Development of a Safest Routing Algorithm for Evacuation Simulation in Case of Fire

Denis Shikhalev[1], Renat Khabibulin[1] and Armel Ulrich Kemloh Wagoum[2]

[1]*The State Fire Academy of EMERCOM of Russia, 129366, B. Galushkina 4, Moscow, Russia*

[2]*Jülich Supercomputing centre, Forschungszentrum Jülich GmbH, 52428 Jülich, Germany*

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Abstract: Route choice of pedestrians during an emergency evacuation can be influenced by many factors. In this contribution we elaborate three criteria to consider during an evacuation with a fire hazard. The criteria are combined in an objective function which is minimized during the simulation. The function defines the safeness of a route. In addition an algorithm is presented which evaluates and redirects the pedestrians to the safest path during the simulation. The algorithm shows a positive impact on the evacuation time and overall on the safety during an evacuation simulation. A long term goal of the presented algorithm could be the integration in an evacuation system that gives instructions or recommendations during the evacuation process using dynamic indicators.

1 INTRODUCTION

Remembering the location of emergency exits certainly plays an important role during an emergency evacuation. Some empirical studies have shown that in some cases almost 80% of adult visitors were not able to recall the finding of at least one of an emergency exit. The survey was conducted in a shopping mall in the city of Fiume Veneto in Italy by interviewing people (Carattin, 2011). It is also known that the availability of safe escape routes during an evacuation constitutes one of the most critical aspects of a building's safety in case of fire (Kobes, Helsloot et al, 2010). Moreover the analysis of some existing escapes route systems from different countries (Shikhalev and Khabibulin, 2013) shows that only one third of the systems were able to determine the direction of the escape route using a scientifically well founded method. This way, there is a problem of calculating the safest escape route for people in case of fire. This problem is related on one hand to the difficulty in finding the best escape route (from the point of view of people's safety) to outside and on the other hand to the limited functionality of escape route system.

Considering these factors some thought should be given on decisions support systems that are able to determine the safest route during an emergency evacuation. In this paper we propose an escape route assessment algorithm. Based on actual input data (the numbers of pedestrians, the value of fire hazards), the algorithm computes the safest route for people out of the danger zone. The algorithm can be integrated into escape route systems. This work is structured as follow: the second section presents some related works in the area of computing safe routes during evacuations. The newly introduced criteria are presented in the third section. This is followed by a case study and analysis. Some concluding remarks are given in the last section.

2 RELATED WORKS

The problem of calculating the safest escape route has been considered from various points of view (Pu and Zlatanova, 2005; Jalali and Noroozi, 2009; Filippoupolitis, Gorbil et al, 2011). The main similarity between those approaches is the fact that they operate on a graph-based structure. Generally, the Dijkstra or the Floyd-Warshall's algorithms are used to compute the paths (Evans and Minieka, 1992). The choice of the algorithm depends on the features of the problem to be solved (for example, in some cases the weight of edges is negative and this cannot directly be handled by the Dijkstra algorithm). The

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main differences in the approaches are the definition of the weights of the edges in the constructed evacuation graph. (Filippoupolitis, Gorbil et al, 2011) expresses the weight of the edges as the effective length which gives indications about the threat level of a part of the escape route. This metric consists of two variables. The first variable is the physical length of the escape route section. The second variable is the intensity of the hazards. The presented results of their simulation show a reduction in the percentage of fatally injured evacuees. (Jalali and Noroozi, 2009) defined a certain elapsed time used as the weight of the edges in their model. They investigated the evacuation of an underground mine and calculated the elapse time as a function of the length of a mine escape route coupled with a passage simplicity factor. Other authors focused on the quickest path taking into account different factors like queue size at exits (Kemloh Wagoum et al., 2012; Kretz, 2009). These approaches however did not include a direct threat source, a fire for instance.

The first steps to address this shortcoming is already taken by some simulation tools, for instance FDS+Evac (K., Simo Hostikka, S. et al., 2007) which combines a pedestrian evacuation model with a fire spreading model. While the presented approaches are very promising, we think that other factors need to be considered while calculating alternative routes during evacuation under imminent danger.

3 THE SAFEST PATH CRITERION

While assessing the safety of a route during an evacuation under imminent danger, a fire hazard for instance, the focus has to be on the building as a whole and on some of its sections in particular (Predtechenskii and Milinskii, 1978). A section can be the portion between two crossings of escape routes for example. So the very first step is to identify the different segments of the evacuation routes network. There are two different sources of hazards. The primary source is the imminent danger (e.g. fire) and the second sources is the process of the evacuation itself, where jamming at bottlenecks may cause severe injuries or even be fatal, and excessive speed may cause tripping related injuries even without jamming. Also the physical length of the escape route should be considered. Thereby, at least three parameters (fire, evacuation, length) should be taken into account to objectively assess people's safety during evacuation.

