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A dynamic approach for evacuees' distribution and optimal routing in hazardous environments

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ABSTRACT

In a complex built environment, the situation changes rapidly during an emergency event. Typically, available systems rely heavily on a static scenario in the calculation of safest routes for evacuation. In addition, egress route calculation and evacuation simulations are performed separately from path-finding for rescue teams. In this paper, we propose a state-of-the-art dynamic approach, which deals not only with a 3D environment, shape of spaces and hazard locations, but also with the dynamic distribution of occupants during evacuation. A database of densities and information about hazard influence are generated and used to calculate optimal paths for rescue teams. Three simulation scenarios were rigorously compared in this study, namely static with constant density values determined for subsequent stages of evacuation, semi-dynamic with densities representing an actual people distribution in a building during evacuation simulation, and dynamic with temporal distribution of evacuees stored in a database, and dynamically used in optimal path calculations. The findings revealed that static simulation is significantly different from semi-dynamic and dynamic simulations, and each type of simulation is better suited for the decision task at hand. These results have significant implications on achieving a rapid and safe evacuation of people during an emergency event.

1. Introduction

In rapidly growing and complex urban environments, both natural and human induced disasters are inevitable. When an emergency situation happens in such populated areas, a reliable hazard mitigation plan and rapid response should be in place in order to avoid a large number of casualties, injuries and economic loss. Major disaster events may result in fast environmental modifications, such as changes to the layout of a building, where plans prepared in advance are no longer applicable in a current situation. Consequently, rapid situation analysis should be performed and a new response plan swiftly developed.

Hazard analysis and routing for evacuees and first responders are essential elements of emergency support systems [12]. The main issue is to minimise time necessary to get people from a dangerous area to a safe zone [4, 5]. Different areas affected by disaster are taken into consideration, for example regions, urban areas, transportation networks and buildings [5], or combination of them [9]. Evacuation planning in complex buildings, investigated in this paper, is influenced by several factors, including elements such as building layout, location and propagation of hazard, location of occupants and emergency personnel, location of safe places, exits, and human behaviour [5]. These factors are critical for calculating the shortest or the quickest routes, while information about hazard is used to permanently or temporally exclude some areas strongly affected by the propagation of hazard (e.g. fire or smoke) from areas available for navigation. Necessary parameters about hazard propagation and its influence on evacuation areas are calculated and then used to identify routes, which scale from the areas of a higher hazard value to areas with a lower hazard value – opposite direction is avoided. Although this is deemed to be a reasonable approach, it may be justified to move to a more dangerous area for a short period of time, instead of remaining longer in an area with a moderate hazard level [17].

Within evacuation modelling, two major approaches may be distinguished: micro- and macroscopic [5]. In the first approach, objects such as people, vehicles or interaction between them are introduced and their behaviour is modelled, while the latter is focused on optimisation models and no individual objects are included. A microscopic simulation is performed using agents representing individual objects. It helps to determine densities of objects in certain areas and, thus, it can be used to detect congestions and bottlenecks [4]. In order to perform

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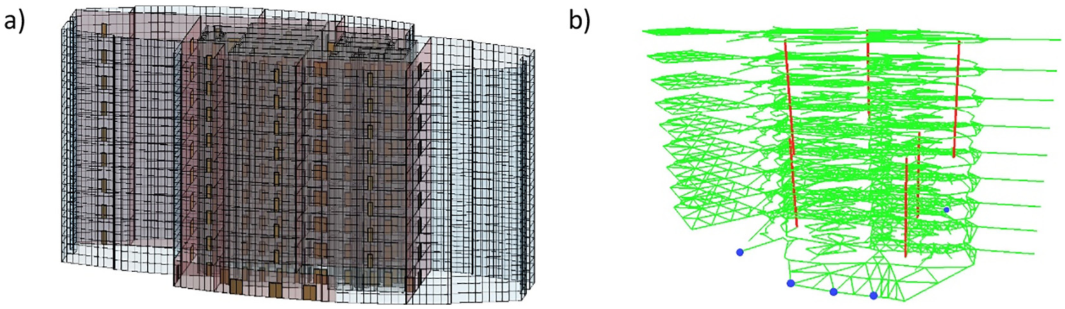

Fig. 1. Generation of a navigable network from a BIM model: a) initial BIM model; b) navigable network. Red vertical lines represent staircase links, while blue nodes represent exit doors. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

such analysis, it is necessary to generate a navigable network and apply a path-finding algorithm [2, 6, 11, 13, 15, 16].

