Enrico Ronchi[1]

AN INTRODUCTION TO HUMAN BEHAVIOUR IN FIRE AND EVACUATION MODELLING

Abstract: This short educational document (i.e., lecture notes) briefly introduces some of the basic concepts concerning human behaviour in fire and evacuation modelling. While not exhaustive, it presents a selection of the key explanatory theories of human behaviour in fire along with some introductory concepts on the psychology of mass behaviour. Additional concepts that are discussed include the use of the engineering time-line of evacuation and level of service as currently employed by evacuation modelling tools. The document also discusses the use of evacuation calculations and models in the context of performance-based design for fire safety engineering. To address this issue, examples of pedestrian evacuation movement models are presented, including Helbing's social force model and the hydraulic capacity model included in the Society of Fire Protection Engineering handbook. An overview of the main type of results provided by evacuation models is also given.

Keywords: Evacuation; Human Behaviour; Modelling; Level of Service, Engineering Time-line; Egress

Cite as: *Ronchi E. (2018). An introduction to human behaviour in fire and evacuation modelling. Lecture notes from the Knowledge for Resilient Society (K-Force) project. Lund University, Lund, Sweden.*

[1] Senior Lecturer, Department of Fire Safety Engineering, Lund University P.O. Box 118, Lund, Sweden. e-mail: enrico.ronchi@brand.lth.se

1. THE EVACUATING CROWD

A crowd can be defined as a multitude of individuals moving through the same space at a certain movement in time. Fire safety engineers are often in the challenging position to deal with increasingly large and complex buildings in which a crowd will move, while trying to minimise costs. Larger buildings can be associated with potential larger incidents, as demonstrated by a series of evacuation disasters around the world [1]. In this context, the design of adequate evacuation can play a fundamental role in minimizing the consequences of a fire disaster.

Crowd evacuation disasters are not a novel issue, as the need for evacuation design in large buildings and infrastructures able to accommodate large crowds was known since the Roman Empire [2]. As an example, the Coliseum in Rome – able to accommodate up to 73,000 people - has been designed with 60 entrances, thus making it possible to be evacuated in approximately 5 minutes [2], [3]. Such type of evacuation efficiency would be hard to reach in modern stadia due to the reduced number of exits.

To date, different tools are available to perform fire evacuation design. Modelling tools are based on the study of the behaviour of people in the crowd. In this context, it is important to understand the role of *Crowd Science*, the science that deals with the study of the movement of the crowd, both in normal movement conditions as well as in case of emergency evacuation [4]. The study of crowd evacuation is a sub-category of Crowd Science which involves aspects and thematic areas belonging to different disciplines, among which engineering, psychology, applied mathematics, physics, biomechanics, etc.

Theories that are developed and adopted within Crowd Science can rely on different types of data. Data with the highest level of ecological validity are those based on the observation of evacuation behaviour and crowd movement during real emergencies. These can be characterized by the presence of a varying number of people and by different types of fire events. In addition to naturalistic data, laboratory and field experiments are conducted by research groups [5], [6] in order to study and systematically analyse the variables that determine the movement and behaviour of an evacuating crowd. This type of data is often characterized by a lower ecological validity being the participants in the experiments generally informed of the fact of being part of an experiment; this type of data collection efforts are often called announced evacuation experiments, e.g. a fire drill is a typical example of such type of data-set [7]. This type of experiments allows the study of different variables that could hardly be studied in a real event. The degree of ecological validity can depend on the experimental procedure, i.e., unannounced evacuation experiments can also be conducted and people behaviours may get closer to the one in a real emergency.