3.1 Obstruction

The first criterion gives information about the usage of the current section. 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. Usually, the density is expressed as the ratio between the number of people and the area of the escape route section. The value of the obstruction is given in Equation 1. D_{cur} is the current density on the considered section of the escape route. D_{max} is the maximal density on a section of the escape route. The value for D_{max} can be retrieved from different empirical studies (Kholsgevnikov et al, 2008; German Fire Protection Association, 2012; Huang et al, 2013).

$$a = \frac{D_{cur}}{D_{max}} \tag{1}$$

3.2 Timeliness

The second factor is directly linked to the fire hazard. During a fire in shopping mall people can be damage by fire hazards (high temperature, a large amount of smoke, low visibility, toxic products of combustion etc.) due to long pre-evacuation time for instance. A criterion of timeliness leads away from routes where fire hazards will be reached. The timeliness is defined in Equation 2. X_{cur} is the current value of one of the fire hazards on section of an escape route. X_{cr} is the critical value of one of the fire hazards on the section of the escape route. K_s is a safety coefficient. The values of X_{cur} are obtained from fire detectors. X_{cr} is obtained from various empirical studies (Gann, R., Babrauskas et al., 1994; Raj, 2008).

$$b = \frac{X_{cur}}{K_s \cdot X_{cr}} \tag{2}$$

3.3 Length

The third criterion is the relative physical length of the current section. It is defined in Equation 3. l_{cur} is the current length of the section and l_{max} is the maximal length of a section found in the complete network of the investigated structure.

$$l = \frac{l_{cur}}{l_{max}} \tag{3}$$

3.4 Multi-objective Optimization

Due to the aforementioned criticality criteria should be taken into account together to solve an optimization problem which is characterized by the following features:

- the impact factor of the different criteria is not known and their real influence on the assessment of the escape routes is uncertain;
- it is hard to find good compromise when each criterion has its own minimal value;
- best values of each criterion are located as closer to zero as possible.

Based on these features we built the following optimization strategy: firstly we calculate a node in 3 - dimensional space which is obtained by the criteria. Secondly, we find the distance between the obtained node and zero because we have the constraint that all values of each criterion should be minimal. So the distance is a complex criterion which is named as the safest path criterion.

The first task is solved by getting value of the criteria from different sources described in the previous section. The second task is to find the shortest distance between two nodes in an n-dimensional space. The Euclidean distance is applied to this purpose (Marler and Arora, 2004; Deza and Deza, 2013). This is explained in Equation 4. q_i and p_i are the nodes in the n-dimensional space.

$$d(q,p) = \sqrt{\sum_{i=1}^{n}(q_i - p_i)^2} \qquad (4)$$

Applying equation (4) for our task we combine the criteria (1), (2), (3) in one φ - safest path criterion (Figure 1). The process of combining is presented in Figure 1.

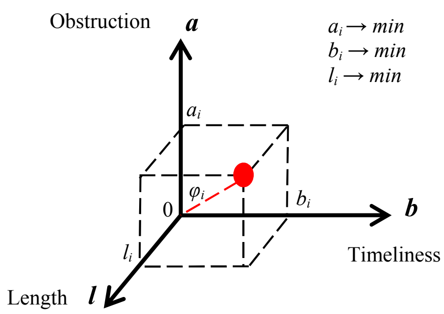

Figure 1: The process of combining.

The problem can then be formulated as:

Calculate the safest escape route for person N_1, $N_2,\dots,N_i$ from the starting positions m_1, $m_2,\dots,m_i$ to the safety areas s_1, $s_2,\dots,s_i$. The constraint is that the value of each criterion (1), (2), (3) should be minimal. As an optimization criterion we use the safest path criterion φ:

$$\varphi = \sqrt{(\alpha \cdot a_i)^2 + (\beta \cdot b_i)^2 + (\gamma \cdot l_i)^2} \qquad (5)$$

at:

$a_i \rightarrow min,\ i=1,\dots,n$;

$b_i \rightarrow min,\ i=1,\dots,n$;

$l_i \rightarrow min,\ i=1,\dots,n$.

where:

α, β, γ – the weight coefficient at a_i, b_i, l_i.

The coefficients (α, β, γ) are added to regulate the importance of the individual criterion. Besides a length the safest path criterion provides important information about people's density and fire hazards spreading on an escape route section.

