98/58

PERGAMON

Building and Environment 34 (1999) 741–749

BUILDING AND ENVIRONMENT

A review of the methodologies used in the computer simulation of evacuation from the built environment

S. Gwynne, E.R. Galea*, M. Owen, P.J. Lawrence, L. Filippidis

Fire Safety Engineering Group, Centre for Numerical Modelling and Process Analysis, University of Greenwich, London, U.K.

Received 26 February 1998; received in revised form 14 September 1998; accepted 7 October 1998

Abstract

Computer based analysis of evacuation can be performed using one of three different approaches, namely optimisation, simulation or risk assessment. Furthermore, within each approach different means of representing the enclosure, the population, and the behaviour of the population are possible. The myriad of approaches which are available has led to the development of some 22 different evacuation models. This article attempts to describe each of the modelling approaches adopted and critically review the inherent capabilities of each approach. The review is based on available published literature.

1. Introduction

As architects continue to implement novel concepts in building design, they are increasingly faced with the dilemma of demonstrating in some manner that their concepts are safe and that the occupants will be able to efficiently evacuate in the event of an emergency. Traditionally, two techniques have been used to meet these needs: (1) full-scale evacuation demonstration, and (2) the adherence to prescriptive building codes.

The full-scale evacuation demonstration involves staging an evacuation exercise using a representative target population within the structure. Such an approach poses considerable ethical, practical and financial problems that bring into question its viability.

The ethical problems concern the threat of injury to the participants and the lack of realism inherent in any demonstration evacuation scenario. As volunteers cannot be subjected to trauma or panic nor to the physical ramifications of a real emergency situation such as smoke, fire and debris, such an exercise provides little useful information regarding the suitability of the design in the event of a real emergency.

On a practical level, when evacuation drills are performed, usually only a single evacuation trial is undertaken. Thus there can be limited confidence that the test—whether successful or not—truly represents the evacuation capability of the structure. In addition, from a design point of view, a single test does not provide sufficient information to arrange the layout of the structure for optimal evacuation efficiency.

The need to perform repeated experiments should come as no surprise as even under the most controlled experimental conditions, no evacuation exercise involving crowds of real people will produce identical results if the exercise is repeated—even if the same people are used. Hence it is unwise to make definitive statements such as 'the evacuation time for the structure will be 187.7 s' on the basis of a simple one off experimental analysis. For any structure/population/environment combination, the evacuation performance of the combination is likely to follow some form of distribution, a purely hypothetical example of such a distribution is provided in Fig. 1 (readers should draw no inference from the actual shape of the depicted distribution). A single observation of evacuation performance could fall anywhere on the curve.

However, what can be achieved is an understanding of how the structure/population/environment system is likely to behave given a set of pre-defined conditions. Hence, for a given building configuration, specified type of occupancy and specific type of scenario, it is necessary to determine the range of evacuation performance likely to be achieved.

Finally, to perform a single full-scale evacuation demonstration can be expensive, if many such experiments need to be performed then the task can become prohibitively expensive. Furthermore, the evacuation demonstration is usually performed after the structure has