Theories, mathematical models and simulations allow the study of the evacuating crowd, thus permitting the study of optimal evacuation design solutions which allow considering the optimization of pedestrian flows in case of emergency evacuation and the appropriate usage of emergency routes. Studies may be focused on both the physical aspects of people movement (i.e. navigation choices in different geometrical configurations, collision avoidance, flows, bottlenecks, etc.) as well as behavioural aspects (evacuation decision making). Some basic concepts on such theories and models are presented in these lecture notes. Due to the nature of this document – i.e., providing a general overview of the field of human behaviour in fire and evacuation modelling - literature references are often omitted. However, a good starting point for the reader can be the reviews performed by Kobes et al on the existing theories for the study of human behaviour in fire [8] and Kuligowski et al [9] for evacuation modelling.

2. PERFORMANCE-BASED DESIGN AND EVACUATION MODELS

Evacuation modelling tools can be used in the context of performance-based design (PBD). Given a threat, such as a fire disaster, PBD assumes that a building is safe enough as long as the conditions in the building are not such that critical conditions are exceeded during the evacuation process [10]. Different thresholds are proposed in the literature for critical conditions and they often refer to some of the basic variables concerning a fire (e.g., temperature, visibility, toxic products, and radiation). PBD is performed by a comparison between the Required Escape Time (RSET), which consists of the time needed by people to reach a safe place, and the Available Safe Escape Time (ASET), which is the time until critical conditions are reached. This comparison is made by calculating both times using different types of tools, such as hand calculations or simulation models. The calculation of RSET can therefore be done either performing an estimation of the time needed for evacuation using a set of equations or using evacuation simulation models.

During fire evacuation design, a prescriptive-based design would require to meet prescribed dimensions of the egress components (e.g. exits, stairs, etc.), prescribed maximum distances to an exit or maximum time to reach an exit, etc. In contrast, the performance-based design would allow any egress component dimensioning as long as the designers are able to demonstrate a sufficient level of safety for evacuation. This means that any maximum distance to/time to reach an exit can be used as long as the building can be evacuated safely.

3. BASIC CONCEPTS OF HUMAN BEHAVIOUR IN FIRE

As discussed earlier, the understanding and prediction of human behaviour in fire requires a multidisciplinary approach which includes the study of several fields of science. A set of misconceptions concerning human behaviour has been discussed for instance in the field of psychology research. One of the most common misconception in human behaviour in fire is the concept of panic. This word is often used in media accounts and survivors' statements to refer to the behaviour of people during a fire emergency. Evidence exist that such type of behaviour is in reality very rare in case of fires [11]. The cinema often supports the panic misconception by portraying the behaviours of people in case of emergency as hysterical. Although movies are not intended to be reality, they often contribute to shape the public opinion about a subject matter. The consequence of this is that the majority of people associates fire evacuation events with the concept of a chaotic, irrational, disorganized and competitive scenario. The term panic is often referred by survivors as an unsuccessful outcome observed in other people [12] or to describe their own state of increased anxiety. In contrast, the actions observed are generally logical and appropriate. Several studies have in fact reported altruistic rather than competitive behaviours. Actual behavioural investigation from crowd evacuation events in fact shows that anti-social or selfish behaviours are rare and tend to not spread to others [13], [14]. Evacuation takes place often in orderly manner and cooperation/helping behaviours are common. Flight behaviours which might seem disorganized to an observer, might actually be linked to a rational response and decision making adopted by the evacuating person or group of persons.

A currently accepted theory, the affiliation theory [15], states that evacuees tend to seek the familiar rather than simply an exit during an emergency. In addition, the presence of familiar others may have a calming effect during an emergency evacuation. Affiliation theory seems to explain quite well cases in which the crowd is made up of small groups of families or friends, while actual fire events may involve much larger crowds. Since mutual help and cooperation have been observed also in these cases, the concept of social identity has been developed. This concept suggests that social identity determines social behaviour. In other words, people may not have a single personal identity but as many social identifies as we have memberships of social groups or categories [14], [16]. This theory allows explaining a set of a commonly accepted group behaviours. These include the fact that people tend to have greater commitment in collective actions (rescuing and helping in this case) the more they identify themselves with their group. Leadership and social influence occur and they can have a key role in uncertain or confusing situations [17]. People may tend to look for those who they think they know what they are doing. This is often associated with the roles of people and the role-rule model [18], which relates the trustworthiness of the information received with the source of the information.

