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Dynamic Evacuation Planning by Visual Analytics—An Expert Survey

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Abstract

In a formative user study, we evaluated the requirements of visual analytics for dynamic evacuation planning. To this end, we created a prototype that implements the visual analytics methodology and is able to compute, visualize, and interact with evacuation routes in emergency situations in buildings. Using this prototype, we conducted an expert survey including a psychologist, a consultant for building safety measures, and a building planner. The survey provides essential information needed to build a tool that is able to evacuate people inside a building safely. Additionally, we report on results of the survey regarding technical limitations in obtaining data such as the evacuees' position and their number to calculate the shortest routes during evacuation.

Categories and Subject Descriptors (according to ACM CCS):
F.2.2 [Nonnumerical Algorithms and Problems]: Sequencing and scheduling—Routing and layout
H.5.2 [Information Interfaces and Presentation]: User Interfaces—Graphical user interfaces (GUI)
K.4.1 [Computers and Society]: Public Policy Issues—Human safety

1. Introduction

In the last years, many tragedies occurred due to failed evacuations in emergency situations. Incidents at festivals, such as the Love Parade 2010[1] and the Madrid arena tragedy[2], as well as working places, such as the fires at a German workshop[3] and a Bangladesh textile factory[4] demonstrated that it can be disastrous if evacuations are not prepared thoroughly. Therefore, public spaces or buildings have to be planned carefully to create safe evacuation routes and avoid bottlenecks at all cost. Afterwards, the evacuation has to be supervised to lead the evacuees to safety and create secure routes without generating bottlenecks and avoiding blocked areas due to fire or smoke spreading.

For building planning as well as for evacuation supervision, a tool is needed to assist the users with visualization of the building and follow the progress of the evacuation. Interactivity is crucial to allow building planners to run multiple simulations with different evacuation scenarios or to intervene live evacuations if required.

To create such a tool, the knowledge and experience of experts in related fields needs to be incorporated. Psychologists provide knowledge about the human behavior in panic situations and can predict the actions of evacuees during evacuation. Their knowledge is also important to create good user interfaces that are intuitive and easy to use. Building planners and consultants know the guidelines that have to be taken into account for evacuation. They are also aware of the technical possibilities and familiar with the issues that arise when planning an evacuation. Therefore, the experts' knowledge is fundamental to create a tool that adheres to all requirements necessary to fulfill the legal regulations and to ensure safe evacuation.

[1] http://www.spiegel.de/international/germany/analysis-of-the-love-parade-tragedy-the-facts-behind-the-duisburg-disaster-a-708876.html
[2] http://elpais.com/elpais/2012/11/29/inenglish/1354205787_673115.html
[3] http://www.independent.co.uk/news/world/europe/fourteen-disabled-people-die-in-fire-at-german-workshop-8352798.html
[4] http://www.guardian.co.uk/world/2012/nov/25/bangladesh-textile-factory-fire

In this paper, a visual analytics tool is developed for building planning and evacuation supervision with the purpose to conduct a user study including a psychologist, a consultant for building safety measures, and a building planner. This survey provides important insights related to evacuation scenarios and will be relevant to future development of reliable tools that support evacuation.

2. Previous Work

To create a tool for building evacuation, several steps are necessary. First, an algorithm is required to find the shortest paths for the evacuees to reach the exits. Then, we need a visualization to monitor the evacuation and detect critical situations. Interactivity is important for users to be able to switch between different visualizations and modify parameters to detect problems before they occur and solve them. This section discusses the related approaches of these topics.