3.5 Routing Algorithm

The criteria presented in the previous section are incorporated in a route choice algorithm, which evaluates the safest path during the evacuation. The algorithm is described in Figure 2. The *Re-routing* is triggered when a better route than the current is identified. The necessary input data for the algorithm (the numbers of pedestrians, the value of fire hazards on the escape route sections) are updated every 10 seconds.

Once the safest path criterion φ is calculated, the optimal escape route is determined using the Floyd-Warschall algorithm. It is suitable to use the algorithm of Floyd-Warschall in this case (Evans and Minieka, 1992) since the location of the fire is unpredictable and it is always necessary to compute all possible paths. This algorithm finds the shortest path between between all pairs of edges in a graph.
Normally, the means of the algorithm are expressed by following equation (Evans and Minieka, 1992):

$$d_{ij}^{m} = \min\{d_{im}^{m-1} + d_{mj}^{m-1}, d_{ij}^{m-1}\} \qquad (6)$$

where:

d_{ij}^{m} – the shortest distance from i – vertex to j-vertex.

m – intermediate vertices of path.

For our task we used the safest path criterion φ instead of the shortest distance. Actually our criterion has already contained information related to distance (see section 3.3).

For our task we used the safest path criterion φ as the weight of the edges. At each time step the algorithm evaluate the need for a re-routing on the section. The directions of the pedestrians are updated in the case that they are not already on the safest route.

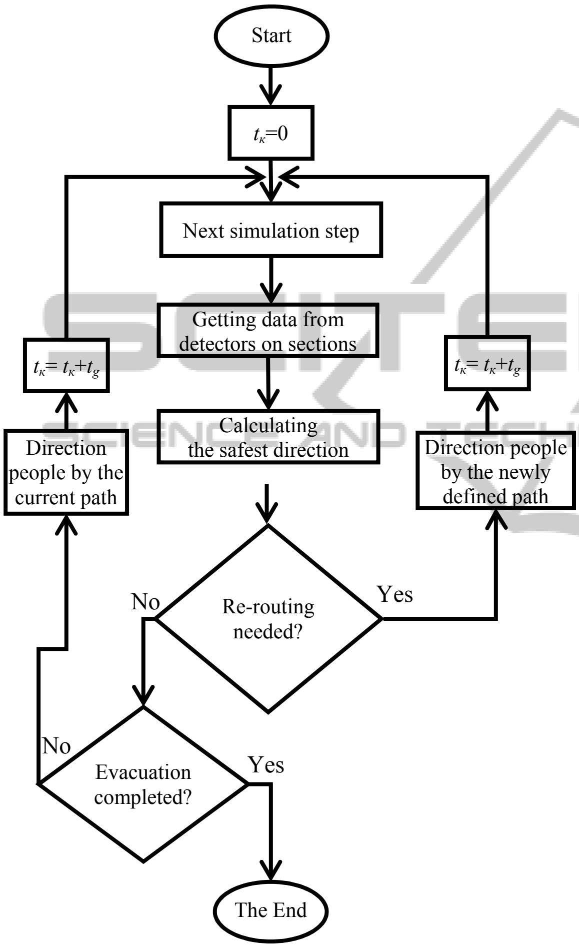

Figure 2: Safest route algorithm. t_k is the current evacuation time and t_g the step time (10 seconds)

4 CASE STUDY

We investigate a section of a shopping mall in the centre of Moscow. Figure 3 shows the plan of the simulated object. The two exits are annotated on the plan.

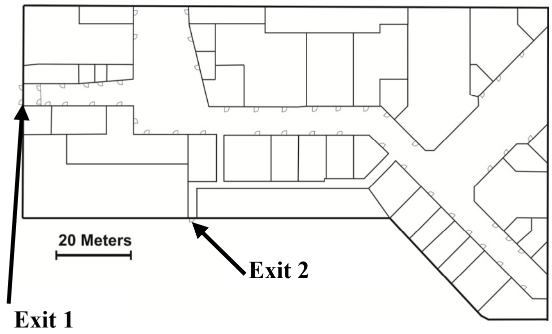

Figure 3: Plan of the simulated shopping mall.

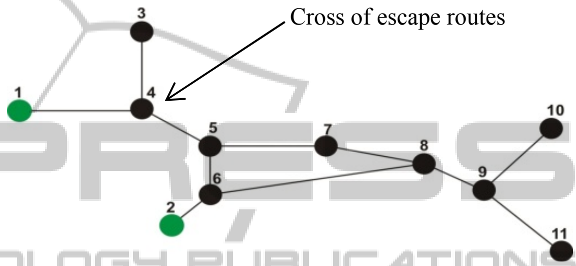

Figure 4 shows the structure of the graph extracted from the plan. The vertices of the graph are located at the crossing of escape routes and represented by dark circles. The rescue areas are represented by the green circles. The edges are weighted by the safest path criterion φ defined in the previous section.