* Corresponding author. Tel.: +44 181 331 8730; fax: +44 181 331 8925

0360-1323/99/$ - see front matter
PII: S0360-1323(98)00057-2

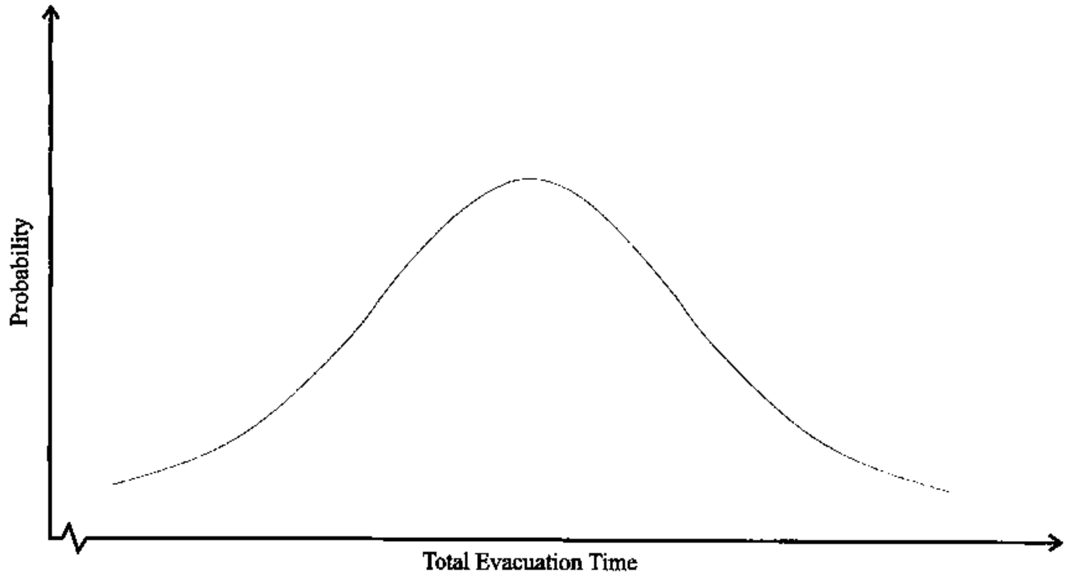

Fig. 1. Hypothetical distribution of the total evacuation time for a given structure/population/environment combination.

been constructed. Any design alterations that may be required will thus prove extremely expensive to implement.

Thus experimental means of assessing building design in a routine manner is undesirable. An alternative to evacuation demonstrations is simply to adhere to prescriptive building codes. Prescriptive building codes set out to accept/reject a proposed design on the basis of its adherence to a set of rigid regulations set down in the code.

However, in order to fully assess the potential evacuation efficiency of an enclosure, it is essential to address the configurational, environmental, behavioural and procedural aspects of the evacuation process (Fig. 2).

Configurational considerations are those generally covered by traditional building codes and involve building layout, number of exits, exit width, travel distance etc. In the event of fire, environmental aspects need to be considered. These include the likely debilitating effects on the building occupants of heat, toxic and irritant gases and the impact of increasing smoke density on travel speeds and way-finding capabilities. Procedural aspects cover the actions of staff, level of occupant evacuation training, occupant prior knowledge of the enclosure, emergency signage etc. Finally, and possibly most importantly, the likely behavioural responses of the occupants must be considered. These include aspects such as the occupants initial response to the call to evacuate, likely travel speeds, family/group interactions etc.

Traditional methods of building design fail to address all these issues in a quantitative manner preferring to rely almost totally on judgement and a set of prescriptive rules. As these prescriptive rules have an almost total reliance on configurational considerations such as travel-distance and exit width they can prove to be too restrictive. Furthermore, as these traditional prescriptive methods are insensitive to human behaviour or likely fire scenarios, it is unclear if they indeed offer the optimal solution in terms of evacuation efficiency.

Computer based evacuation models [1–31] offer the potential of overcoming all these shortfalls and addressing the needs not only of the designers but also the legislators in the emerging era of performance based building codes.

Research into quantifying and modelling human movement and behaviour has been underway for at least 30 years. This work has progressed down two routes, the first is concerned with the movement of people under normal non-emergency conditions. The second is concerned with the development of a capability to predict the movement of people under emergency conditions such as may result from the evacuation of a building subjected to a fire threat.

Some of the earliest work concerned with quantifying the movement of people under non-emergency conditions is that of Predtechenskii and Milinksii [32] and Fruin [33]. This research into movement capabilities of people in crowded areas and on stairs eventually lead to the development of movement models such as PEDROUTE [22–24].