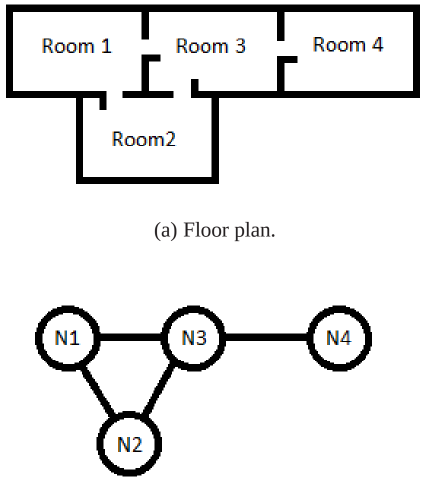
2.1. Shortest Path Finding Algorithms

To find the shortest paths in an evacuation scenario, an algorithm is required that calculates the fastest routes from all occupied rooms to the exits. There are several algorithms that can be used for this purpose. Most of them first divide the structure of the building into nodes and edges and then calculate the fastest routes. A small example is shown in Figure 1. For instance, the *Capacity Constrained Route Planning* (CCRP) algorithm [LGS05] considers the capacities for each node and each edge whilst finding the shortest paths. There are also many advances to this approach, such as *Intelligent Load Reduction* [KGS07], which neglects bottlenecks found in previous iterations, or the *Incremental Data Structure* [KGS07], which reuses already calculated information to reduce the computation time. CCRP++ reduces unnecessary load in computation [Yin09]. There are also other approaches based on CCRP such as the *Hierarchical Route-Planning Algorithm* [YLJ*11], or the *Priority based Distributed Evacuation Routing* [RHDW12], which include priorities in their calculations. Since the purpose of the tool is the usage in the formative user study, the standard CCRP algorithm is adequate and, hence, used to calculate the shortest routes in the developed prototype.

2.2. Visualization Approaches for Building Evacuation

Two software tools that use visualization approaches for building evacuation are SIMULEX[5] and buildingEXODUS[6]. Both tools create simulations of building evacuations. For visualization, they calculate the paths for the evacuees to

[5] http://www.iesve.com/software/ve-pro/analysis-tools/egress/simulex
[6] http://www.fseg.gre.ac.uk/exodus/



(a) Floor plan.

(b) Nodes and edges representation.

Figure 1: The floor plan shown in (a) includes 4 rooms and is divided accordingly into 4 nodes (b) connected through edges, which represent the doors between the rooms.

the nearest exits, first. To this end, they divide the building into a grid where the evacuees move from one square to the next. Individual evacuee parameters, such as body shape and size, walking speed, and time to respond to an alarm can be defined. The simulation starts after parameter definition. Additionally, parameters, such as walking speed, can be reduced when evacuees enter an area filled with smoke or fire.

After parameter definition, the evacuees go to the nearest exit. The evacuation is then presented as 2D or 3D visualization. The parameters can only be modified until the visualization starts, but specific data, such as general occupant flow or the individual movements, can be extracted after the simulation has finished. This allows the users to detect bottlenecks or other dangerous situations occurring during the evacuation.

2.3. Evacuation Utilizing Visual Analytics

Visual analytics is used to gain insight in complex scenarios by combining automatic processing, visualization, and human-machine interaction to take advantage of the strengths of both human and machine. In the context of this paper, a loop is used where an algorithm calculates the shortest paths and the visualization of the computed paths are presented to the users (Figure 2). Parameters can be modified to change the routes ensuring a safe evacuation. After adjusting the parameters, the background algorithm recalculates the data and shows the results in the visualization, again. This approach has been mainly applied to the evacuation of cities or large areas using vehicles to create the scheduling for the evacuations (e.g., [AAB08b], [AAB08a]).

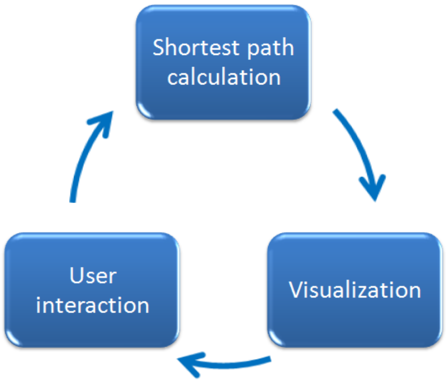


Figure 2: Visual analytics loop for dynamic evacuation planning. First, the shortest paths are calculated. A visualization communicates relevant information to the users, and the users can modify evacuation parameters and interact with the visualization. When parameters are modified, the loop is started from the beginning.

