calculate the safest path for people in a danger zone, and to direct them to a safer area (Shikhalev, Khabibulin et al, 2014).

In a first estimation the model showed a positive impact on the evacuation time and overall on the people's safety during evacuation simulations (Shikhalev, Khabibulin et al, 2014). Nevertheless, it is needed to complete a full estimation of all features of the model as well as determine the best combination of properties for evacuation simulations.

Shikhalev, D., Khabibulin, R., Kemloh, U. and Gudin, S.
Evacuation Simulation under Different Conditions using a Safest Path Routing Algorithm.
In *Proceedings of the 18th International Conference on Enterprise Information Systems (ICEIS 2016) - Volume 2*, pages 62-69
ISBN: 978-989-758-187-8

In this paper we consider the results of evacuation simulations using the algorithm. Simulations were performed using the Jülich Pedestrian Simulator, JuPedSim (Kemloh, Chraibi et al, 2015) with various numbers of people and different objects.

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. Some concluding remarks 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 by a path (current or newly defined). The algorithm of Floyd-Warschall (Floyd, 1962) was applied for calculating the safest path to the nearest gate. Normally, 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 Equation 1:

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

at:
a → min, i=1,…,n
b → min, i=1,…,n
l → 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 criterion and manners of its computing are found in previous work (Shikhalev, Khabibulin et al, 2014).

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 a place of cross 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 (Chraibi, Seyfried et al, 2010). GCFM belongs to the class of forces based models (Helbing and Molnar, 1995) and describes the movement of people at the operational level (Hoogendorn, Bovy et al, 2002) 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" (Helbing and Molnar, 1995). 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 (Burghardt, 2009; Meunders, 2011). Verification and validation of the GCFM, as well as a more detailed description is given in (Chraibi, Seyfried et al, 2010; Chraibi, 2012; Kemloh, 2012).

At each step of the simulation, the evacuees are sent through 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).

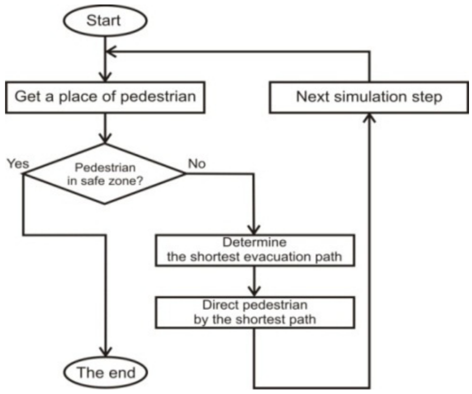

Figure 1: The shortest path route algorithm (*ShPA*).

However, there is a need to change the *ShPA* with regards to the problem of determination of the