Evacuation research is somewhat more recent, one of the earliest published papers appeared in 1982 and concerns the modelling of emergency egress during fires [34].

Attempts to simulate evacuation essentially fall into two categories of model, those which only consider human movement and those which attempt to link movement with behaviour.

The first category of model concentrates solely on the carrying capacity of the structure and its various components. This type of model is often referred to as a

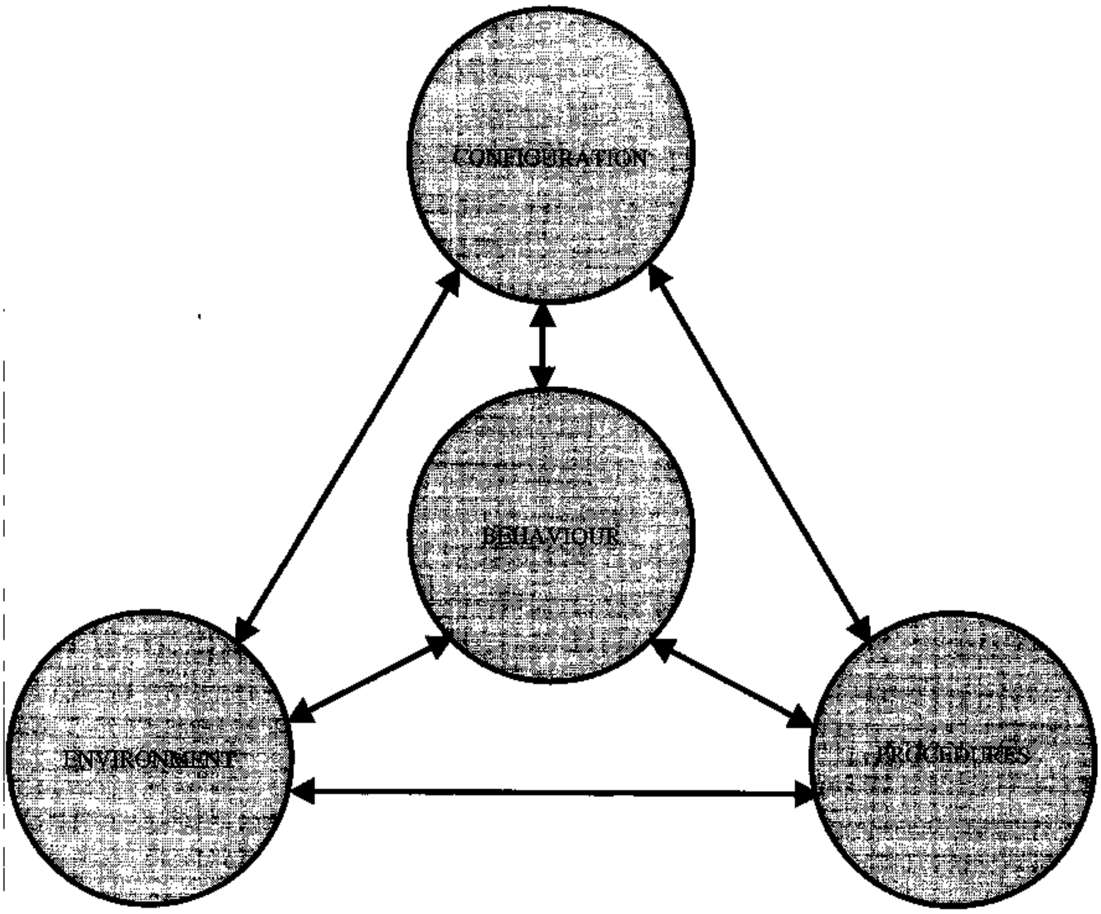

Fig. 2. The four main interacting aspects to be considered in the optimal design of an enclosure for evacuation.