In building evacuation, a recent example of applying visual analytics is described by Reddy et al. [RHDW12]. The shortest paths to the exits are calculated and a visualization shows the building divided into a set of nodes connected by edges that represent the different rooms and their links. Each node includes a graph showing the occupancy rates inside the building during the whole evacuation. In our approach, we create a prototype based on this idea to receive feedback from experts related to building evacuation. This enables us to extract useful information to create a qualified tool for building evacuation in the future.

3. Evacuation Tool Prototype

Our visual analytics system creates an interactive loop that calculates the shortest routes first and then visualizes the information on screen. The user is then able to interact with the visualization: modifications lead to the recalculation of the shortest paths and the visualization is updated (see Figure 2). This offers the possibility to filter and extract data regarding the building evacuation, while the simulation is running. This represents the main novelty compared to previous approaches (Sections 2.2 and 2.3), where data can only be extracted after a simulation has been completed. These approaches can only be used for building planning or to analyze an evacuation after it took place. With our tool an evacuation can also be followed while it takes place to help the evacuees get out of the building safely.

3.1. Path Finding Algorithm

The CCRP algorithm is applied to calculate the shortest paths considering the capacities inside the building. Dijkstra's algorithm is used to determine the shortest routes from the nodes sheltering evacuees to the exits. Afterwards, CCRP reserves the capacities throughout the calculated escape routes to ensure that the evacuees will not be blocked once the evacuation has started. Using this process, bottlenecks are avoided in advance. Several routes can be taken to the exits instead of only one static evacuation route for all people inside the building. The algorithm runs in the background to recalculate the paths if modifications are made in the visualization.

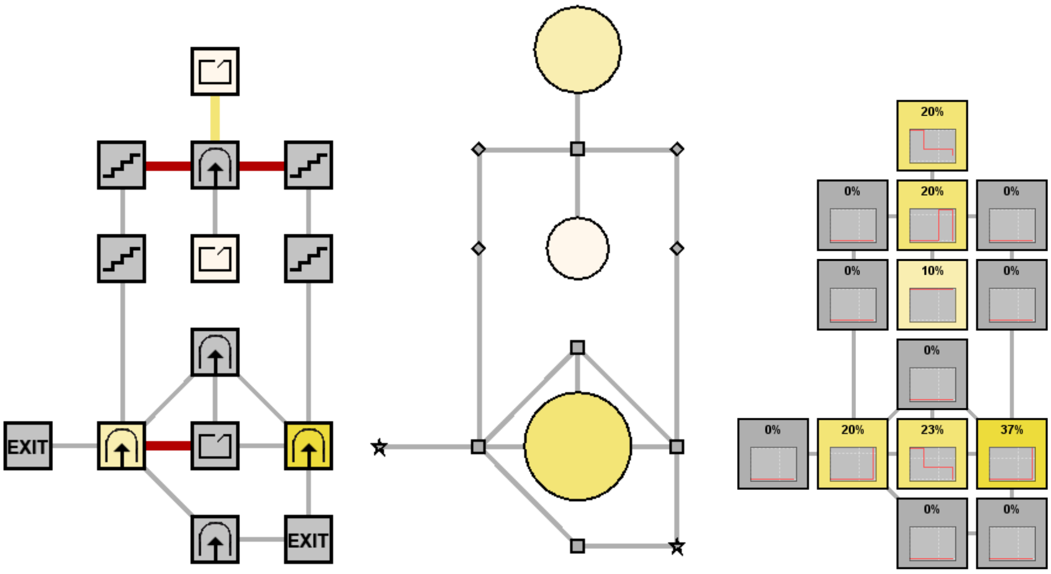
3.2. Visualization

The visualization includes several types of coordinated views (*Icons*, *Nodes*, *Statistics*, *Escape Routes*, and *Maximal Occupancies*) that display different kinds of information needed for building planners or in live evacuations (see Figure 3). The *Icons* visualization shows the rooms in a building represented by nodes that are connected with edges wherever there is a door in the building (see Figure 3 (a)). A different icon is used for each type of room (office, stairway, passageway, and exit) and colors are used to display the occupancy level of each room and edge. The movement of the evacuees inside the building is represented by the changing colors of the different items (nodes/edges). Rooms getting filled tend to have a reddish color while rooms where evacuees are leaving get white. Grey color is used for empty items.