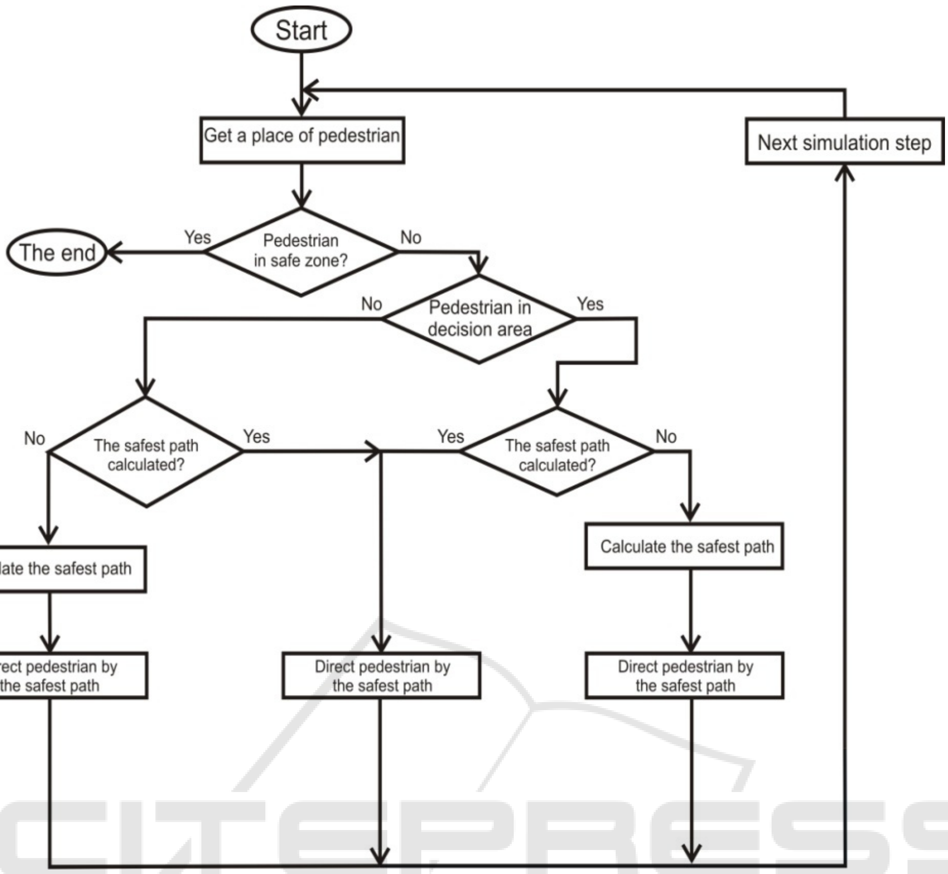

Figure 2: The safest path route algorithm (*SaPA*).

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

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 applying dynamic indicator (Shikhalev and Khabibulin, 2013). 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 answered during simulation:

- How are the *a*-criteria and *b*-criteria changed in the process of evacuation and under what quantitative values of criteria 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 it is 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 series of 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).

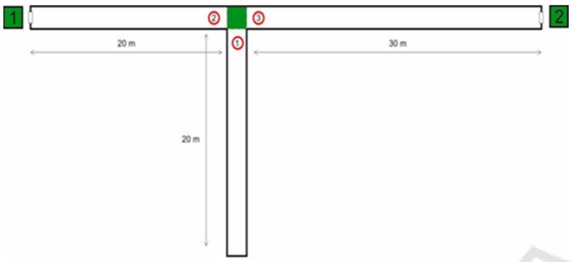

Figure 3: Objects of simulation within a preliminary assessment – *T*-junction.

Simulation results at the *T*-junction identified one of the features of the *SaPA*: the safest path route algorithm behaves itself 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 its turn, 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 importance 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 a-criteria. Reducing the importance of a-criteria leads to an increase in evacuation time;
- It is possible to regulate (zoom or zoom out) a moment of re-routing of evacuation flows by applying different weight coefficients.

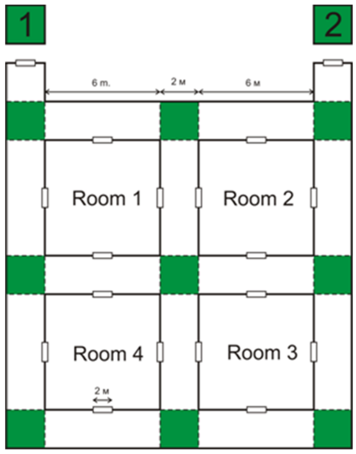

Figure 4: Objects of simulation within a preliminary assessment – Abstract model of the building.

After simulations at *T*-junction we continue in the abstract model (fig. 4). Simulation results in the abstract model allow us to state 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. Under efficiency we understand the ratio of evacuation time with the *SaPA* to evacuation time with the *ShPA*.

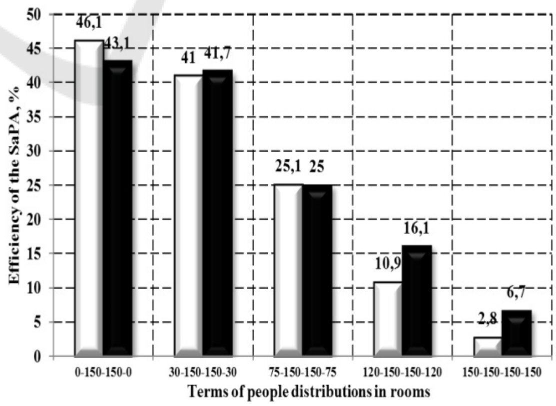

Figure 5: Efficiency Distribution of the *SaPA* depending on terms of people distributions. (0-150-150-0 value corresponds to the people distribution in rooms 1,2,3 and 4, respectively (Fig. 4)). White – scenario 1, black - scenario 2.

