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An efficient partially dedicated strategy for evacuation of a heterogeneous population

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ABSTRACT

When a heterogeneous population evacuates from a high-rise building, residents who occupy a large area and move at a slow pace, such as people in wheelchairs, tend to block pathways and significantly affect the evacuation of other occupants. In this study, we propose a partially dedicated evacuation strategy, in which an evacuation path is dedicated to a high-speed subpopulation of people without disabilities while another route is dedicated to the remaining heterogeneous population to minimize the blocking effect. The key factor in this strategy is determining the exact proportion of people without disabilities at each floor to each route. We use a time-expanded network flow model and a simulation-based optimization approach to solve the problem systematically. Simulation experiments show that the proposed evacuation strategy can reduce the average evacuation time of the entire population by 10%. The proposed partially dedicated evacuation strategy can be applied to other problems.

1. Introduction

Evacuation plans have become increasingly important in recent years and have thus attracted the attention of both building construction managers and researchers in the field of operations management [17]. Effective evacuation strategies, rapid initial response, regular fire drills, and disaster countermeasures are necessary to minimize the number of victims and the extent of property damage caused by disasters. In this study, we focus on the development of an effective evacuation strategy.

One of the important points to consider in the development of effective evacuation strategies for a building is the population of people with disabilities. Approximately 12% of the population in the US can be categorized as having physical, mental, or emotional disabilities [[7]]. As regards the population in Europe, 10–20% has various types of disabilities [11]. People with disabilities who use wheelchairs occupy a relatively large area because of the wheelchair space, and people with low stamina tend to move at a slow pace. These characteristics may cause them to block narrow exit passages and significantly affect the evacuation of the entire population of a building. A building manager who wants to set up an effective evacuation plan should consider the situation of the tenants with disabilities. Otherwise, the evacuation process could result in congestion and delays.

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In the present study, we propose an efficient evacuation strategy for a heterogeneous population in a 24-story building environment. We propose a partially dedicated evacuation strategy, in which an evacuation path is dedicated to a high-speed subpopulation of people without disabilities while another route is dedicated to the remaining heterogeneous population to minimize the blocking effect caused by people with disabilities. The key factor in this strategy is determining the exact proportion of people without disabilities at each floor to the first dedicated route. We propose a hybrid approach that combines the network flow model and the simulation-based optimization approach to minimize the average evacuation time effectively and to solve the problem systematically. The effectiveness of the proposed approach is evaluated by using a simulation model. The proposed partially dedicated evacuation strategy can reduce the average evacuation time of the entire population of the simulated building by 10%.

2. Literature review

Researchers have studied evacuation strategies for high-rise buildings. One of the most popular strategies for high-rise buildings is phased evacuation, in which different parts of an area evacuate sequentially with different time delays. Cepolina [1] implemented a phased evacuation by controlling the alarm times and the egress routes of a building to minimize the building evacuation time. Cepolina concluded that a well-designed phased evacuation could reduce the building evacuation time. Proulx [20] mentioned that phased approaches are well accepted by stakeholders such as occupants and fire safety officials. Luo and Wong [16] discussed three evacuation strategies for super high-rise buildings, namely, total evacuation, phased evacuation, and stay-in-place approach, and evaluated the effectiveness of using a lift in evacuation. They claimed that most high-rise buildings guide people to follow a phased evacuation procedure because a single-stage total evacuation strategy is not practical when the building has a large number of people in it.

However, phased evacuation is not a panacea for all situations. Using the same simulated building of this paper, Koo et al. [10] tested three evacuation strategies, namely, a vertically phased evacuation strategy that varies delay times by floors, a horizontally phased evacuation strategy that applies a fixed evacuation delay to occupants with wheelchairs, and a strategy that enables occupants with wheelchairs to use elevators. Extensive simulation experiments showed that the vertically phased evacuation strategy that varies delay times by floor is ineffective for the building considered. The horizontally phased evacuation strategy that applies a fixed evacuation delay to occupants with wheelchairs is effective in terms of the average evacuation time. However, it is not an implementable strategy because delaying the evacuation of a specific group of individuals may not be ethical. The strategy that enables occupants with wheelchairs to use elevators is also not a practical option because using elevators during an emergency is difficult.

In the field of emergency evacuation, which is not limited to high-rise building evacuation, some studies including Chalmet et al. [2], Lim et al. [13], Lin et al. [14], and Luh et al. [15] have attempted to use mathematical models (mainly network flow models) to find efficient evacuation strategies. Lin et al. [14] proposed a multi-stage, time-varying quickest flow model to obtain the minimum time for evacuating occupants. In this study, we adopt their model to find an initial solution for our strategy.

Heterogeneous population is another important issue in the building evacuation research. Oven and Cakici [18] differentiated agents with different behavioral patterns and physiological characteristics, such as gender, age, height, and patience value. They used buildingEXODUS to simulate evacuation scenarios from a 34-story building in Istanbul and found that exit knowledge and the preferences of agents are important factors in the evacuation process. Pelechano and Badler [19] assumed that agents might not know the structure of a building and classified the roles of agents such as leaders, trained personnel, and followers. They observed that the grouping behavior occurs when there are many dependent agents and that inter-agent communication improves evacuation efficiency. Sagun et al. [22] discussed how a crowd simulation improves the design of the guidelines and built environment. They showed that different exit preferences affect the evacuation time in high-rise buildings.

Although the abovementioned studies have implemented the heterogeneity of populations, they have not considered people with disabilities explicitly. Christensen and Sasaki [4] first applied the heterogeneity of people with disabilities to an evacuation simulation. They developed an agent-based simulation model called Bottom-up Modeling of Mass Pedestrian flows—implications for the Effective Egress of individuals with disabilities (BUMMPEE). They used BUMMPEE for a four-story office building evacuation analysis and showed that the model is appropriate for representing the diversity and prevalence of disabilities. Koo et al. [9] discussed the effect of people with disabilities on an evacuation in a high-rise building using a modified BUMMPEE model. They showed that residents with disabilities considerably delay the evacuation time of the entire population.

To our knowledge, researchers have not yet found efficient evacuation strategies for high-rise building evacuation with consideration of a heterogeneous population. In this study, we propose a partially dedicated evacuation strategy and a systematic hybrid approach to find good parameter values for the strategy.

3. Evacuation situation and simulation model

In this study, we use a 24-story office building located in the US. The length of the building is estimated to be approximately 102 m, and the width is approximately 46 m. Fig. 1 shows a typical floor layout of the building. The white area is the space where occupants can freely move. The gray polygons indicate stairs and the small polygons next to the stairs are