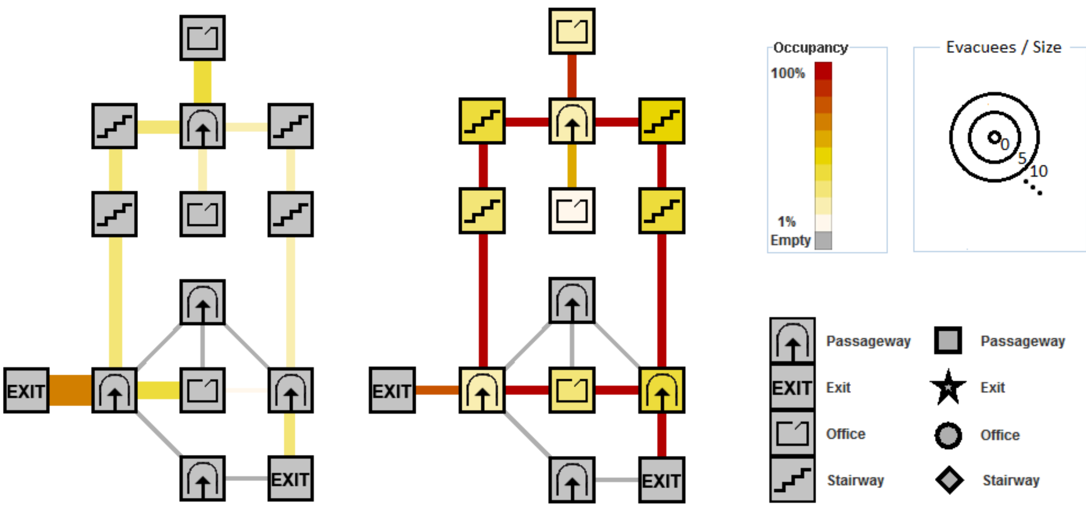
In the *Nodes* visualization, simple shapes such as circles or squares are used to represent the nodes (see Figure 3 (b)). In this case, the size of the nodes changes depending on the number of evacuees inside. This visualization provides an overview of the number of evacuees in each node whereas the node colors still represent the occupancy level of the items.

The *Statistics* visualization is based on the approach used in [RHDW12] (see Figure 3 (c)). Each node is represented by a graph that shows the number of evacuees that have passed through this node until the current time instant. Using this visualization, each node can be analyzed independently looking at each graph. The color coding used here depends on the maximal occupancy level of a node from the beginning of the evacuation until the current point in time. The exact value is also displayed above every graph.

The escape routes that were taken during the evacuation are displayed in the *Escape Routes* visualization. Here, the size and colors of the edges change both according to the number of evacuees that passed through them in relation to the total number of evacuees in the building at the starting point (see Figure 3 (d)). Hence, the more evacuees crossed an edge during the whole evacuation, the bigger its size and darker its color. Using this visualization the overall paths



(a) *Icons* visualization. (b) *Nodes* visualization. (c) *Statistics* visualization.



(d) *Escape Routes* visualization. (e) *Maximal Occupancies* visualization. (f) Legends.

Figure 3: Visualization types of the prototype for evacuation planning. The *Icons* visualization (a) includes figures representing the nodes that show the room type (office, passageway, stairway, or exit). The colors are linked to the occupancy level of each node/edge. The *Nodes* visualization (b) uses simple shapes, such as circles or squares, for the nodes. The size of the nodes indicates the number of evacuees. The larger the node, the more evacuees inside. In the *Statistics* visualization (c), each node is represented by a small graph that shows how many evacuees are inside from the starting point until the current time instant. The percentage as well as the background color of each node represents the maximal value reached inside a graph. In the *Escape Routes* visualization (d), information aggregated through time is represented. The size as well as the color of an edge show how many evacuees went through this path with respect to the total count of evacuees. The thicker an edge, the more evacuees crossed it during the whole evacuation. In the *Maximal Occupancies* visualization (e), the color of each item (node/edge) shows the maximal occupancy level of this item. The more a color tends to red, the more evacuees have been inside simultaneously in one time instant. Figure (f) shows the legends related to the colors, the sizes of the nodes in (b), and the icons used.

taken by the evacuees can be followed and analyzed with the purpose of optimizing the number of paths in a building and their capacities.