A number of additional behavioural issues can be taken into consideration when discussing decision making during emergency evacuation. They include the assessment of the seriousness of the threat, the level of perceived urgency, risk perception [19] and many more. The key concept to be understood for any evacuation study, is that rather than irrationality and *panic*, a common issue in a fire scenario is that people may question the seriousness of the scenario and continue their activities that they were conducting prior hearing an alarm. This means that design efforts and solutions have to be performed to make people responding quickly to a fire threat situation rather than dealing with an irrational response. In this context, it is important to understand that the starting point of fire evacuation design or an evacuation model is the representation of people as agents acting rationally.

4. PREDICTING BEHAVIOUR WITH EVACUATION MODELS

Evacuation models are tools adopted for the representation of human behaviour in fire. They can significantly vary in nature in relation to their level of sophistication and modelling assumptions adopted. A common classification divides existing tools into conceptual model, hand calculations and evacuation simulation models or computational models of evacuation [20]. The latter are often referred simply as evacuation models (or egress models) and they may adopted different modelling techniques, e.g., cellular automata (people movement is represented through a system of cells) or agent-based modelling (people movement is represented through a list of rules of interactions).

Conceptual models aim at the interpretation of a certain phenomenon or a set of behaviours that the crowd or an individual may have during an evacuation. This is often made by representing the individual or group decision-making process.

Hand calculations represent a set of simplified calculations which permit to calculate variables such as the time to pass from a certain point of a building to another for an evacuating crowd. Examples of such models include the hydraulic capacity model presented in the handbook of the Society for Fire Protection Engineering (SFPE) [21] or the equations presented by Predtechenskii and Milinskii [22].

Evacuation models greatly vary in relation to the assumptions they adopt for the representation of the geometrical layout of the building, movement of the agents and interactions between the agents and the environment [23]. Those models are generally based on a simplified engineering time-line model [24]. Such time-line includes a set of sequential times to be represented in an evacuation model for the representation of human behaviour in fire. The first part of the time-line model includes the time for the detection of the fire and the alarm. Such components are often not necessarily explicitly considered in evacuation models [25]. The decision making process which takes place once the alarm goes off can be represented in evacuation models making use of distributions of pre-evacuation times. Evacuation models may include a single delay time distribution or a sum of more distributions, for instance one distribution representing the recognition time (the time to understand that a fire emergency is taking place) and the response time (the time to take an active decision to reach a safe place). Once a purposive movement towards a safe place has started, the next element of the engineering time-line should be considered, the movement time. Such time refers to the time needed by the evacuees to reach a safe place from their initial location in the building. This can be influenced by several variables, such as flow constraints given the presence of geometrical obstacles (depending on the layout of the buildings) or other people along the evacuation route. Once all people have reached a safe place, the evacuation can be considered concluded. Such time can be called total evacuation time and it corresponds to the Required Safe Egress Time.

During the evacuation process, models can represent different types of crowd movement behaviour. They include a range of individual and emerging behaviour. Emerging behaviour are intended here as the behaviour resulting from the combination of individual behaviour. Examples of such behaviours can be collision avoidance (i.e. people avoiding the physical contact with others), crowd pressure (in case of physical contact), group behaviours (e.g. lane formation [26], etc.). Crowd behaviour include uni-directional and bi-directional movement (also called counter-flow) on horizontal or vertical egress components. Uni-directional movement can be on a corridor, around a corner, entering or exiting an opening, on a staircase, etc. Bi-directional movement is particularly relevant when there is a need to represent within an evacuation model the intervention of fire-fighters in the opposite direction of the flow of evacuees [27]. Crossing or merging flows can also take place and can be represented in evacuation models. This case represents the situation in which two or more flows of people merges into a single flow [28]. Other relevant aspects include the process of route and exit choice (*way-finding*) and the methods adopted for its representation [29].

