

EVACUATION MODELING: DEVELOPMENT, CHARACTERISTICS, AND LIMITATIONS

Rani A. Muhdi, Auburn University

muhdira@auburn.edu

ABSTRACT

As buildings and structures are designed more creatively, evacuation procedures to assure acceptable building fire safety standards have been a major concern of fire safety professionals. One way to assure occupants' safety lies in evacuation drills. Another potential alternative to confidently evaluate occupants' safety in buildings lies in computer-based evacuation models. The basis on which evacuation models have been developed are discussed. Human performance and behavior research during evacuation are also presented. The shortcomings of current evacuation models and the need for new features and capabilities are suggested for more accurate and representative evacuation models.

INTRODUCTION

The science of crowd dynamics has been of interest to many researchers such as psychologists, computer scientists, safety engineers, risk managers, and architects. This interest has originated from the fact that crowd dynamics involves the study of pedestrians, traffic control, planning and evacuation, preparedness for natural disasters and building egress. As architects creatively design novelistic structures, evacuation procedures to assure acceptable building safety standards have been a major concern of fire safety engineers. Although real emergencies and experimental evacuation drills have enough similarities in between (Pauls, 1980), evacuation drills still present significant ethical, practical and financial challenges to researchers (Gwynne et al., 1999). Potential alternatives to conquer these challenges and confidently assure safety in buildings lie in computer-based evacuation models.

Human movement and behavior have been studied and modeled for more than 30 years. Some of the earliest studies on movement of people in non-emergency conditions were conducted by Predtechenskii and Milinskii (1969) and Fruin (1971). Predtechenskii and Milinskii (1969) studied merging large population flows in order to measure population sizes, densities, speeds and flow rates. In his studies, Fruin (1971) considered flow of pedestrians on stairs and flat surfaces by incorporating the size and shape of occupants' bodies, level of clothing, queuing in enclosures, flow speed as a function of passage width and population density. Fruin (1971) also introduced the concept of "Level of Service" which identifies the relationship between flow density and speed of crowd. Henderson (1971) obtained the distribution functions of speed for three crowds which are students, pedestrians, and children and compared each crowd to the Maxwell-Boltzmann energy theory. A similarity was obtained between crowds' movement and the energy theory which indicated that most pedestrians moved in a gaseous phase and statistically independent of each other.

EVACUATION MODELING

The Development and Characteristics of Evacuation Modeling

Stahl (1982) introduced one of the earliest evacuation models that predicted emergency movement, namely BFIRES-II, a model of emergency egress during fires. Other early emergency evacuation models included ASET (Cooper, 1982) and EVACNET+ (Kisko and Francis, 1985). Recently, the number of evacuation models has significantly increased. Olenick and Carpenter (2003) reported that approximately four times as many evacuation models have been identified in their recent survey than were identified by Friedman (1992). One of the earliest evacuation model reviews was conducted by Watts (1987). Furthermore, 22 evacuation models have been classified based on three different approaches, namely optimization, simulation and risk assessment (Gwynne et al., 1999). The most recent evacuation model review was performed by Kuligowski (2004). The review classified 28 different egress models based on the level of complexity in occupant behavior. These levels are movement models (no behavioral capabilities), partial-behavioral models and behavioral models. The review process also listed 14 features and capabilities of all 28 egress models, in addition to 10 specialized features. The features and capabilities that are of interest to researchers and the specialized features are listed in table 1. Most computer simulation evacuation models are structured based on flow dynamics, cellular automata, and agent-based design. Santos and Aguirre (2004) conducted a critical review of emergency evacuation simulation models based on these structures.

Table 1. Features and capabilities of egress models (Kuligowski, 2004)

Features of interest to researchers	Specialized features
<ul style="list-style-type: none"> - Purpose of models - Public availability - Modeling method - Model structure - Fire data - Output - CAD drawings - Visualization - Validation - Limitations - Perspective of models & occupants - Occupant movement & behavior 	<ul style="list-style-type: none"> - Counterflow - Exit obstacles - Fire conditions - Groups defining - Disabilities - Pre-movement - Elevators - Toxicity - Impatience - Route choice

Flow-based modeling. A flow-based approach has been adopted in evacuation models which are usually referred to movement models. Some examples of movement models are EVACNET4, EESCAPE, and EGRESSPRO. Movement models provide a network representation (nodes and arcs) for a floor plan. Both nodes and arcs have limited capacity. The nodes represent different rooms, departments, or wings in a floor, while the arcs represent occupants' flow between nodes in terms of quantity and direction. Although movement models are relatively easy to construct in order to determine an optimal plan to evacuate a building in a minimum time, they lack social interaction between evacuees, human behavior in emergency conditions and hazards representation.

Cellular automata modeling. In cellular automata evacuation models, building spaces are divided into discrete cells. Evacuees, who are modeled on the center or perimeter of a grid, maintain a probabilistic movement pattern from cell to another towards an exit. Series of time-steps update a cellular automata model to tracking the movement of individuals. EGRESS, TIMTEX, and the magnetic model of Okazaki and Matsushita (1993) are some examples of cellular automata evacuation models. Since individuals are placed on grids and controlled by probabilistic choices during evacuation simulation, movement could occur in all directions, which makes such models lack social behavior, personal space in emergency situations and evacuees' initial speed and movement.

