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Design of Variable Guidance for Pedestrian Evacuation

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Abstract

A methodology for optimizing variable pedestrian evacuation guidance in buildings with convex polygonal interior spaces is proposed in this paper. 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 while the prediction of congestion provided the variable guidance is the lower-level problem. The problems were solved using a local search. Our proposed methodology has three major contributions. First, a logistic regression model for guidance compliance behaviour is calibrated using a virtual reality experiment and the critical factors for the behaviour are identified. Second, a microscopic pedestrian simulation model that incorporates the guidance compliance and following behaviours is developed for the lower-level problem. Finally, benchmarks are calculated to evaluate the performance of optimized variable guidance.

Keywords: Variable evacuation guidance, Pedestrian simulation, Congestion, Guidance compliance, Dynamic network, Mixed-integer programming

1. Introduction

The planning for evacuation guidance in buildings is critical for the building safety. The evacuation guidance in buildings facilitates way-finding to safe locations, and thus reduces evacuation time during emergencies (Tang et al., 2009). The past studies on evacuation guidance focused on the design of evacuation signs (Johnson and Feinberg, 1997; Kobes et al., 2010; Chow and Liu, 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. Chu and Yeh (2012) proposed a method to design evacuation guidance in complex geometry. The majority of existing methodologies for evacuation guidance considered fixed guidance. However, the distribution of hazards and

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congestion are expected to change over time. To address these issues, variable evacuation guidance has been studied (Wang et al., 2009; Luh et al., 2012).

Meanwhile, numerous studies regarding route guidance for highway traffic can be found (Hamad et al., 2003; Rothkrantz, 2009). 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.

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. Three indications are available for each sign: (1) an arrow pointing toward the door, which guide pedestrians to pass through the door, (2) an arrow pointing away from the door, which advice pedestrians not to pass the door, and (3) a blank, which means do not provide guidance to pedestrians. Signs are also installed at exits because they are also doors.

The major assumptions of the proposed variable evacuation guidance are as follows:

1. The building is comprised of convex polygonal rooms.
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.
4. The design of the evacuation signs is clear, such that pedestrians comprehend the instructions through guidance without any confusion.
5. The evacuation guidance functions normally in emergencies.

The optimization of variable evacuation guidance is considered as a bi-level problem. The upper level problem is considered from the perspective of the planner of the variable guidance. In this problem, the planner instructs the pedestrians to evacuate to the exits via the variable guidance based on the prediction of congestion and hazards, which is the outcome of the lower level decisions. The lower level problem is considered from the perspective of pedestrians. In this problem, pedestrians are moving toward the exits under the instruction of variable guidance, which is the decision of the upper level problem. A procedure similar to the local search approach for optimizing bi-level mathematical programming models is developed to solve the problem (Migdalas, 1995). To start the optimization procedure, we generate the initial guidance, ignoring the congestion and hazards in the upper level problem. This initial guidance is also called the “fixed guidance” because it indicates the shortest (distance) paths to the exits that do not change over time. The initial guidance is then passed to the lower level to predict the congestion, and the newly predicted congestion is passed to the upper level problem. The procedure is repeated until the required number of iterations is achieved. The best solution among all the iterations is selected as the final solution. The objective of the optimization is to minimize the “maximum evacuation time” for pedestrians, which is adopted in most of the related studies.

2.2 Calculating variable guidance considering congestion and hazard

The variable evacuation guidance considering hazards and congestion is calculated in two steps. First, the dynamic shortest paths, considering hazards and congestion, are calculated. Second, the dynamic shortest paths are converted to sign indications to generate variable evacuation guidance.

2.3 Cellular automata pedestrian simulation with guidance compliance and following behavior

FFCA models are widely used in simulating pedestrian movement behaviors (Burstedde et al., 2001; Duives et al. 2013; Bandini et al., 2014; Hsu and Chu, 2014). In this study, a FFCA that incorporates guidance compliance and following behaviors is developed for predicting congestions.