It should be noted that given the uncertainties associated with the prediction of human behaviour, a stochastic modelling approach is generally employed [30]. This means that evacuation models make use of pseudo-random sampling from distributions [31] to determine possible different input values for different variables characterizing the evacuees in the model (e.g. pre-evacuation time, walking speeds of the agents, body size in continuous models [23]) and then repeated simulations are performed.

5. SPACE USAGE AND LEVEL OF SERVICE

Apart from the main theories and models adopted to represent crowd behaviour during fire evacuation, it is equally important to identify the personal space necessary for each individual according to comfort and safety requirements. In this context, the spaces in which individuals interact with others can be classified and they depend on a set of factors, among which body size, movement paths, the need to avoid collisions with other people, the cultural background of the people involved in the emergency, etc.

The definition of the space that an individual needs during a crowd evacuation can be made considering the science of proxemics, which investigate the human usage of space. People can have several spaces which vary in relation to the level of interaction with others; they include 1) the intimate space (for physical interaction), 2) the personal space (for interactions with familiar people such as friends or family members), 3) the social space (for interactions with acquaintances) and 4) the public space (for public interaction) [32], as shown in Fig. 1. Entering some of these individual spaces may be associated with issues associated with comfort or safety depending on the scenario under consideration.

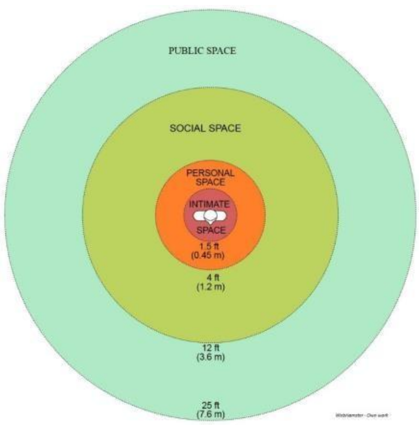

Fig. 1 – Personal spaces according to E. T. Hall [32].

After the definion of the personal spaces, it is necessary to quantify the usage of the space made by evacuees. This can be represented in several manners. Oftentimes people density is the most common variable adopted to measure the number of people in a certain space (its unity of measure is generally people/m^2). In other instances, space usage can be expressed as area per number of people; this is represents the reciprocal of people density (and it is expressed as m^2/person). It should be noted that several debates exist on the choice of the reference area for density estimations [5].

Evacuation models can also make use of the concept of Level of Service [33], in which the human body is assumed to be approximated as an ellipsis. Different level of services can be adopted to represent the situations that vary from free circulation (LoSA) to complete congestion (LoSF). In case of very high densities (6+ people/m^2), there is no space between individuals and push forces are transmitted through the crowd. This is linked with the so-called *crowd turbulence* phenomenon, in which one individual in the crowd may not be capable of moving on its own, but clusters of pedestrians may move with wavelike patterns.

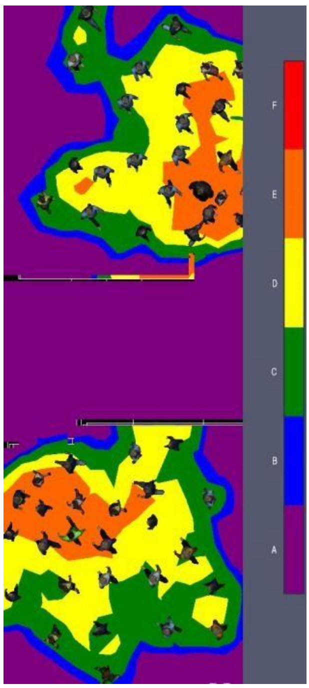

Fig. 2 – Example of level of service according to Fruin [33] in an evacuation model [34].