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 meters by 2 meters). 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 decision area to the exit;
- A *SaPA* update frequency of 1 has a negative impact on evacuation process given a small number of pedestrians;
- The *SaPA* allows evenly "download" sections of evacuation routes when there is an uneven distribution of pedestrians. Other words the *SaPA* directs pedestrians by routes which are not using during evacuation but can be.

3.2 Simulation of a Shopping Mall

After preliminary assessment we performed simulations in a shopping mall. The plan is shown in figure 5. 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.

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

The number of people in evacuation simulation was chosen in the rate of 1 person per 1 m^2 of retail premises (total number of evacuees in 2609 person).

The influence of the update frequency on the evacuation process was considered in the first series of simulation. The simulation results are shown in figure 7.

Analysis of figure 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). 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.

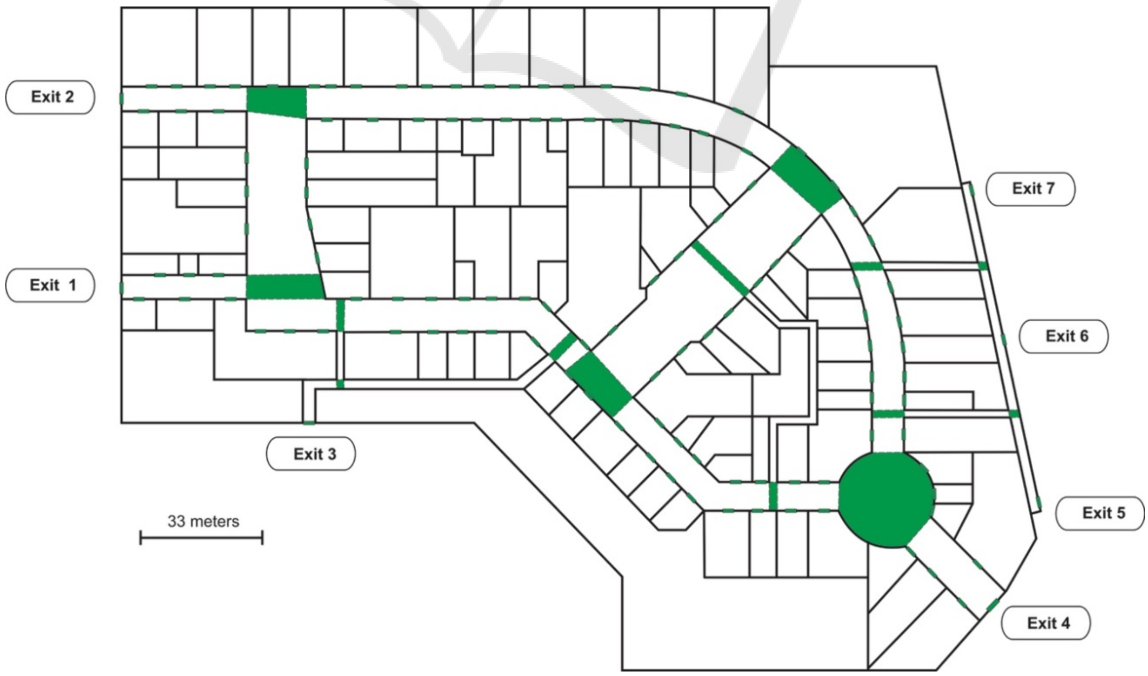

Figure 6: Layout of shopping mall.

