European Journal of Operational Research 237 (2014) 1105–1118

Contents lists available at ScienceDirect

European Journal of Operational Research

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

Innovative Applications of O.R.

Modeling framework for optimal evacuation of large-scale crowded pedestrian facilities

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ARTICLE INFO

Article history:
Received 29 May 2013
Accepted 22 February 2014
Available online 3 March 2014

Keywords:
Crowd dynamics
Evacuation
Simulation
Cellular automata
Genetic algorithms

ABSTRACT

The paper presents a simulation–optimization modeling framework for the evacuation of large-scale pedestrian facilities with multiple exit gates. The framework integrates a genetic algorithm (GA) and a microscopic pedestrian simulation–assignment model. The GA searches for the optimal evacuation plan, while the simulation model guides the search through evaluating the quality of the generated evacuation plans. Evacuees are assumed to receive evacuation instructions in terms of the optimal exit gates and evacuation start times. The framework is applied to develop an optimal evacuation plan for a hypothetical crowded exhibition hall. The obtained results show that the model converges to a superior optimal evacuation plan within an acceptable number of iterations. In addition, the obtained evacuation plan outperforms conventional plans that implement nearest-gate immediate evacuation strategies.

1. Introduction

Large-scale crowded pedestrian facilities such as stadiums, worship facilities, airport terminals and exhibition halls require adequate crowd management plans to ensure visitors' safety and comfort. The development of these plans tends to be more challenging in emergency situations where hasty evacuation of these facilities is required. When hazardous incidents occur in crowded pedestrian facilities, with the absence of a safe and efficient evacuation plan, the casualties are likely to be more catastrophic in terms of both numbers and severity. During most evacuation events, chaos is the norm. Evacuees tend to be panicked and egocentric, while seeking their own safety and paying less attention to their surroundings. Nonetheless, safe and efficient evacuation could be achieved in large-scale pedestrian facilities, if an effective evacuation plan is designed and properly disseminated to the users of the facility. This plan should be able to guide each pedestrian, or group of pedestrians, through their safe evacuation, such that a desirable overall evacuation performance is achieved. An evacuation plan provides information for each user on the exit gate, the path to follow to reach this gate, and possibly the time at which evacuation should start. The overall objective could be minimizing the evacuation time of the facility (i.e. time period at which the facility is totally evacuated), minimizing the users' average evacuation time, or maximizing the cumulative exit throughput within a given time period. Each representation will have its own safety consequences depending on the facility configuration and demand levels.

In small and medium size pedestrian facilities, evaluating the efficiency of any proposed evacuation plan is usually performed by conducting real-world experiments. In these experiments, users of the facility are given instructions to evacuate the facility following a certain plan and the corresponding performance of this plan is recorded. For large-scale facilities, experimenting with large crowds is impractical. Simulation models have emerged as an alternative approach by providing a realistic representation of the facility and the behavior of the evacuees considering all possible extreme conditions. Nonetheless, most of these simulation models are descriptive in nature. They are limited to representing crowd dynamics and associated system performance under the predefined evacuation scenarios. They lack the capability to provide the facility managers with the optimal evacuation schemes.

Several challenges pertain to the problem of developing an optimal evacuation plan for large-scale pedestrian facilities. For example, the problem is computationally cumbersome as numerous plans could be generated for most large-scale facilities. A developed framework should be able to efficiently search for the optimal plans to minimize the time required to produce an optimal or near optimal plan. In addition, the problem is naturally nonlin-

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http://dx.doi.org/10.1016/j.ejor.2014.02.054
0377-2217/

ear since the decisions of pedestrians on how to evacuate depend on the congestion dynamics at the gates and along the used evacuation routes, which are determined by the pedestrian evacuation decisions. Finally, methodologies used to develop the evacuation plans should provide accurate representation of the facility as well as the pedestrians' heterogeneous behavior especially under extreme conditions. Inadequate representation of the facility and the pedestrians' behavior could result in unrealistic or less efficient evacuation plans.

This paper presents a simulation-based optimization modeling framework to determine the optimal evacuation plan for a large-scale crowded pedestrian facility. The framework adopts a genetic algorithm (GA) that is integrated with a microscopic crowd simulation model. The GA iteratively searches for the optimal evacuation plan, while the crowd simulation model guides the search by evaluating the performance of the solutions generated by the GA. Given the configuration of the facility and the spatial distribution of the users, the model determines the optimal exit gate and associated routes for all pedestrians in order to minimize the average evacuation time. The model is also extended to provide the optimal evacuation start time of the pedestrians as part of the provided evacuation instructions. In the latter case, the model allows examining the effectiveness of phased evacuation strategies where the pedestrians exit rate is metered. A micro-simulation assignment model for multidirectional pedestrian movement in crowded facilities is used as part of the modeling framework (Abdelghany, Abdelghany, Mahmassani, & Al-Gadhi, 2005; Abdelghany, Abdelghany, & Mahmassani, 2014). The model adopts a Cellular Automata (CA) discrete system, which allows detailed representation of the pedestrians' movements in the facility. The modeling approach seeks to capture crowd dynamics in the facility through representing the pedestrians' behavioral rules and decisions at the individual level. These rules and decisions include destination and path choice, walking speed adjustment, and congestion aversion attitude.

