Evacuation Route Assessment Model for Optimization of Evacuation in Buildings with Active Dynamic Signage System

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Abstract

In this paper a model for active and dynamic people evacuation is presented. Proposed model optimizes evacuation process according to chosen evaluation factor. Model contains an algorithm for determining all possible evacuations plans which are represented as a sets of graphs. This two-layer approach allows for fast calculations, which can be conducted in a time short enough for the results to be used for active dynamic evacuation signage system. In certain times of the evacuation simulation or real evacuation, route assessment calculations are carried out. When the calculations are completed, the result is presented as a recommended direction of evacuation.

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1. Introduction

The main problem, which results from the currently used static evacuation signage of buildings, involves possibility of evacuation towards a hazard. Such a situation may also occur in places where alternative evacuation routes are possible. It is caused by using the evacuation signage, which is permanently pointed in one direction. This situation may not be accepted in buildings with a large number of occupants, or in strategic objects. Evacuation may

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be optimized by applying a dynamic signage provided that the changes in the scope of hazard development and distribution of people in any given moment are taken into account when performing relevant calculations. The proposed model of evacuation route assessment allows for evacuation optimization during real time of evacuation.

2. Static and dynamic evacuation routing

Evacuation is usually conducted according to trained or predefined plans and procedures when specific requirements are fulfilled. None of the currently existing systems is not actually compatible with actions, which take place during a real evacuation. It happens so because they do not collect the full picture of a situation and they do not concurrently take into account a hazard and people who are at risk. Table 1 presents three types of systems designed for evacuation routing. The first one is a basic, classical one, which is present in every building equipped with a fire detection system. Its role is to trigger an alarm and lead to people evacuation according to predesigned evacuation directions. Such a system can locate a hazard, however, this location is confined only a fire zone in which this hazard was detected. The next level of the evacuation routing system is the solution currently applied in few objects and it consists in defining evacuation directions based on a hazard location. In this case, the evacuation directions are presented by means of illuminated arrow signs, which are able to display more than one direction of evacuation. However, these systems do not take into consideration a hazard development or a change in people distribution during evacuation. Third, a type that is a postulated one, is tasked to dynamically react to people’s behavior, that is their direction of evacuation or occurring hazard, which may develop. This model is to be closely correlated with a building, its systems and employees. It is to be a personal guide who sees a hazard, who can chose the right way out from the existing in a given moment hazard with simultaneous execution of the strategy, which is selected in advance and depends on the type of hazard.

Table 1. Data acquisition before and during an event. Source: the authors’ study.

| Level            | People | Hazard     |
|------------------|--------|------------|
| Present basic    | no acquisition | statically |
| Existing systems | statically | statically |
| Postulated model | statically | dynamically |
|                  | dynamically | dynamically |

In case of using the postulated model of evacuation routing, the result of an analysis may be presented as follows:

- Recommended one direction of evacuation
- No recommendations as to the direction of evacuation
- Forbidden one of evacuation directions
- Distance to travel
- Estimated time to evacuation completion

Based on given information, individuals present in a given area may, but do not have to, make a decision in line with recommendations provided by the information system.

3. Assumptions of the system of evacuation direction optimization

A diagram presenting the system of evacuation direction optimization is given on Fig. 1. In the assumption, it contains the following:

- Hazard detection system
- Movement measurement system
• Movement control system
• Building database
• Measurement database
• Hazard identification module
• Evacuation strategy selection module

And additionally it consists of a Simulation mode, which simulates real building and where different strategies and situation can be tested.

![Diagram of system components](image)

### 3.1. Hazard detection system

Hazard detection system – it consist of detectors selected for a given type of hazard or alarm buttons connected with a central unit, which transfer information about a location and time of hazard occurrence, alternatively about its features and intensity. These could be detectors of temperature, smoke, flames, gas concentration or biological hazard. Information about a hazard may require confirmation by the additional element of a system or by a human. The system interprets received signals from detectors and consequently identifies a hazard and its location.

Hazard detectors should be located in places correspondent to nodes in a graph model.

### 3.2. Movement measurement system

Movement measurement system is responsible for permanent and ongoing monitoring the number of individuals in specific rooms of a building. The system is not designed to track individual persons, but to count the number of movements between rooms including a movement direction.

The existing technical solutions, except detectors in passageways, also provide for systems counting people in rooms based on the methods of vision analysis or based on detection of additional devices carried by individuals such as proximity cards or infrared transmitters.

Hazard detectors should be located in places correspondent to curves in a graph model. Alternatively, the systems counting the number of individuals in rooms should be located in places correspondent to nodes in a graph model.

Hazard detection system and movement measurement system will be characterized by asynchronism due to lack of...
information flow towards detectors.

3.3. Movement control system

The movement control system consists of directional signs with an option to change visualization of an evacuation direction, or other devices informing about a recommended evacuation direction. These devices should be located in appropriate places in a building where the selection and change of an evacuation direction is possible. It is also possible to use information devices in order to stop evacuation in specific places in a building.