In this paper, the proposed innovative and rigorously tested methods are scalable to various areas (e.g. outdoors) because strong mathematical foundations for network representation, hazard analysis and path-finding algorithms were applied [2, 17]. A microscopic evacuation planning is used for evacuation simulation, however, in people's movement simulation, some aspects typical for macroscopic planning are adapted, such as taking into consideration maximum flow and density of evacuees. The proposed step change innovation could have a significant impact on swift evacuation of trapped people in a complex built facility.

1.1. Problem statement

Egress routes from buildings are commonly calculated taking into consideration only a limited number of factors that influence the shape and characteristics of resulting routes. Very often, the shortest or the quickest paths are calculated. Areas affected by hazards (e.g. fire or smoke) are included in calculation, but they are often excluded from navigation. In the case of evacuation simulations, where the aim is to estimate time necessary to empty a building, various aspects are taken into consideration, such as speed of evacuees' movement depending on their age, health conditions and human/crowd behaviour.

The evacuation process affects the speed of emergency response. Congestions may be formed at bottlenecks, where too many people seek to use the same exit point, with a maximum flow capacity much lower than the actual demand. Typical values of occupancy density at different stages of evacuation may be obtained from simulations or from observations during fire drills. When access routes for search and rescue teams are calculated, densities are included in the estimation of the best possible – reasonably safe and quick – egress route. However, typical values may not reflect the real situation in various scenarios. In office buildings, various occupancy profiles may be expected during working hours, large events with many visitors and evenings and weekends. Therefore, the initial location of people in a building has an effect on densities during evacuation and thus, on the optimal routes for rescue teams.

In this research, agent-based evacuation simulation is performed in order to estimate occupancy density at each node of a navigable network reconstructed from a 3D building model. The capacity of nodes and the maximum flow capacity of links are calculated and used in path-finding calculations. During simulation, transient densities are determined and stored in the network. The network with the density values is called the database of densities. The 'database' term used in this paper is understood as a method of data storage in a topologically connected structure with no formal query language, such as SQL. It is employed together with information about hazard locations and their influence on a building to dynamically calculate optimal paths that are safe and fast for search and rescue teams. The aim is to develop an effective and novel approach, where only a small set of input parameters is considered in order to achieve results comparable with other, more complex solutions that are computationally more expensive. This makes real-time analysis and rapid decision making possible. Additionally, the proposed method can be used for building safety evaluation, where detection of bottlenecks in pathways may be identified in the early design stages.

2. Methodology

The initial stage in this research is the generation of a navigable network from a BIM model (see Fig. 1). The method proposed by Boguslawski, et al. [2] is adopted for irregular tessellation of space and the variable density network generation. Each network node is associated with a cell of a specific area calculated in the tessellation process. A logical structure of the building, including non-navigable connections among adjacent spaces, used for hazard propagation, is also available in the spatial model (for more details, see [1]). The nine-floor mock model was created based on a typical floor plan of the Doha WTC building in Qatar. Layout of indoor spaces is the same on all floors with the following exceptions: there are exit doors on floor 1 and location of staircases on top floors is different than on lower floors. More precisely, there are three staircases between floors 1 and 4, and three staircases placed on different locations between floors 6 and 9, which meet on floor 5. The rationale for the selection of this specific staircase distribution is to introduce more options (i.e. possible exit pathways) for the path-finding algorithm, thus allowing better illustration of the method. There are five exit doors from the building on floor 1: three main doors in the main lobby and two side doors.

The navigable network is a core structure for path finding. Any graph-based algorithm may be applied to such a network. In this research, Dijkstra's algorithm is used for determining routes for evacuees. Temporal information about evacuees' density is included in calculations of optimal routes for rescue teams in hazardous indoor environments.

2.1. Agent-based evacuation simulation

In order to estimate the density of people in the navigable network during building evacuation, an agent-based evacuation simulation is performed. An initial set of agents is generated, involving the location of agents in all indoor spaces, except for main communication passageways, for example corridors, lobbies and staircases. A specific network node representing a cell is attached to each agent that defines its location – no precise location of an agent is calculated. In addition, no agent's size is considered in this research. The number of agents at a single node is then taken into consideration for calculation of the node occupancy and, consequently, agent's speed. The speed depends on local agent's density calculated for nodes.