The research work presented in this paper contributes to the existing literature in several aspects. First, as presented hereafter, limited research work is devoted to developing optimization-based models that can be used to design efficient evacuation plans for large-scale facilities. The presented modeling framework closes this gap through adopting a meta-heuristic optimization methodology that determines a near optimal evacuation scheme in terms of the exit gate, evacuation route, and evacuation start time. In addition, the use of a microscopic simulation model to evaluate the generated evacuation plans ensures accurate representation of the facility performance and the associated crowd dynamics pattern under these plans. Also, the research presents a comparison between optimal evacuation strategies and traditional nearest-gate evacuation strategies. The obtained results emphasize the importance of developing optimal evacuation plans as they could significantly outperform widely-adopted plans that implement nearest-gate evacuation strategies. Finally, the model allows examining the effectiveness of phased evacuation strategies where the pedestrians exit rate is metered. This paper is organized as follows. The following section provides a summary of main recent studies on pedestrian evacuation models. Next, a detailed description of the modeling framework is provided. The application of the developed models to generate the optimal evacuation plan for a hypothetical facility is presented. Main results that illustrate the different capabilities of the developed modeling framework are also presented. The last section provides concluding comments and possible research extensions.

2. Literature review

Extensive research effort has been devoted to studying the evacuation of pedestrian facilities. These models could generally be classified into two main categories. The first category includes models that are developed to replicate crowd dynamics during evacuation and evaluate the overall performance of the evacuation process considering different crowd management schemes. The second category includes models that seek to determine the optimal evacuation plan for a facility using an optimization-based methodology. Most existing models fall under the first model category. These models differ in their assumptions, underlying theory, scalability and scope of application. Zheng, Zhong, and Liu (2009) compared seven different modeling approaches for crowd evacuation. These modeling approaches include cellular automata models, lattice gas models, social force models, fluid-dynamic models, agent-based models, game theoretic models, and approaches based on experiments with animals. They conclude that these approaches could be used to answer different questions about the evacuation process and an analyst might need to combine different modeling approaches to adequately study the crowd evacuation phenomena.

As an example of the first models category, Kirchner and Schadschneider (2002) presented a cellular automata simulation-based model to study pedestrian evacuation. A simple scenario is considered where a single space facility is evacuated using one or two doors. Daoliang, Lizhong, and Jian (2006) developed a two-dimensional cellular automata model to simulate the egress dynamics during evacuation. The developed model is used to derive useful information on the required width of the exit gates and recommended gate separation. In a similar effort, Varas et al. (2007) presented a cellular automata model to simulate the process of evacuation of pedestrians in a room with fixed obstacles. They compared different door configuration: single (where only one person can pass) and double (two persons can pass simultaneously). The results show that replacing the double door by two single doors does not improve evacuation times noticeably. Abdelghany, Abdelghany, Mahmassani, Al-Ahmadi, and Alhalabi (2010) presented a cellular automata crowd simulation model for large-scale facilities. A behavioral module in the form of a logit-based model is used to replicate how evacuees select their exit gates. The model captures the trade-off between travel distance to the gate and the level of congestion at the gate. The model is applied to study the evacuation of a crowded pilgrimage facility in Mecca, Saudi Arabia. Alizadeh (2011) presented a dynamic cellular automaton (CA) model to simulate the evacuation process in spaces with obstacles. The model considers basic parameters such as human psychology, placement of the gates and their width, and position of the obstacles. The model shows that the initial distribution of the crowd plays an important role in the obtained results. Fu, Luo, Deng, Kong, and Kuang (2012) presented a cellular automaton model to simulate the evacuation processes in a large classroom by considering the different exit choices and movement rules. Similar to the results in Alizadeh (2011), they showed that the local density distribution of pedestrians could have significant impact on the evacuation performance. Zheng and Cheng (2011) presented a game-theoretical model to study the evacuees' cooperative and competitive behavior during an emergency evacuation. The model is used to determine the density at which cooperative and competitive behaviors are observed and their corresponding evacuation performance. Xiong, Tang, and Zhao (2013) proposed a hybrid model which integrates a macroscopic model and microscopic model. The integrated model represents the crowd movement tendency as well as the individual's heterogeneous behavior to accurately simulate crowd evacuation.

Helbing, Farkas, Molnar, and Vicsek (2002) presented a generalized force simulation model of interactive pedestrian dynamics. Spatial–temporal patterns in pedestrian crowds are interpreted as self-organized phenomena. A single parameter, the "nervousness", is used to reflect fluctuation strengths, desired speeds, and the tendency of herding. Helbing, Isobe, Nagatani, and Takimoto