Finally, the *Maximal Occupancies* visualization shows the maximal occupancy level of each item inside the building throughout the whole evacuation (see Figure 3 (e)). This allows the users to see which nodes or edges reached their limit and detect bottlenecks inside the building swiftly. The time each node or edge reached its maximal occupancy level can also be reviewed in this visualization.

3.3. Interaction

It is important to enable the users to modify the parameters of the visualization dynamically for building planning as well as for live evacuations. Therefore, the tool includes several interaction possibilities to modify the simulations, which can be used to test different simulations to create safe escape routes in a building. Different evacuation scenarios have to be examined to rule out any problems that can emerge. In the following, the included interaction possibilities are explained.

First, users can obtain detailed information of items by clicking. The other options can be found in the user interface depicted in Figure 4: a timeline allows the users to move backward or forward in time showing the evacuation situation at each time step. The different evacuation routes of the evacuees can be highlighted to see which paths the people are currently following. Finally, users can modify different parameters of the simulation, such as the evacuee number, the capacity, and the travel times of items. Nodes and edges can also be added or deleted to create new evacuation routes for the evacuees. The tool visualizes the modified evacuation routes and new situations directly.

4. Expert Survey

The discussed prototype was developed to collect user feedback for improvements of the system in a formative process and to guide the design of future applications. Some examples demonstrating the performance of the tool in different situations were shown to experts (a psychologist, a consultant for building safety measures, and a building planner) to obtain their opinion about the tool and additional aspects that have to be considered further. Moreover, technical limitations that may cause problems during implementation of such tools in real evacuation scenarios were discussed. In the following, the conclusions of this surveys are presented. As every expert provided information related to different fields (psychological aspects, technical limitations, etc.) we decided to divide the areas in which the feedback was gathered into four main groups: conceptual issues, psychological aspects, important features, and technical limitations. Therefore, general ideas and concepts will be explained in the first

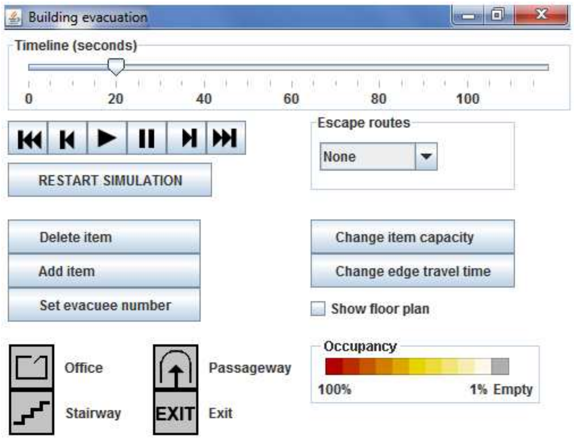


Figure 4: Dialog for user interaction. The timeline can be modified with the buttons below to show other time steps. The calculated escape routes can be highlighted using the *Escape routes* drop-down list. The buttons in the middle are used to change different parameters of the evacuation, such as deleting or adding an item, changing the number of evacuees in one node, changing the maximal capacity of an item, or changing the travel time of an edge. The building plan can be visualized by the checkbox on the lower right. The legends of the visual mappings for each visualization are shown on the lower part of the screen.

two groups, and then the more specific and technical problems discussed in the surveys will be outlined in the last two subsections.

4.1. Participants

The participants were chosen from different fields of research, related to building evacuation. The psychologist as well as the consultant for building safety measures work in an international company that is involved in different fields of research including building safety planning. The building planner works in his own company and has different projects regarding the planning and implementation of buildings.

The psychologist works in a group related to human-machine interaction. His task was to analyze the interface and the building representations of the tool to improve the overall visualization in further versions. The consultant for building safety measures was invited to analyze the feasibility of the features included in the tool, as well as the problems concerning the technology available to get data necessary for the building evacuation (evacuee count, position, etc.). The building planner's task was to analyze the features as a potential target user and give recommendations regarding the features of the tool.