6. EXAMPLES OF PEDESTRIAN EVACUATION MOVEMENT MODELS

This section presents two evacuation movement models as examples of possible methods currently adopted in evacuation models. The first example is the hydraulic model [21], a macroscopic model which is also used to perform hand calculations of evacuation movement. The second example is the social force model [35], a self-driven particle model which is often used in agent-based modelling of evacuation.

The hydraulic model presented in the SFPE handbook [21] includes movement equations based on the effective width concept and an analogy between people and a fluid. The effective width concept is used to describe the fact that an evacuating crowd does not make use of the entire space available, but there is a boundary layer to the edges of each egress component (e.g. a stair, a corridor, etc.) which is unused by people during evacuation. The model assumes that there is a threshold value of people density (often represented as people/m^2) equal to 0.54 people/m^2 before which the movement of people is unimpeded (i.e., people move at their desired speed regardless of the movement speed of others). Between 0.54 people/m^2 and 3.8 people/m^2 people move at a reduced speed due to the presence of others in accordance with a linear model. Above this density limit, no movement will take place until enough of the crowd has passed (see Equation 1).

$$v=k-akD \qquad (1)$$

Where:

v is the walking speed along the line of travel

D is the population density expressed in people per unit area

k and a are constants depending on the units of measures (ft/min or m/s) and the exit route element

The social force model is a self-driven multi-particle model developed by Helbing and Molnár [35], which is used to represent emergent behaviours of people in a crowd. Self-driven particles [36] relate to the representation of a swarm modelled by a collection of particles that move with a constant speed but respond to a random perturbation. Each particle is an autonomous agent and represents a moving pedestrian, but the direction of each particle is updated using local rules (caused by the behaviour of the other particles). The motion of people is described as subject to “social forces”, which represent a measure for the motivations of individuals to acts.

The social force model considers a vectorial quantity (the social force) to describe the systematic temporal changes of the movement speed desired by each individual. This force takes into consideration the effects of the environment (i.e. the interaction with other people and obstacles). The social force is a representation of the pedestrian motivation to act, and it is expressed as an acceleration or deceleration force which results from the reaction to the perceived information about the environment. Equation 2 presents the formulation of the differential equation of the social force model for the representation of the change in movement speed and direction for each individual. The movement speed of an individual is obtained by taking into account a total motivation force for each pedestrian *i*, $\vec{f}^{\,i}(t)$, and a fluctuation term, $\vec{\xi}^{i}$ (see Equation 1). The total motivation force in the first term adjusts the speed and direction by comparing the difference between the desired movement speed v_d^i and direction $\vec{e}^{\,i}$ against the actual movement speed and direction $\vec{v}_a^i$ within a certain relaxation time τ^i. The other terms adjust the pedestrian speed and direction to avoid collisions with other pedestrians *k* and obstacles *o* (see Equation 3).

$$\frac{d\vec{v}_a^i(t)}{dt} = \vec{f}^{\,i}(t) + \vec{\xi}^{i} \qquad (2)$$

$$\vec{f}^{\,i}(t) = \frac{1}{\tau^i}\left(v_d^i \vec{e}^{\,i} - \vec{v}_a^i\right) + \sum_{i(\neq k)} \vec{f}^{\,ik}(t) + \sum_i \vec{f}^{\,io}(t) \qquad (3)$$

Where:

v_d^i is the desired movement speed of an individual pedestrian *i*

v_a^i is the actual movement speed of an individual pedestrian *i*

t is time

ξ^i is the fluctuation for a pedestrian *i*

τ^i is the relaxation time for a pedestrian *i*

f are forces associated with an individual pedestrian *i* which may relate to other pedestrians *k* or obstacles *o*

7. EVACUATION MODEL RESULTS

Evacuation models allow the obtainment of a set of results which are useful for the performance of fire evacuation design. The key output of the model for Fire Safety Engineering applications is the total evacuation time, which corresponds to the Required Safe Egress Time. Evacuation models also provide the output corresponding to the evacuation time of each individual occupant of the building. This is often represented as a curve in which one axis includes the number of people progressively out of the building and the other axis their individual evacuation time. In the example in Fig. 3, 25 people are leaving a building in less than 125 s. The RSET or total evacuation time is equal to 121 s and the curve represents the evacuation time of all occupants of the building.