Agent-based modeling. An advanced approach in modeling emergency evacuation is found in agent-based simulation models. The premise lies in assigning a certain set of attributes to each evacuee (agent) in the model. Each rational agent acts independently from other agents in the model to assess optimal escape route. SIMULEX and EXODUS, which are examples of agent-based evacuation models, are designed to allow an agent to assess individual walking speed, physical motions, proximity of other evacuees, building structure and influence of gender and age (Santos and Aguirre, 2004).

Regardless of the structure of any evacuation model, data on the characteristics of occupants, their behavior or actions, delays and travel speeds are required in developing any evacuation simulation model. Fahy (2004) identified three sources for such data, videotaped observations, laboratory experiments and post incidents surveys and interviews. Videotaped observations can provide evacuation modeling with evacuation times, movement and some individuals' characteristics. However, videotapes are indirectly applicable to movement and behavior of occupants since videotapes are rarely available for actual fires. Another source for data lies in laboratory experiments. Jin (1997) tested the effect of smoke on decision making and travel speed. Researchers rarely take this route due to legal restrictions and ethical issues. Finally, evacuation researchers can obtain valuable information from survivors of actual fires (Best, 1977; & Fahy and Proulx, 1996). The recollections and descriptions are subjective due to the fact that details can be lost over time and elapsed times are not recorded objectively.

The Limitations of Evacuation Modeling

Validation is one of the most important limitations of evacuation models. In evacuation modeling, validation refers to a systematic comparison of model predictions with reliable information (Galea and Gwynne, 2005). Model predictions are dependent upon the data and codes of the evacuation model and the user of the evacuation model. The lack of suitable experimental data to feed evacuation modeling causes a challenge to evacuation modelers. Most evacuation experiments are designed and conducted for practical purposes and not necessarily to support the development of evacuation models (Galea and Gwynne, 2005).

Another limitation of evacuation models lies in the presentation of occupants in the models. Accurate occupants' representation based on comprehensive anthropometric data and human performance and behavior should be used in evacuation modeling to provide additional level of validity to the models. Furthermore, building codes and standards should be reformed according to the dynamic changes of individuals' sizes and ages. The reader is advised to draw a

comparison between occupants' dimensions found in the Life Safety Code® (Coté & Harrington, 2003) and a more realistic and accurate representation of occupants in the transverse plane that is more practical in evacuation modeling (Still, 2000).

CURRENT AND FUTURE RESEARCH

Regardless of the complexity of evacuation models, they account for occupant characteristics such as human performance and behavior in emergency conditions. Muhdi, Davis, and Blackburn (2006) have expanded previous research on occupants' physical movement. Their study indicated significant differences between normal walking speed and each of maximum walking speed, normal and maximum crawling speeds. The study also called for additional human performance measures such as fatigue and physical exertion to be accounted for in future evacuation models.

Evacuation models have been developed to simulate the movement and behavior of individuals during evacuation to estimate evacuation time and assess the safety of building designs. Due to the complexity of fire behavior, building designs and interior layout, the means of egress could not be fully utilized. As a result, Garrett et al. (2006) implemented evolutionary computations in the form of Genetic Algorithms (GAs) and Estimation of Distribution Algorithms (EDAs) to evolve the placement and number of exits in order to optimize overall evacuation time for two practical design problems, namely banquet halls and lunar habitation modules. In a similar study, Muhdi et al. (2006) applied evolutionary computations in evacuation planning.

Finally, Fahy (2004) concluded a comprehensive list of research needs to enhance the reality of evacuation modeling. This includes movement capabilities of a wide cross-section of society, evacuation of disabled people, delay times before beginning evacuation, occupants' behaviors before, during and after evacuation, risk perception and its impact on judgment and interaction between individuals and groups. Santos and Aguirre (2004) also concluded that there is a need for further research in the impact of group sizes, cohesion on the individual risk of fire fatality and the incorporation in evacuation modeling the concept of leadership in response to crisis.

CONCLUSION

Computer-based evacuation models are a potential alternative to evacuation drills to confidently evaluate occupants' safety in buildings. The models have been developed on the basis of human movement and behavior studies. Although the number of evacuation models has significantly increased in the past few years, the same mathematical concepts and design structures are still followed. Evacuation models require data on the characteristics of occupants, their behavior or actions, delays and travel speeds. In spite of the complexity and details of evacuation models, validation along with accurate representation of occupants in terms of behavior and performance represent challenges to evacuation researchers. There is always a need for additional data on human behavior and performance. Experiments should be designed solely for the purpose of supporting evacuation models to continuously improve their validity. The emerging mathematical and computing algorithms present a potential application in emergency planning and evacuation.

ACKNOWLEDGEMENTS

The author would like to thank his primary advisor, Dr. Jerry Davis, for his continuous assistance, direction, and guidance during this research. Thanks are also due the National Institute for Occupational Safety and Health (NIOSH) for their financial support of my education at Auburn University.

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