4.2. Study Procedure

The prototype features were presented to the experts independently, simulating several evacuation scenarios including the different representations available. They did not interact with the tool themselves, but observed and stated their questions during the presentation. These questions led to several discussions related to the areas that will be presented in the next subsections. The length of each study sessions was about two hours inside private conference rooms. After the presentation, the experts gave their overall opinion about the tool. The results include the pending problems that will have to be solved in future versions.

4.3. Conceptual Issues

First, the purpose of visual analytics for evacuation planning was discussed with the experts. They insisted that the goals have to be clear to adapt the different visualizations and interactive options. In this case, two goals for an evacuation tool have to be distinguished: live evacuation, and building planning.

For live evacuation, users can intervene in evacuations when required. Blocked paths due to collapsed ceilings, fire, or smoke spreading can be dangerous when evacuating people; here the tool can help recalculate the shortest routes and lead the evacuees through safer paths. As important decisions need to be made in time critical situations, it is important to keep the visualizations as well as interaction as simple as possible. The experts also emphasized that users need to be able to recognize dangerous situations as well as bottlenecks swiftly to intervene in a fast and efficient way.

The objectives for building planners are different. They need a tool to plan buildings as safe as possible. Therefore, they need to do different simulations using several scenarios. Parameters, such as door widths, room properties, or travel times need to be changed to find optimal solutions, which requires a lot of simulations to compare different solutions.

Hence, according to the experts, the interaction possibilities should be adapted according to the purpose of the tool: live evacuation or building planning. The developed tool is a prototype including options suited for both scenarios. Consequently, the different visualizations and interactive options have to be planned thoroughly to concentrate only on one of these purposes. Ideally, two separate tools have to be developed to achieve both objectives.

4.4. Psychological Aspects

Psychological aspects have to be considered in an evacuation tool to understand the evacuees' behavior and predict their actions. The key issues that became apparent in the discussion are listed below:

- *Family members tend to stay together* instead of escaping the building as fast as possible, also see Kobes et al. [KHdVP10].
- *Evacuees cannot be stopped once the evacuation started*, even if bottlenecks were avoided this way. The only option is to start the alarm signal in each room at a different time according to the output of the developed evacuation tool.
- *Group building* is important in an evacuation. Evacuees can be grouped together, but they cannot be split afterwards. The splitting would take too much time and there would be nobody to decide on how to split the group.
- *Response time* after the alarm starts has to be considered. When an alarm sounds, the evacuees need a certain time to realize that the situation is real and that they have to leave the building. This response time has to be included in the calculation of the evacuation schedule. In [Hos09], the effects and reactions influencing the so-called premovement time are summarized. Mainly the time to perceive the alarm, the interpretation time of the perceived alarm, and the time used for actions that are not directly related to the evacuation itself have to be considered here.

4.5. Important Features

The features that emerged to be important during the survey are discussed as follows starting with the primary issues that have to be modified, followed by secondary problems related to more specific aspects of building evacuation:

- *Including priorities* in the calculation of the shortest paths. Applying different priorities on the evacuees depending on the degree of danger of their location can ensure the safety of all the evacuees. In [RHDW12], the priority-based distributed evacuation routing algorithm is developed to include such priorities in the calculations of the shortest paths. The evacuees with high priorities are evacuated to safe areas first, to ensure their safety. The other evacuees have to wait for the paths to be empty to start with their evacuation. Therefore, the alarms in the areas with high priority have to start earlier than the others to make sure the evacuation routes are still free.
- A *large number of simulations* is required with changing parameters automatically to identify worst case scenarios and difficulties that arise during an evacuation. Tools, such as PedGo[7], compare up to 500 different variants that are analyzed afterwards. The large number of variants enables one to achieve reliable results. Preferably, a tool communicates the results in predefined visualizations and alerts if critical locations in the building were found.
- The *travel times* estimated for the evacuees to move through the rooms in a building were researched: Predtetschenski and Milinski [PM71], for example, analyzed the traffic flow of people inside a building in normal as well as in panic situations. This data has to be used to

[7] http://www.traffgo-ht.com/de/pedestrians/products/pedgo/index.html

calculate the travel times in the evacuation tool to have a legal basis for future applications.