The location of elements of a movement control system is correspondent to information peaks in a graph model.

3.4. Building database

The building database includes a whole range of information concerning:
1. general characteristics of users - data on the assumed typical population, including information about age, gender, movement ability, familiarity of building, knowledge of procedures in the case of a hazard, social relationships, a type of activity;
2. exact characteristics of a building - detailed information concerning its architecture, function, intended use of a building mapped in the form of a graph, including data concerning the length of escape routes, surface area of rooms, the width of passageways between rooms, connections to exits leading to a safe place;
3. basic graph of a building - mapping the internal geometry of a building on the basis of which graph families are created, which are then used to determine an optimal evacuation plan;
4. matrix of detectors assignment to rooms and passageways.

3.5. Measurement database

Measurement database is collected from the signal processed from the movement measurement system. The database includes both the real and historic data. Historic data is used for simulations and to determine a strategy depending on the moment of a hazard occurrence. Strategies may vary depending for instance on time of the year or a daytime. Real data is used to feed the model of evacuation optimization system.

Historic data may be also used in the case of a failure of the movement measurement system.

3.6. Hazard identification

Hazard identification consists in recognizing the type of activated detector, its location, and possibly additional data from this detector on intensity or a hazard type. Additionally, a hazard may be detected based on information about a failure of one or more detectors. It is possible to use more complex identification algorithms and acknowledgement of information on a hazard, which take into account coincidence of detectors activation, people’s response by the way of pushing alarm buttons and passing time.

There is an option that a person who directly operates the system identifies a hazard, e.g. a terrorist attack based on other information and pinpoints a hazardous place on a building plan.

4. Evacuation optimization system

Evacuation optimization system is based on a formal model with a space presented in the form of an undirected graph, where each node maps a logical space (usually a single room, corridor, staircase...) and a line between nodes defines a possibility to move between spaces. The basic elements of a formal model are presented in Table 2.

Table 2. Variables in evacuation optimization model.

| Variable symbol | Description |
|-----------------|-------------|
| $G$             | $G = < W, U >$, undirected graph defining a space structure, $W$ - collection of nodes, $U$ - collection of lines, |
The variables presented in the table are used to:

- determine possible evacuation plans
- evacuation plan evaluation

The modified graph $G$ is used to determine all possible evacuation plans. The graph modification is linked with cases where a hazard detection or adoption of a selected strategy may result in exclusion some nodes from available evacuation routes. The modified graph $G$ is the basis of determining all possible evacuation plans involving graph algorithms: determining all spanning trees and determining the shortest route.

![Diagram](image_url)

Fig. 2. The process of defining possible evacuation plans; (a) a basic graph (exit: node 6); (b) a modified graph (nodes 4 and 5 removed due to a hazard); (c) possible evacuation plans.

Upon determination all possible evacuation plans, each of them is the subject to evaluation, which takes into account the assumed criteria. The process of evacuation simulation is used to evaluate each evaluation plan. In order to save calculation time, the evacuation simulations for individual plans are run simultaneously. The adequate monitoring variables are activated in the simulation process depending on the examined criterion. An authorial simulator has been employed for this simulation, which is based on the queuing systems theory and idea of flow in network (Ford and Fulkerson (1962) and Hoppe and Tardos (1995)) for which:

- Each node is replaced with two systems of queuing channeling connected in a serial manner.
- Adequate ins and outs of the queuing channeling systems are connected for adequate nodes.
Upon starting a simulation, a number of persons in individual nodes is initiated by current data from the movement measurement system. The system of A type in the adopted solution reflects the process of evacuees movement from a given room towards a door. Time of reaching the door of a room $j$ by each person present in a room $i$ in a moment of time $t = 0$ is determined based on equation (1), in which $n$ defines the person’s number.

$$T_{ij}^n = T_i + \frac{L_{ij}}{v_i \cdot P_i(0)} \cdot n$$  \hspace{1cm} (1)

For individuals moving through rooms $i, j$ (for times $t > 0$) time to reach the next doors is determined based on equation (2):

$$T_{ijk} = \frac{L_{ijk}}{v_j}$$  \hspace{1cm} (2)

The queuing system of type B maps the process of evacuees movement through a door with a possibility to include changes in movement speed depending on density. In a basic version, time of crossing the doors between rooms $i, j$ is determined based on equation (3):

$$F_{ij} = F \cdot W_{ij}$$  \hspace{1cm} (3)

The following main stages may be distinguished in the process of evacuation optimization:

- Defining an evacuation strategy and modifying a base graph,
- Designating a set of permitted solutions by generating any possible evacuation plans (whereas one of these plans shall be an optimal solution),
- Conducting an evacuation simulation for each of the designated plans and calculating the indicator values for each of them,
- Choosing an optimal solution based on the indicator values.