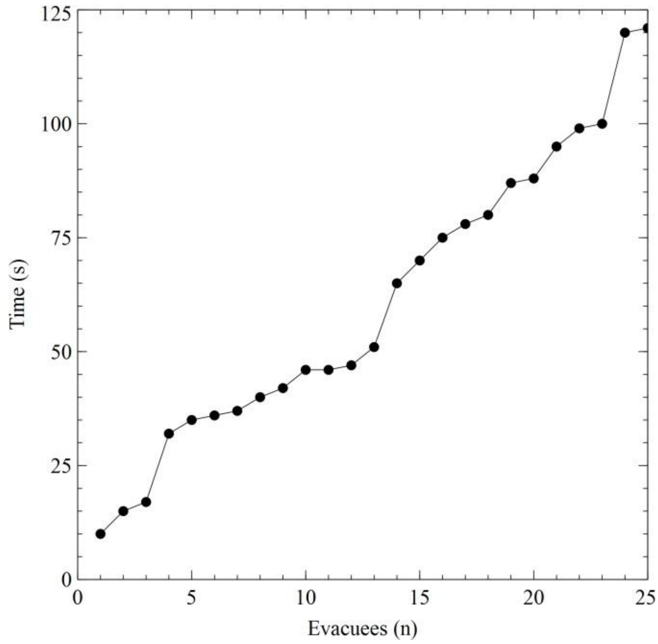

Fig. 3 – Example of occupant-evacuation time curve.

Additional outputs that can be obtained with an evacuation model include the prediction of the pedestrian congestion levels (i.e. bottlenecks within the building) in relation to different assumptions made in the scenarios (e.g. occupant load, route choice, etc.) and space usage in general (generally presented as people density or level of service). To some extent and depending on the model capabilities, evacuation models can also allow the prediction of other emergent behaviours (i.e. the interaction between people or the evacuation process as a function of the interaction with the environment [37]). Evacuation models may also allow to perform toxicity assessment in case of a combined simulation of fire and people movement. This is often performed using Purser's Fractional Effective Dose model (FED) [38]. This model relates the dose of toxic gas inhaled by different individuals over time with the dose of gas which is associated with incapacitation.

8. CONCLUSIONS

This short lecture notes have provided information about some of the basic concepts on human behaviour in fire and evacuation modelling. This document is by no means exhaustive and it is intended only as a first reading for people who are not familiar with the subject and are interested in an introductory reading on these topics.

9. QUESTIONS FOR STUDENTS

- Explain the misconception about the occurrence of panic in evacuation scenarios.
- Explain the difference between prescriptive-based and performance-based design from an evacuation design perspective.
- What is the Required Safe Escape Time (RSET)?
- Do evacuation models assume the occurrence of irrational behaviours? Explain why.
- Explain the concept of *Level of Service.*
- List and explain the results that can be obtained with an evacuation model.