'ball-bearing' model (also referred to as environmental determinism [35]) as individuals are treated as unthinking objects which automatically respond to external stimuli. In such a model, people are assumed to evacuate the structure, immediately ceasing any other activity. Furthermore, the direction and speed of egress is determined by physical considerations only (e.g., population densities, exit capacity, etc.). An extreme example of this type of model is one which ignores the population's individuality altogether and treats their egress en mass [28].

The second category of model takes into account not only the physical characteristics of the enclosure but treats the individual as an active agent taking into consideration his response to stimuli such as the various fire hazards and individual behaviour such as personal reaction times, exit preference etc. An example of this type of model is building EXODUS [7–12].

A variety of different modelling methodologies are available by which to represent these different categories of evacuation model. Within the modelling methodologies adopted, there are also a number of ways in which to represent the enclosure, population and the behaviour of the population. The myriad approaches which are available has led to the development of some 22 different evacuation models. To a certain extent the range of models reflects the purpose for which they were originally intended, the nature of the model developer (i.e., engineer/physical scientist/psychologist/architect) and the computer power available to the developers at the time of development.

In the following sections of this document an attempt is made to describe each of the modelling approaches and critically review the capabilities of the models represented by these approaches.

2. Evacuation models

A total of 22 evacuation models are described in this section. This includes 16 models which are currently available and six models known to be under development. The models are subdivided into sections concerning their approach and level of sophistication. Each model will be outlined, identifying their common methods and major components. The discussion focuses on their purpose (see Section 2.1), the method used to represent the enclosure (see Section 2.2), the population perspective adopted (see Section 2.3) and the behavioural perspective used (see Section 2.4).

To maximise clarity and brevity, the following key will be used throughout this section:

Models Currently Available:

BG = BGRAF [1]
C = CRISP [2,3]
DE = DONEGAN'S ENTROPY MODEL [4]
EG = EGRESS [5, 6]
EXO = EXODUS [7–12]
EP = E-SCAPE [13]
EV = EVACNET+ [14, 15]
ES = EVACSIM [16, 17]
E89 = EXIT89 [18]
E = EXITT [19, 20]
MG = MAGNETMODEL [21]
PP = PAXPORT [22–24]
S = SIMULEX [25–27]
TF = TAKAHASHI'S MODEL [28]
V = VEGAS [29, 30]
WO = WAYOUT [31]

The interrelationship between these various models is graphically illustrated in Fig. 3.

In addition to the above mentioned models, six other models are known to be at various stages of development at the time of writing [36-42]. To the best knowledge of the authors none of these models are generally available or fully implemented. Thus the information regarding these models is incomplete and so will not be discussed further.

2.1. Nature of model application

While all the models under consideration address the common problems of evacuation, they tackle this problem in three fundamentally different manners: that of optimisation, simulation, and risk assessment (Fig. 3). The underlying principles related with each of these approaches influences the associated model capabilities.

Several of the models assume the occupants evacuate in as efficient a manner as possible, ignoring peripheral and non-evacuation activities. The evacuation paths taken are considered optimal as are the flow characteristics of people and exits. These tend to be models which cater for a large number of people or who treat the occupants as a homogenous ensemble, therefore not recognising individual behaviour. These models are generally termed *optimisation* models {EV [14, 15], TF [28]}.

Alternatively, designers might attempt to represent the behaviour and movement observed in evacuations, not only to achieve acceptable quantitative results, but to realistically represent the paths and decisions taken during an evacuation. These models are termed *simulation* models {BG [1], DE [4], E [19, 20], EG [5, 6], EP [13], ES [16, 17], E89 [18], EXO [7–12], MG [21], PP [22–24],

