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Variable guidance for pedestrian evacuation considering congestion, hazard, and compliance behavior

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ABSTRACT

A methodology for optimizing variable pedestrian evacuation guidance in buildings with convex polygonal interior spaces is proposed. The optimization of variable guidance is a bi-level problem. The calculation of variable guidance based on the prediction of congestion and hazards is the upper-level problem. The prediction of congestion provided the variable guidance is the lower-level problem. A local search procedure is developed to solve the problem. The proposed methodology has three major contributions. First, a logistic regression model for guidance compliance behavior is calibrated using a virtual reality experiment and the critical factors for the behavior are identified. Second, the guidance compliance and following behaviors are considered in the lower-level problem. Third, benchmarks are calculated to evaluate the performance of optimized variable guidance, including the lower bound of the maximum evacuation time and the maximum evacuation time under a fixed guidance. Finally, the proposed methodology is validated with numerical examples. Results show that the method has the potential to reduce evacuation time in emergencies.

1. Introduction

The evacuation guidance in buildings, such as evacuation directions and exit signs, facilitates way-finding to safe locations, and thus reduces evacuation time during emergencies (Tang et al., 2009). Therefore, the planning for evacuation guidance in buildings is critical for the safety of a building. The past studies on evacuation guidance focused on the design of evacuation signs, including shape, instructions, pattern, illumination, and position (Johnson and Feinberg, 1997; O'Neill, 1991; Kobes et al., 2010; Chow and Lui, 2002; Wong and Lo, 2007; Jin, 2002). Very few studies discussed the design of evacuation guidance at the system level. Chen et al. (2009) adopted the maximum coverage model to calculate the optimal locations of exit signs. The quality of the sign locations was evaluated with a cellular automata (CA) pedestrian simulation model. The proposed maximum coverage model is unrealistic because only sign locations and visibility are considered while the evacuation routes are ignored. Chu and Yeh (2012) proposed a method to design evacuation guidance in complex geometry. Visibility graph is used to calculate the shortest paths between locations considering the building geometry. A maximum coverage problem with side constraints is then used to find the locations of signs that maximize coverage and constitute connected paths. The performance of the guidance design was evaluated with virtual reality experiments (Yeh, 2011).

The majority of existing methodologies for evacuation guidance considered fixed guidance. That is, guidance is predetermined and does not respond to contemporary evacuation situations. The distributions of hazards and congestion are expected to change over time. Instead of reducing evacuation time, fixed guidance could cause congestion and long delay when too many pedestrians attempt

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to leave an area through the same exit. Moreover, fixed guidance could lead pedestrians toward dangerous areas when hazards are on the evacuation routes. To address these issues, variable evacuation guidance has been studied. Wang et al. (2008, 2009), and Luh et al. (2012) conducted a series of studies where guidance changes according to hazard status and pedestrian flow to optimize evacuation guidance. These studies adopted a macroscopic network-flow pedestrian model, which was developed based on the behaviors observed in other microscopic pedestrian models, to reduce the problem complexity. To incorporate randomness in the evaluation, the guidance optimization problem was formulated as a Markov decision problem and a solution method of stochastic dynamic programming was proposed. The effectiveness of the methodology was evaluated with a separate microscopic simulation model.

The above literature review shows that related studies on indoor evacuation guidance has been limited. Meanwhile, numerous studies regarding route guidance for highway traffic can be found. For example, Hamad et al. (2003) conducted questionnaire surveys to understand the user behaviors in response to route guidance systems. Based on the questionnaire, the study estimated a neural network-based behavioral model to predict the route guidance acceptance behavior. The variables used to predict the acceptance of route guidance include individual characteristics (e.g., gender, education level), route-specific attributes (e.g., length, capacity, free-flow travel time), origin-destination specific attributes (e.g., demand, number or routes), information (e.g., travel time on all alternative routes, incident information), expectations (e.g., expected travel time), and habit (e.g., habit persistence of the individual driver). Rothkrantz (2009) developed a dynamic routing algorithm called ant-based control. The algorithm calculates the shortest travel time over time based on real-time information. In the simulated experiment, the dynamic routing was continuously updated and provided to the drivers. The results showed that dynamic routing information can reduce traffic time and the improvement was the highest when 40% of the drivers followed the dynamic routing. These studies indicated that road users do not always comply with the guidance and that more users following the guidance does not imply better outcomes. Although these findings are from the highway studies, similar behaviors can be expected in the response of pedestrians to evacuation guidance. Ignoring the guidance compliance behavior could lead to serious bias in the optimization of evacuation guidance.

In this study, the optimization of variable guidance in buildings with convex polygonal interior spaces is modeled as a bi-level problem. The calculation of variable guidance using a dynamic network and a dynamic shortest path algorithm given the prediction of hazard and congestion is the upper-level problem. The prediction of congestion using a pedestrian simulation model under the variable guidance is the lower-level problem. A local search approach is developed to solve the bi-level problem. Three major contributions are identified in the proposed methodology, all of which are firsts in the literature of pedestrian evacuation. First, a logistic regression model for guidance compliance behavior is calibrated using a virtual reality experiment. The critical factors for the behavior are identified in the estimated model. Second, the guidance compliance and following behaviors are considered in a microscopic pedestrian simulation model that responds to congestion and hazard. It is then incorporated in the optimization for realistically predicting congestion and estimating evacuation time. Such a microscopic model is expected to be more accurate than the macroscopic models adopted in the past studies. Third, a local search solution approach is adopted due to the high complexity of solving a bi-level optimization problem involving a simulation model. Benchmarks are calculated to evaluate the quality of the heuristic solution. One is the lower bound (LB) of the maximum evacuation time obtained by a mixed-integer programming (MIP) model. Another is the base line performance given by the maximum evacuation time under fixed guidance.

The remainder of the paper is organized as follows. Section 2 describes the methodology for optimizing variable evacuation guidance. Section 3 validates the methodology with numerical examples. Section 4 provides the conclusions and the future research directions for this study.

2. Methodology for optimizing variable guidance

2.1. Problem description and assumptions

First, we define the variable evacuation guidance considered in this study. The evacuation guidance is conveyed to pedestrians visually through the evacuation signs installed on doors. Two direction signs are installed on the opposite sides of each door. The design of the guidance is simple because pedestrians are distracted by many things during evacuation. Only three indications are available for each sign: (1) an arrow pointing toward the door, (2) an arrow pointing away from the door, and (3) a blank. Three types of instructions are provided for each door, as shown in Fig. 1. The signs in Fig. 1(a) guide pedestrians to pass through the door. In this example, pedestrians are instructed to move from the room on the right side of the door to the one on the left. The signs in Fig. 1(b) advise pedestrians not to pass the door. The signs in Fig. 1(c) do not provide guidance to pedestrians. Signs are also installed at exits because they are also doors. However, their sign indications are fixed, that is, always guiding pedestrians to move toward them. The major assumptions of the proposed variable evacuation guidance are as follows:

1. The building is comprised of convex polygonal rooms. Therefore, all the signs are visible from any point in the room.
2. The initial positions of pedestrians and the progression of hazards are known.
3. All pedestrians recognize and move away from hazards. No specific type of hazard is assumed, except that the hazard is non-fatal. Thus, no fatality would occur in the evacuation. This assumption simplifies the pedestrian simulation model and does not impose restriction on the proposed methodology.
4. The design of the evacuation signs, including the text, pattern, shape, and illumination, is clear, such that pedestrians comprehend the instructions through guidance without any confusion.
5. The evacuation guidance functions normally in emergencies.