- *Waiting times* at bottlenecks have to fulfill certain requirements, too. Although the tool tries to prevent bottlenecks at all costs, it is sometimes impossible to cope with this condition. By reconstructing the calculations of [PM71] for the venue regulations, the maximal waiting time used for traffic jams was one minute. To reach this goal, the minimal stipulated door width has to be 1.2 meters. As there is also a prescribed width for a person crossing a door (60 cm), the minimal amount of people that can cross a door simultaneously is 2.
- A tool should also consider the guideline that stipulates that the *maximal evacuation time for a fire area* is around 10 minutes. For this purpose, the maximal length for an evacuation route must not be exceeded. The program should also be able to alert the users if any of the prescribed guidelines or rules are broken.
- *Include an alarm*, signaling the users of the tool that a dangerous situation emerged during evacuation. The alarm has to ensure that every critical situation is detected. For large buildings, this feature is mandatory, as it is impossible to have an overview of the whole building at once.
- To use a tool that supports evacuation in *buildings with large halls*, such as theatres, cinemas, etc., it is important to review the concept of a node. Therefore, a big hall should not be regarded as single node, but as separate graph including a set of nodes and edges.
- The *use of elevators* in evacuations. Nowadays, some elevators can be used during fire emergency situations. These elevators have to be considered when calculating the shortest escape paths. Nevertheless, these elevators should only be used for people with disabilities to avoid chaos due to capacity limitations.

4.6. Technical Limitations

Now, the technical limitations related to an evacuation tool are summarized. The more critical problems will be explained first:

- *Number and position of the evacuees inside a building*. It is difficult to assess these parameters for shortest path calculations in real evacuation scenarios. A possible solution is to use microchips inside badges in office buildings. The problem is that it cannot be assured that the workers always carry their ID cards. If the exact locations is unknown, another option is to count the number of people inside the building. Turnstiles are a possible solution for this. Another option is to use video surveillance. Various methods exist to count people in video. In [HBD05], for example, people are recognized using a skin color model and a probabilistic shape model of faces, while in [ZC07] a method is used to count the number of people in groups through the combination of human segmentation and group tracking. So-called intelligent buildings are able to incorporate these video surveillance systems to make an approximation of the evacuees inside the building and then calculate the escape routes with the evacuation supporting tool.
- The *guidance of the evacuees* through the building. Nowadays, the only suitable option is to use LEDs on the floor to guide the people dynamically through buildings. This method is used in air planes and is applicable even with smoke. Right now, this method seems to be the easiest and safest one to use in large buildings. In [Pet04], an example of remotely controlled signaling can be found. There, the signs are used to prevent traffic jams by signaling the drivers that there is a traffic jam ahead and lead them through alternative routes. These signs are remote controlled and the information displayed can be modified at any time. This technology can be used to control the signs or LEDs inside buildings, too.
- *Visualization of large buildings* suffers from their complexity. Only small parts of the building can be displayed simultaneously to keep track of the evacuation. A solution would be to display only one floor at once. Therefore, the software has to be able to switch between floors easily so that the visualization is kept simple. Another interesting feature would be a 3D view of the building to gain insight of the construction.
- *Visualization of the evacuees' movement*. The prototype shows that nodes and edges that change their colors and sizes abruptly are difficult to understand. A smooth transition between the different states of the items is important and ease to understanding of what is happening during the evacuation. Another option would be to represent groups of evacuees by small symbols that move through the building to show the positions of the evacuees clearly.

5. Conclusion

We developed a prototype to receive expert feedback. The result of the conducted expert survey can be used to develop efficient tools to support building evacuations. Beside legal aspects that have to be taken into account, the evacuees behavior and several technical limitations have to be considered. The survey also showed that some issues cannot be solved easily with the technology available nowadays. Knowing the exact number of people and their positions inside a building and guiding them to the nearest exit are problems that could be solved using different sensors that will be available in future. The survey shows useful insights to improve the tool and add features that will be essential in live evacuations or for building planning.

Acknowledgments

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