In assumptions, the system allows for using different variables as evaluating values (e.g. total evacuation time, mean evacuation time, exposure time to a hazard and others). It is possible to define evacuation strategies, which assume taking into account more than one indicator. However, the selection of the right method of multi-criteria optimization may prove to be problematic in such situations. The methods of lexicographical order or override indicator may be the easiest to use (and justify).

The main evaluating indicator connected to evacuation is time needed to escape from endangered area. However, it is possible to extend the list of available evaluating indicators from the point of view of possibility to analyze different hazards and their development as well as due to suggested model of evacuation routing. The list, which is presented below (Cisek and Kapalka (2010, 2011)), is subject to division due to the phase of analyzing the evacuation process.

Evaluation indicators obtained on the basis of a space geometry analysis:

- distance
the nodes number, receipts number, branches in the graph number
length to width ratio
the constrictions number, the narrowing to the average width ratio
route complexity, the turns and u-turns number
route characteristics - horizontal, vertical up, vertical down
exit attractiveness, exit popularity, route knowledge

Evaluation indicators obtained during the simulation:
- maximum/average density, distribution of congestion with respect to the space, distribution of congestion with respect to time
- lowering space rate, the uniformity of exit rate, leaving efficiency, the highest minimum door flow per width unit
- uniformity of emergency exit doors usage
- people streams motion vector angle during their linking

Evaluation indicators obtained by the simulation:
- minimum / maximum / average people evacuation time
- minimum / maximum / average personal evacuation distance
- average / maximum cumulative waiting time
- forces acting on the person (too high density)
- changes direction number
- defeated constrictions number
- nodes (, information) number of on the escape route
- proximity to danger, toxic substances amount, thermal radiation dose

Beside the mentioned evaluating indicators, it is also possible to evaluate evacuation direction based on less tangible factors such as a sense of safety, a risk level.

It is possible to use more than one evaluating indicator or to create a formula containing a few indicators along with a weight assigned to them.

5. Experiments

A series of experiments for the selected building was carried out in order to analyze the efficiency of model operation. The graph presenting the building is included in Fig. 4.

The selected building has three floors, three staircases and three exits leading to the outside. There is a possibility to move between staircases at each floor. It has been assumed that the building is occupied by 450 persons. 8 simulations according to Table 3 were carried out during the experiment. Hazard in relevant simulations covered the middle staircase by its range.

The results of conducted calculations are presented on Fig. 5 and Table 3. It should be noted that some people are treated as casualties.
Table 3. Experiment plan and results.

| Simulation | People placement | Hazard | Evacuation guidance | Evacuation time [s] | Casualties [ppl] |
|------------|------------------|--------|---------------------|---------------------|------------------|
| 1          | Evenly           | No     | No                  | 126                 | 0                |
| 2          | Evenly           | No     | Yes                 | 120                 | 0                |
| 3          | Unevenly         | No     | No                  | 202                 | 0                |
| 4          | Unevenly         | No     | Yes                 | 149                 | 0                |
| 5          | Evenly           | Yes    | No                  | 146                 | 48               |
| 6          | Evenly           | Yes    | Yes                 | 180                 | 25               |
| 7          | Unevenly         | Yes    | No                  | 165                 | 57               |
| 8          | Unevenly         | Yes    | Yes                 | 209                 | 0                |

The analysis of results indicates that the evacuation time is made shorter every time when the system of evacuation routing is used in situation where there is no hazard taken into account. In cases where a hazard is present, the evacuation time with guidance is longer but the expected number of casualties is smaller. Particularly big differences are observed in case of uneven distribution of people in the building.

Fig. 5. Graph of the experiment results.

6. Summary

Static evacuation plans, which are available in most buildings, have many disadvantages in cases when conditions change during evacuation. Those changes can occur during sever fires, arson situation, terrorist attacks, or chemical accidents. The dynamic signage system is a solution, which would take into account both, the hazard source and the people distribution in buildings. Combining those two sets of information needs evacuation route assessment and allows for optimization of evacuation in buildings.

Proposed model can optimize evacuation process according to chosen evaluation factor i.e. evacuation time, hazard proximity, cumulative cueing time. Additionally, the model contains an algorithm for determining all possible evacuations plans which are represented as a sets of graphs. This two-layer approach allows for fast calculations, which can be conducted in a time short enough for the results to be used for active dynamic evacuation signage system. Proposed algorithm can be used in buildings at places where the choice is possible. An example of such place is the intersection of corridors, from which there is possibility to go outside of the building or a hallway on any floor of high-rise building, on which there are at least two exits to two different staircases.
In certain times of the evacuation simulation or real evacuation, route assessment calculations are carried out. These moments can be established in advance or in case of situation when a specific parameter has exceeded a certain level (e.g. congestion, waiting time). When the calculations are completed, the result is presented as a recommended direction of evacuation in areas where such a choice can be made.

The experiment results gives an example what difference the evacuation route assessment models can make in evacuation time and level of safety in case of evacuation during normal conditions and with a hazard present in a building. This model can use different strategies according to chosen type of evaluation indicator.

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