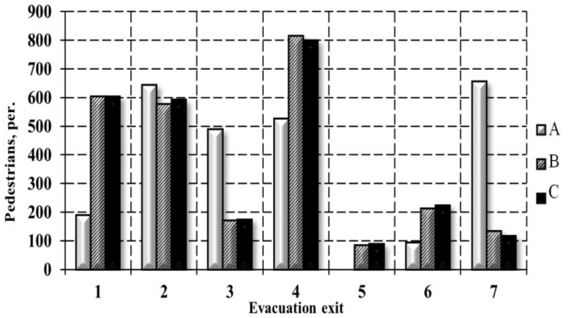

Figure: 7: People distribution to emergency exits. A - *ShPA*; B - *SaPA* with update frequency equal 5 (result of minimal evacuation time); C - *SaPA* with update frequency equal 13 (result of maximal evacuation time).

Application of the *SaPA* allows to reduce evacuation time up to 63% depending on the update frequency of the algorithm.

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 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 pedestrian's distribution to emergency exits was conducted in the next stage of simulation. The simulation results are shown in Figure 8.

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.

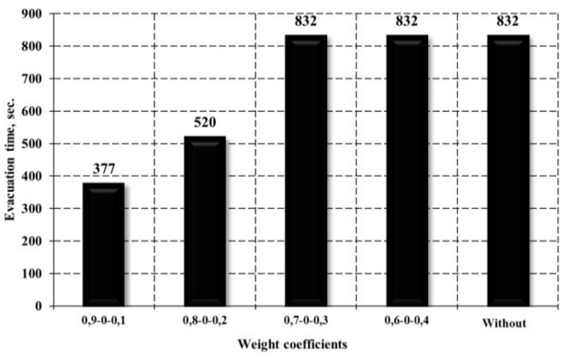

Figure 8: Weight coefficients vs. evacuation time.

Figure 9 presents the data with more details on the distribution of people to emergency exits.

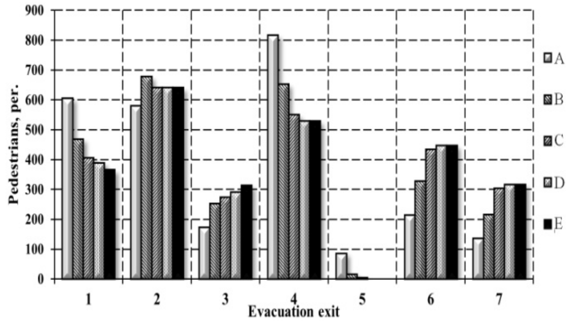

Figure: 9. The pedestrian distribution to emergency exits depending on the weights. A – Weight coefficients are 0,9-0-0,1. B - weight coefficients are 0,8-0-0,2. C - weight coefficients are 0,7-0-0,3. D - weight coefficients are 0,6-0-0,4. E – without weight coefficients.

Figure 9 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 "loading" narrow exits.

It was also interesting to consider the fairly frequent assertion of researchers in the field of human behaviour, that people in a fire will follow the escape routes they used to get into the building (Kobes, Helsloot et al, 2010; Samoshin, 2004; Sandberg, 1997). 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 figure 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 figure 10.

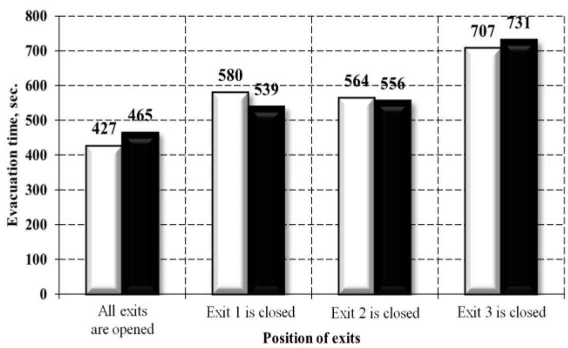

Figure 10: Dependence of the evacuation time to an algorithm (*SaPA* vs. *ShPA*). White – *SaPA*. Black – *ShPA*.

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

- 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 11 shows the simulation results with mentioned 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 cases where the only possibility is to direct people through the shortest path, it is necessary to use strategy 4.

