Safety Science 87 (2016) 167–178

Contents lists available at ScienceDirect

Safety Science

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

Review

A review of optimisation models for pedestrian evacuation and design problems

Hendrik Vermuyten [a,*], Jeroen Beliën [a,b], Liesje De Boeck [a,b], Genserik Reniers [c,d], Tony Wauters [e]

[a] KU Leuven Campus Brussels, Faculty of Economics and Business, Department of Information Management, Modeling and Simulation, Research Centre for Quantitative Business Processes, Warmoesberg 26, B-1000 Brussels, Belgium
[b] KU Leuven, Faculty of Business and Economics, Department of Decision Sciences and Information Management, Research Center for Operations Management, Naamsestraat 69, B-3000 Leuven, Belgium
[c] KU Leuven Campus Brussels, Research Centre for Economics and Corporate Sustainability, Warmoesberg 26, B-1000 Brussel, Belgium
[d] KU Leuven, Research Centre of Energy, Transport and Environment, Naamsestraat 69, B-3000 Leuven, Belgium
[e] KU Leuven, Technology Campus Ghent, Department of Computer Science, CODeS Research Group, Gebroeders De Smetstraat 1, B-9000 Gent, Belgium

A R T I C L E I N F O

Article history:
Received 18 February 2016
Received in revised form 30 March 2016
Accepted 1 April 2016
Available online 9 April 2016

Keywords:
Pedestrian and crowd behaviour
Optimisation models
Literature review

A B S T R A C T

This article presents a review of the use of optimisation models for pedestrian evacuation and design problems. The articles are classified according to the problem type that is studied, the level of model realism, and the modelling or solution technique. To substantiate the classification criteria and to provide a background for the reader, relevant empirical research and descriptive models (e.g., social-force and cellular automata models) are discussed. We conclude that most of the recent models explicitly include pedestrian dynamics, specifically congestion, but more attention should be given to calibration and implementation of the proposed models. Furthermore, optimisation models could benefit from including some of the modelling techniques used in descriptive models.

Contents

* Corresponding author.
E-mail addresses: hendrik.vermuyten@kuleuven.be (H. Vermuyten), jeroen.belien@kuleuven.be (J. Beliën), liesje.deboeck@econ.kuleuven.be (L. De Boeck), genserik.reniers@kuleuven.be (G. Reniers), tony.wauters@cs.kuleuven.be (T. Wauters).

http://dx.doi.org/10.1016/j.ssci.2016.04.001
0925-7535/

1. Introduction

There are many situations in which a large number of people gathers in a single location. Examples include spectators at music and sports events, commuters in railway and metro stations, and employees in large office buildings. To ensure the safety and comfort of the people present, a careful design of pedestrian facilities and good crowd management are required. Furthermore, in the event of emergencies, such as a fire, a gas leak, or a bomb threat, the efficient evacuation of the facility is of primary importance. The recent terrorist attacks at the Bataclan theatre in Paris, where 89 people died, and the stampede during this year's Hajj pilgrimage in Mecca, where more than 2070 people died, illustrate the need for developing good crowd management and emergency evacuation procedures.

The study of pedestrian and evacuation dynamics is very complex, due to the large number of people involved and the nonlinear interactions between them, psychological factors influencing human behaviour, and the influence of external factors such as the layout of a pedestrian facility. As a consequence, the topic has received attention from researchers in different fields, including psychologists, sociologists, physicists, computer scientists, and traffic scientists (Helbing and Johansson, 2010).