5 SIMULATION

The simulation is conducted in two scenarios. In the first scenario we did not used the safest route algorithm therefore the evacuated people did not change their current route. After simulating the first scenario we got evacuation and fire hazard spreading's data which would be compared with data of the second scenario.

In the second scenario we used the safest route algorithm described in Figure 2. For both scenarios we used a flow model for people movement (Kholsgevnikov, Shields, et al., 2003) and FDS (K., Simo Hostikka, S. et al., 2007) for the simulation of the fire hazards spreading. Also, pedestrians are in both scenarios first directed to the shortest route to the outside. In the second scenario however, they change their initial route after some time.

The following constraints were used in the simulations:

- 1323 persons were randomly distributed in the plan presented in Figure 3;
- The pre-evacuation time is set to 60 seconds;

- All people were healthy and the initial space occupied by each person is 0,125 m^2 .

For the simulations the maximum density D_{max} is chosen 9 persons/m^2 based on the following sources (Kholsgevnikov et al, 2008; German Fire Protection Association, 2012; Huang et al, 2013), the maximal length of a section measured is 58 meters (section 6-8, figure 4).

Scenario 1
The simulation results from scenario 1 are presented in table 1. The percentage use of each exit gives information about how long this exit was effectively used during the entire evacuation. It is calculated as the ratio of the evacuation time through the considered escape to the total evacuation time.

Table 1: Simulation results of simulation by scenario 1 without the safest path algorithm.

Exit ID	Number of evacuated persons	Evacuation time, [s]	Percentage use (%)
1	395	124,6	25,2
2	928	316,8	100,0

From the results presented in Table 1 it can be inferred that 30% of people are evacuated during the first minute (from the start moving). The remaining 70 % of people are evacuated during the last 4 minutes. The escape 1 had been available for 145 seconds, but people were still going to the escape 2. A section is avoided in the simulation only if the fire hazards reach its critical value on that section. During the process of evacuation the fire hazards did not spread as fast as the pedestrians were evacuated and therefore did not reach its critical value in the places where pedestrians were going. By the end of evacuation the fire hazards spread up to the node 8.

Scenario 2
In this scenario, the safest route algorithm described in Figure 2 is used. The following weight coefficients were used in (5): a – 0,7; b – 0; l – 0,3. Those coefficients values were chosen because from our point of view the a-criterion (which reflects people density) is more important than l-criterion. The value of b is zero because the fire hazards did not reach a critical value. Actually, the definition of the coefficients is another task which can be investigated in future work. The simulation results from scenario 2 are presented in Table 2.

The results of people evacuation show that evacuation time is reduced. Moreover, re-routing for pedestrians take place at time 120 sec in the node 5. The re-routing of evacuation flows happened when

Table 2: Simulation results of simulation by scenario 2 using the safest path algorithm.

Exit ID	Number of evacuated persons	Evacuation time, [s]	Percentage use (%)
1	707	190,5	82,8
2	616	230,6	100,0

section 5-4, 4-1 were empty and section 5-6, 6-2 had a density of approximately 3 persons/m^2.

6 ANALYSIS

The comparison of the results of simulation leads to several conclusions. Firstly, the pedestrians were directed to the shortest path (scenario 1) and as the result the non-evenly distribution evacuation flows through exits took place. Also there are many evidences about non-evenly distribution evacuation flows through exits during evacuation (Kobes et al, 2010; Benthorn and Frantzich, 1996). However, application of the safest route algorithm distributed the pedestrians more evenly and reduced the overall time of evacuation.

Secondly, the main criteria of the evacuation process such as the time of evacuation and distribution of people through the exits depend on the re-routing time. Thus, the re-routing time happened when the people's density reached 3 persons/m^2 in the second scenario. It is still not a critical density that could affect people's safety. Nevertheless it has an influence on people's velocity and on the evacuation time. It means that the optimal balance between the weight coefficients in (5) should at least aims at reducing the evacuation time.

7 CONCLUSIONS AND FUTURE WORK

The presented algorithm computes the optimal safest route based on input data from smoke detectors and other sources. The results are therefore influenced by the quality of the input data. We also acknowledge that the algorithm must be coupled to an evacuation system to give the instructions during the evacuation process using dynamic indicators. This could be very useful for guiding impaired persons for instance. A major problem is to give a guidance that will be accepted by the evacuees. In the further work we plan to improve the algorithms and integrate them within a pedestrian simulator. In addition proper validation criteria must also be investigated. In this contribution we limit ourselves to the evacuation time.

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