10. REFERENCES

[1] E. Ronchi, "Disaster management: Design buildings for rapid evacuation," *Nature*, vol. 528, no. 7582, pp. 333–333, Dec. 2015.
[2] D. Helbing and P. Mukerji, "Crowd disasters as systemic failures: analysis of the Love Parade disaster," *EPJ Data Sci.*, vol. 1, no. 1, Dec. 2012.
[3] D. Gutierrez, B. Fricher, E. Cerezo, E. Sobreviela, and A. Gomez, "Virtual crowds in a digital Colosseum," *Virtual Retrosp.*, vol. 82, no. 2005, p. 87, 2005.
[4] G. K. Still, *Introduction to crowd science*. Boca Raton: CRC Press, 2013.
[5] B. Steffen and A. Seyfried, "Methods for measuring pedestrian density, flow, speed and direction with minimal scatter," *Phys. Stat. Mech. Its Appl.*, vol. 389, no. 9, pp. 1902–1910, May 2010.
[6] E. Ronchi *et al.*, "Evacuation travel paths in virtual reality experiments for tunnel safety analysis," *Fire Saf. J.*, vol. 71, pp. 257–267, Jan. 2015.
[7] S. Gwynne, K. Boyce, E. Kuligowski, E. Nilsson, A. Robbins, and R. Lovreglio, "Pros and cons of egress drills," presented at the Interflam, Royal Holloway College, UK, 2016.
[8] M. Kobes, I. Helsloot, B. de Vries, and J. G. Post, "Building safety and human behaviour in fire: A literature review," *Fire Saf. J.*, vol. 45, no. 1, pp. 1–11, Jan. 2010.
[9] E. D. Kuligowski, "Computer Evacuation Models for Buildings," in *SFPE Handbook of Fire Protection Engineering*, M. J. Hurley, D. T. Gottuk, J. R. Hall, K. Harada, E. D. Kuligowski, M. Puchovsky, J. L. Torero, J. M. Watts, and C. J. Wieczorek, Eds. New York, NY: Springer New York, 2016, pp. 2152–2180.
[10] B. J. Meacham, "An introduction to performance-based fire safety analysis and design with applications to structural fire safety," in *Building To Last*, 1997, pp. 529–533.
[11] R. F. Fahy, G. Proulx, and L. Aiman, "Panic or not in fire: Clarifying the misconception," *Fire Mater.*, vol. 36, no. 5–6, pp. 328–338, Aug. 2012.
[12] J. D. Sime, "The concept of panic," *Fires Hum. Behav.*, vol. 1, p. 5, 1980.