Three distinct, yet interrelated, research streams can be distinguished. The first stream focuses on the empirical study of pedestrian behaviour and crowd dynamics, whilst the second is concerned with the development of mathematical models to describe the movement and interactions of pedestrians as realistically as possible (Teknomo, 2002). Finally, the third stream of research uses an optimisation-based methodology to develop models which determine optimal evacuation plans or design solutions (Abdelghany et al., 2014). Most of the research falls under the first two categories. Several review articles discuss the empirical research on and modelling of pedestrian and evacuation dynamics. Schadschneider et al. (2008) provide a summary of the empirical studies and theoretical modelling that has been done and give two examples of possible applications of this research. Helbing and Johansson (2010) give a similar overview, and additionally discuss research into situations of panic and critical crowd conditions. Schadschneider and Seyfried (2009) investigate the quantitative data on pedestrian dynamics for the calibration of evacuation models. They focus on the fundamental diagram (see Section 3.1) and consider the implications for cellular automata models (see Section 4.1). Papadimitriou et al. (2009) assess two different topics of research, namely route choice models and crossing behaviour models, which study how pedestrians cross the street under different traffic conditions. Gwynne et al. (1999) classify 22 evacuation models based on the nature of the model application, the enclosure representation, the population perspective, and the behavioural perspective. Zheng et al. (2009) distinguish seven methodological approaches: cellular automata, lattice-gas, social-force, fluid dynamics, agent-based, game-theoretic models, and experiments with animals. (We give an overview of these approaches in Section 4.1.) They also look at the possibility of modelling heterogeneous individuals, the scale of representation, whether time and space are discrete or continuous, whether a normal or an emergency situation is assumed, and the typical phenomena that the model can represent. In addition, Duives et al. (2013) identify eight motion base cases and six self-organising crowd phenomena which a simulation model should be able to reproduce. Furthermore, they look at ten other model characteristics, such as the ability to simulate pressure in crowds and the computational requirements of the model, in order to assess the models' applicability. Their classification distinguishes between cellular automata, social-force, activity-choice, velocity-based, continuum, hybrid, behavioural, and network models. Kalakou and Moura (2014) present a general overview of models from different research areas to analyse the design of pedestrian facilities, whilst Lee et al. (2003) focus on models for the evacuation of ships. Finally, Bellomo et al. (2012) focus on the mathematical properties of models for pedestrian behaviour. The third category of research has received less attention in the literature. Moreover, to the best of our knowledge, the work of Hamacher and Tjandra (2002) is the only review that focuses on optimisation models for evacuation problems. However, most of the models they discuss are network models with constant (i.e. density-independent) travel times. This article tries to fill the gap by critically reviewing the different properties of the optimisation models that are currently available for evacuation and design problems and identifying opportunities for future research.

We first searched for literature reviews and articles that discuss general topics related to pedestrian dynamics or evacuation and design problems (Bellomo et al., 2012; Duives et al., 2013; Gwynne et al., 1999; Hamacher and Tjandra, 2002; He et al., 2013; Helbing and Johansson, 2010; Kalakou and Moura, 2014; Lee et al., 2003; Papadimitriou et al., 2009; Schadschneider et al., 2008; Schadschneider and Seyfried, 2009; Sime, 1995; Stanton and Wanless, 1995; Zheng et al., 2009) and checked the references therein. Next, we used the *Web of Knowledge* database to find relevant articles. We used combinations of the keywords 'optimisation', 'problem', 'evacuation, 'pedestrian', 'crowd', 'model', 'movement', and 'flow'. No a priori cut-off date was used, since no previous review articles exist that follow our perspective, apart from the work of Hamacher and Tjandra (2002). Articles on the traffic assignment problem and articles on evacuation and design problems which do not focus on pedestrian traffic and crowd dynamics, are not included. This resulted in a broad, but not exhaustive, overview of the current literature on optimisation models for crowd and evacuation dynamics.

In our review, we distinguish between optimisation and non-optimisation articles. The optimisation category consists of all papers that use a methodology to obtain an optimal or a good solution to a specific problem involving crowd dynamics, such as the efficient evacuation of a building. All articles that describe empirical results or descriptive models for the movement of pedestrians that do not use an optimisation methodology, belong to the non-optimisation category. We only take the optimisation articles into account in our classification process. However, we summarise the empirical research and descriptive modelling approaches in our text in order to give the reader the necessary background information for the discussion of the optimisation models. We ended up with 31 optimisation articles that are included in our classification process.

Fig. 1a lists the journals in which most of the articles in this paper have been published. Taking the different types of articles (empirical, descriptive, optimisation, overview) together, *Safety Science* and *Transportation Research Part B: Methodological* are the two journals that publish most of the articles related to pedestrian walking behaviour research. Furthermore, Fig. 1b gives information on the changing number of articles over the years. It is clear that this research topic has received increasing attention in the last five years.

We use different perspectives for organising the literature. Each section discusses a specific perspective and presents detailed tables in which the relevant articles are categorised. Section 2 discusses the different problem types that are studied in the literature, the criteria used to assess the quality of the resulting solutions, i.e. the objective function measures, and the types of decisions that are considered in the model. The realism of the proposed models and their conformity to empirical results on pedestrian dynamics is investigated in Section 3. Finally, Section 4