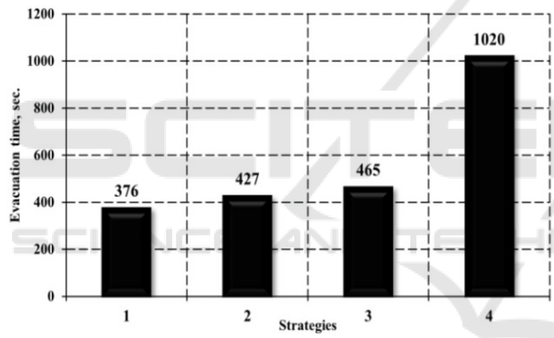

Figure 11: Ratio of evacuation time to an evacuation strategy.

4 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 people are of high density. 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 of people in evacuation.

Obtained results allow as talk about effectiveness of 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;

A plan of future research is to create a decision support system for emergency evacuation in a shopping mall based on obtained results.

ACKNOWLEDGEMENTS

The simulation results of this paper would never have appeared without sincere assistance of member of the «Civil security and traffic» division of Jülich Supercomputing Centre at the Forschungszetrum Jülich GmbH.

REFERENCES

Burghardt, S., 2009. Analyse und vergleichende Untersuchung zum Fundamentaldiagramm a Treppen. *Masterthesis*. Bergische Universität Wuppertal.

Carattin, E., 2011. Wayfinding architectural criteria for the design of complex environments in emergency scenarios. *In Advanced research workshop proceedings*. Santander, Universitad de Cantabria., Spain.

Chraibi, M., Seyfrid, A. and Schadschneider, A., 2010. Generalized Centrifugal Force Model for pedestrian dynamics. *Physical review E.*

Chraibi, M., 2012. Validated force-based modeling of pedestrian dynamics. *PhD thesis*. Forschungszentrum Jülich, Jülich, Germany.

Floyd, R., 1962. Algorithm 97: Shortest Path. *Communications of the ACM 5*.

Helbing, D., Molnar, P., 1995. Social force model for pedestrian dynamics. *Physical review E.*

Hoogendorn, S. P., Bovy, P. and Daamen, W., 2002. Microscopic pedestrian wayfinding and dynamics modelling. *Pedestrian and Evacuation Dynamics*.

Kemloh, U., 2013. Route choice modeling and runtime optimization for simulation of building evacuation. *PhD thesis*. Forschungszentrum Jülich, Jülich, Germany.

Kemloh Wagoum, A.U., Chraibi, M. & Zhang, J. 2015 JuPedSim: An open framework for simulating and analyzing the dynamics of pedestrians. In 3rd

Conference of Transportation Research Group of India.
Kobes, M., Helsloot, I., et al., 2010. Building safety and human behavior in fire: A literature review. *Fire Safety Journal*.
Meunders, A., 2011. Kalibrierung eines Mikroskopischen Models für Personenströme zur Anwendung im Project Hermes. *Masterthesis*. Bergische Universität Wuppertal, Wuppertal, Germany.
Molnar, P., 1995. Modellierung und silmulation der dynamik von Flussgagerstromen. *Dissertation*. Universität Stuttgart, Stuttgart, Germany.
Samochine D.A., 2004. Towards an understanding of the concept of occupancy in relation to staff behaviour in fire emergency evacuation of retail store. *PhD thesis*. University of Ulster, Belfast, UK.
Sandberg, A., 1997. Unannounced evacuation of large retail-stores. *An evaluation of human behavior and the computer model Simulex*.
Shikhalev, D., Khabibulin, R., 2013. Escape route systems at shopping malls. *Fire and explosion safety journal*.
Shikhalev, D., Khabibulin R., 2013. Patent (in Russia) on December 27, 2013 №136212 «*Dynamic indicator*».
Shikhalev, D., Khabibulin, R., Kemloh U., 2014. Proceedings of conferences. Development of a Safest Path Algorithm for Evacuation Simulation in Case of fire. *Proceedings of IV international conferences on agents and artificial intelligence – ICAART 2014*.