[13] C. Cocking, J. Drury, and S. Reicher, "The psychology of crowd behaviour in emergency evacuations: Results from two interview studies and implications for the Fire and Rescue Services," *Ir. J. Psychol.*, vol. 30, no. 1–2, pp. 59–73, Jan. 2009.
[14] J. Drury *et al.*, "Cooperation versus competition in a mass emergency evacuation: A new laboratory simulation and a new theoretical model," *Behav. Res. Methods*, vol. 41, no. 3, pp. 957–970, Aug. 2009.
[15] J. D. Sime, "Movement toward the Familiar: Person and Place Affiliation in a Fire Entrapment Setting," *Environ. Behav.*, vol. 17, no. 6, pp. 697–724, Nov. 1985.
[16] H. Tajfel and J. C. Turner, "The social identity theory of intergroup behavior.," 2004.
[17] M. Deutsch and H. B. Gerard, "A study of normative and informational social influences upon individual judgment.," *J. Abnorm. Soc. Psychol.*, vol. 51, no. 3, pp. 629–636, 1955.
[18] D. Tong and D. Canter, "The decision to evacuate: a study of the motivations which contribute to evacuation in the event of fire," *Fire Saf. J.*, vol. 9, no. 3, pp. 257–265, Aug. 1985.
[19] M. T. Kinateder, E. D. Kuligowski, P. K. Reneke, and R. D. Peacock, "A Review of Risk Perception in Building Fire Evacuation," National Institute of Standards and Technology, NIST TN 1840, Sep. 2014.
[20] S. M. V. Gwynne and A. L. E. Hunt, "Why model evacuee decision-making?," *Saf. Sci.*, Apr. 2018.
[21] S. M. V. Gwynne and E. R. Rosenbaum, "Employing the Hydraulic Model in Assessing Emergency Movement," in *SFPE Handbook of Fire Protection Engineering*, M. J. Hurley, D. T. Gottuk, J. R. Hall, K. Harada, E. D. Kuligowski, M. Puchovsky, J. L. Torero, J. M. Watts, and C. J. Wieczorek, Eds. New York, NY: Springer New York, 2016, pp. 2115–2151.
[22] V. M. Predtechenskii and A. I. Milinskii, *Planning for foot traffic flow in buildings*. Amerind Publishing, 1978.
[23] E. Ronchi and D. Nilsson, "Basic Concepts and Modelling Methods," in *Evacuation Modeling Trends*, A. Cuesta, O. Abreu, and D. Alvear, Eds. Cham: Springer International Publishing, 2016, pp. 1–23.
[24] D. A. Purser and M. Bensilum, "Quantification of behaviour for engineering design standards and escape time calculations," *Saf. Sci.*, vol. 38, no. 2, pp. 157–182, Jul. 2001.
[25] S. M. V. Gwynne, D. A. Purser, and D. L. Boswell, "Pre-Warning Staff Delay: A Forgotten Component in ASET/RSET Calculations," presented at the Pedestrian and Evacuation Dynamics, Gaithersburg, MD (US), 2011, pp. 243–253.
[26] C. Feliciani and K. Nishinari, "Empirical analysis of the lane formation process in bidirectional pedestrian flow," *Phys. Rev. E*, vol. 94, no. 3, Sep. 2016.
[27] I. Cłapa, M. Cisek, P. Tofiło, and M. Dziubiński, "Firefighters ascending and evacuation speeds during counter flow on staircase," *Saf. Sci.*, vol. 78, pp. 35–40, Oct. 2015.
[28] T. Sano, E. Ronchi, Y. Minegishi, and D. Nilsson, "A pedestrian merging flow model for stair evacuation," *Fire Saf. J.*, vol. 89, pp. 77–89, Apr. 2017.

[29] K. Bladström, “Route choice modelling in fire evacuation simulators,” *LUTVDG/TVBB*, 2017.
[30] D. Alvear, O. Abreu, A. Cuesta, and V. Alonso, “A new method for assessing the application of deterministic or stochastic modelling approach in evacuation scenarios,” *Fire Saf. J.*, vol. 65, pp. 11–18, Apr. 2014.
[31] E. Ronchi, P. A. Reneke, and R. D. Peacock, “A Method for the Analysis of Behavioural Uncertainty in Evacuation Modelling,” *Fire Technol.*, vol. 50, no. 6, pp. 1545–1571, Nov. 2014.
[32] E. T. Hall, *The hidden dimension*. Garden City, N.Y: Doubleday, 1982.
[33] J. J. Fruin, *Pedestrian Planning and Design*, (Revised Edition). Elevator World, Inc, Mobile, AL, 1987.
[34] Thunderhead Engineering, “Pathfinder - Technical Reference.” 2018.
[35] D. Helbing and P. Molnár, “Social force model for pedestrian dynamics,” *Phys. Rev. E*, vol. 51, no. 5, pp. 4282–4286, May 1995.
[36] T. Vicsek, A. Czirók, E. Ben-Jacob, I. Cohen, and O. Shochet, “Novel Type of Phase Transition in a System of Self-Driven Particles,” *Phys. Rev. Lett.*, vol. 75, no. 6, pp. 1226–1229, Aug. 1995.
[37] E. Ronchi, D. Nilsson, and S. M. V. Gwynne, “Modelling the Impact of Emergency Exit Signs in Tunnels,” *Fire Technol.*, vol. 48, no. 4, pp. 961–988, Apr. 2012.
[38] D. A. Purser, “Assessment of Hazards to Occupants from smoke, toxic gases and heat,” in *SFPE Handbook of Fire Protection Engineering (4th Edition)*, Quincy, MA (USA): Di Nenno P. J., 2008, pp. 2-96-2–193.