Compared with standard FFCA, two simplifications are adopted to reduce the simulation complexity. First, the pedestrians select the cell with the highest static field without randomness. Second, the dynamic field is ignored and the herding behavior is not considered.

A logistic regression model is proposed to capture the compliance behavior for guidance of pedestrians. The dependent variable of the model (Y) is the compliance decision with the guidance—1 being compliant and 0 being non-compliant. The independent variables of the model are as follows:

1. Consistency of guidance (C): The binary variable indicates whether the signs in the room are consistent.
2. Density (D): The normalized density level is defined as the ratio of the occupied cells to the total number of cells in the room. Thus, it is a real-valued variable between 0 and 1.
3. Familiarity with space (F): The binary variable indicates the pedestrian's familiarity with the building.

The calibrated model is embedded in the FFCA model. For each pedestrian, the probability of compliance is calculated based on the current conditions for each pedestrian at a fixed interval.

The behavior of following guidance in FFCA are discussed as follow. In FFCA, the path finding behavior is represented by static fields. Each cell has a value of static field. A cell with a high static field value is attractive and thus likely to be selected. π value is the travel cost from a sign departing at a time step to the closest exit. Thus, for a specific time step, the cost from a cell to the closest exit is the minimum of "the cost from the cell to the sign" plus "the π value of the sign" for all signs in the room. If the pedestrian decides to ignore the variable guidance, the pedestrian is assumed to take the shortest (distance) path to the closest exit. The π value of the fixed guidance that ignores congestion and hazards should be adopted. If the pedestrian decides to follow the variable guidance, the π value from the variable guidance that considers congestion and hazards should be adopted.

2.4 Lower bound for maximum evacuation time

To evaluate the performance of the proposed methodology for variable guidance, a MIP model is proposed to find an LB of the maximum evacuation time in FFCA. First, the building is discretized into 40 cm × 40 cm cells and expanded in the temporal dimension to construct a solution space compatible with the possible pedestrian movements of FFCA. Next, the constraints that reproduce as many FFCA rules as possible are developed. Finally, a network flow model with side constraints of a majority of FFCA rules is formulated and is solved to find an LB of the maximum evacuation time in the FFCA simulation.

The objective function of MIP model is to minimize the maximum evacuation time for all pedestrians. The main constraints including initial positions of all pedestrians for all non-exit cells, whether a pedestrian reaches an exit for all exits and all time steps, no pedestrian remains in the building in the end. The details of notations and the formulations of the MIP model can be found in Chu et al. (2017). The optimal solution of the MIP model can be seen as the system-optimum of evacuation and provides an LB of the maximum evacuation time in the FFCA simulation.

3. Conclusions and future research

A methodology to optimize the variable evacuation guidance system in buildings with convex polygonal interior spaces is developed in this study. The examples of the proposed methodology can be found in Chu et al. (2017). Three major findings are found in this study.

1. The calibration of the compliance behavior model shows that whether a pedestrian follows guidance depends on the consistency of guidance, pedestrian density, and familiarity with space. The probability of guidance compliance responds positively to consistency of guidance and negatively to density and familiarity with space. In addition to these three major factors, the individual preference is also another important factor for the sign compliance behavior.
2. The methodology is effective for reducing the maximum evacuation time in simulation and has a potential to reduce evacuation time in emergencies.
3. Using a dynamic network and a dynamic shortest path algorithm produces better and more stable reduction in maximum evacuation time than using a static network and a static shortest path algorithm because considering future congestion and hazards is critical for the performance of evacuation guidance.

Future research has three directions. In the future, the methodology can be extended to arbitrary shapes of interior spaces. Second, more realistic models for specific types of hazards can be incorporated in the methodology. Finally, FFCA could be replaced by other microscopic pedestrian models that consider more aspects of pedestrian behaviors without fundamentally changing the core of the proposed methodology of variable guidance optimization.

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This paper is an early version of Chu et al. (2017).

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