Simulation Modelling Practice and Theory 24 (2012) 71–83

Contents lists available at SciVerse ScienceDirect

Simulation Modelling Practice and Theory

journal homepage: www.elsevier.com/locate/simpat

Estimating the impact of residents with disabilities on the evacuation in a high-rise building: A simulation study

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ARTICLE INFO

Article history:
Received 15 June 2011
Received in revised form 3 December 2011
Accepted 10 February 2012
Available online 9 March 2012

Keywords:
High-rise building evacuation
Agent-based simulation
Capacity drop
Controlled evacuation
Emergency evacuation DSS

ABSTRACT

In this paper, we study how seriously residents with disabilities affect the evacuation of other residents in a 24-story high-rise building environment through an agent-based simulation model. In particular, we analyze the trends of the evacuation times in two population scenarios, homogeneous (i.e., only residents without disabilities) and heterogeneous residents (i.e., residents with and without disabilities), while we vary the size of populations and the compositions of disability types of residents. According to our experimental results, residents with disabilities significantly delay the evacuation process by causing congestion and blocking phenomenon. Our experimental results also indicate that the differences in the evacuation time of the homogenous and the heterogeneous population scenarios become more significant as the population size increases because of serious congestion from the increased population size and blocking from the increased proportion of the handicapped. Finally, we present regression models and controlled evacuation strategies that help evacuation administrators ensure the safe evacuation of all the residents by controlling the number of residents and evacuate residents with disabilities efficiently.

1. Introduction

Efficient evacuation plans are strongly required in large and complex structures such as high-rise buildings, airports, schools, stadiums, and large vehicles including airplanes and ships to minimize the casualty of people during catastrophic events. In particular, there are strong needs of developing evacuation plans that consider residents with disabilities as well as residents without disabilities due to the significant proportion of residents with disabilities in our community. For example, about 12.1% of population in the United States has been known to suffer from physical, mental, or emotional disability [12] while between 14% and 17% of the UK population can be classified as the disabled [3]. While these residents with disabilities are more likely to suffer from natural and human caused disasters and slow down the evacuation of other residents due to their larger space requirements and slower evacuation speeds, only very few studies consider them explicitly. In addition, there is a significant lack of studies on the relationship between the structural characteristics of the building and the evacuation of residents with disabilities even if Sagun et al. [29] mentioned that one of the most important contributions of evacuation simulation is improving the design of the built environment. While several studies [1,7,23,24,32,36] considered heterogeneous population including residents with disabilities, their heterogeneity designs only consider the very limited characteristics of residents without disabilities such as age, gender, movement speed, and physical size based on the

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doi:10.1016/j.simpat.2012.02.003

characteristics of residents without disabilities. Christensen et al. [10] also indicated that many evacuation models do not address residents with disabilities appropriately.

We conjecture that the evacuation time of heterogeneous residents with and without disabilities in a building or a large vehicle can be significantly different from that of only residents without disabilities in the same building. Therefore, evacuation administrators need to develop a comprehensive evacuation plan that explicitly considers residents with disabilities because of their unique physical and mental needs under emergency situations. For example, most residents with disabilities such as wheelchair users cannot evacuate using stairs easily. They are also typically slower than the non-disabled and hence may delay the evacuation of other residents by blocking others in narrow paths such as stairs. However, most of evacuation planners and administrators do not know how far residents with disabilities delay the evacuation of other residents and hence cannot revise evacuation plans accordingly. Therefore, in this paper, we intend to estimate the impact of residents with disabilities on the evacuation time of other residents in a 24-story high-rise building environment through an agent-based simulation model. For this purpose, we simulate and analyze the trends of the evacuation times of two population scenarios, homogeneous (i.e., only residents without disabilities) and heterogeneous residents scenario (i.e., residents with and without disabilities), while we vary the size of resident populations and the resident compositions of various disability types in the population.

Another research question we like to explore in this paper is to identify several places in the building that are most likely to cause congestion and reduce the number of evacuees who can exit through the bottlenecked place simultaneously, resulting in so called "capacity drop" [8]. Once several such places are identified, evacuation administrators pay special attention to improve the structural design or clear out any obstacles around such places. Finally, we like to develop regression models based on simulated data sets to help evacuation administrators determine the maximum size of resident population whom can be evacuated within a desired evacuation time or help them estimate the time needed to evacuate all the residents with and without disabilities. This information from regression models then can be used to ensure the safe evacuation of all the residents by regulating the number of residents and visitors in the building. In addition, we also like to develop new evacuation strategies that control the evacuation process of residents by either evacuating residents at lower levels first or evacuating residents at higher levels first to minimize the possibility of congestions and capacity drop phenomenon. Practically, we implement these strategies by controlling the propagation of emergency alarm so that residents only on the intended floors can hear it and start to evacuate.

Note that residents with disabilities have different physical and mental characteristics and needs. Therefore, three different evacuation strategies for residents with disabilities have been studied [27]. The first strategy is to use the designated refuge areas in a building. This strategy is based on the observation that wheelchair users cannot evacuate by themselves via steep stairs during an emergency, and hence it is better for them to move to the designated refuge area where they can wait for rescuers. The second strategy being considered is to provide safe elevators that can be used for emergency evacuation by residents with disabilities in some special buildings. The last strategy is to develop specific evacuation procedures for residents with disabilities with the help of healthy residents. The "buddy" system, for example, identifies one or a few persons who have the responsibility of looking after individuals with disabilities in case of an emergency. In the buddy system, the residents with disabilities will be carried out by buddies with or without using special devices. In this study, we take a buddy system approach to evacuate residents with disabilities.

This paper is organized as follows. We first briefly review the related literature in Section 2. Section 3 presents the agent-based simulation model, the simulated building, and the resident configurations for this study. In Section 4, we present our findings with regard to the effects of resident compositions and sizes, and structural characteristics of the building that are most likely to create congestions on the evacuation times. In Section 5, we develop and compare two controlled evacuation strategies that evacuation administrators can use to efficiently evacuate all the residents while minimizing the evacuation times. Finally, Section 6 provides the conclusion of the paper and suggests several directions of further research.

2. Literature review

Building evacuation planning has started since early 20th century in many countries and has become an important issue after 9/11 terrorists attack in the United States [15]. Researchers have used various models to study evacuation dynamics and these models can be categorized into several sub-categories. For example, Kuligowski and Peacock [17] reviewed 25 evacuation simulation models and categorized them based on availability, purpose, perspective of the residents and the building, algorithms for simulating resident behavior and movement, the incorporation of fire effects, visualization methods, validation techniques, and others. Zheng et al. [37] also categorized previous studies into seven simulation models such as cellular automata models, lattice gas models, social force models, fluid-dynamic models, agent-based models, and two other models, and highlight their characteristics. Pelechano and Malkawi [25] classified the evacuation models into macroscopic (e.g., regression model, route choice model, queuing model, and gas-kinetics model) and microscopic models (e.g., social force model, rule based model, and cellular automata model). According to them, macroscopic models focus on the systems as a whole while microscopic models study the behavior and decisions of individual pedestrians and their interaction with other pedestrians in the crowds.

Agent-based modeling (ABM) has been one of the popular microscopic simulation techniques because of its capability of incorporating multiple perspectives, simplicity, and flexibility [2,14]. For example, various ABM models have been proposed