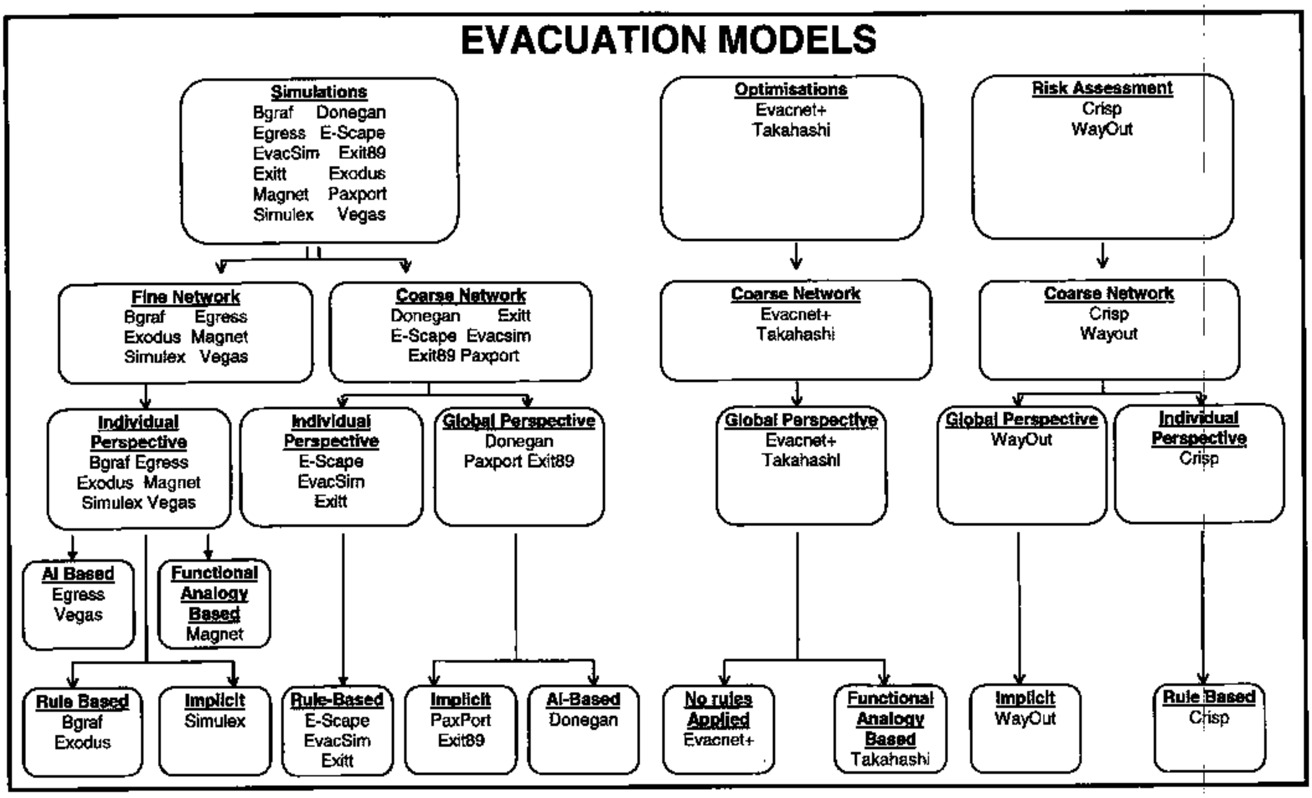

Fig. 3. Diagram representing evacuation methodologies.

S [25–27], V [29, 30]}. The behavioural sophistication employed by these models varies greatly, as does the accuracy of their results.

Risk assessment models {C [2, 3], WO [31]} attempt to identify hazards associated with evacuation resulting from a fire or related incident and attempt to quantify risk. By performing many repeated runs, statistically significant variations associated with changes to the compartment designs or fire protection measures, can be assessed.

2.2. Enclosure representation

In all models, the enclosure in which the evacuation takes place must be represented. Two methods are usually used to represent the enclosure: fine and coarse networks (Fig. 3). In each case, space is discretised into subregions, and each subregion is connected to its neighbours. The resolution of this subdivision distinguishes the two approaches.

Using the *fine network* approach {BG [1], EG [5, 6], EXO [7–12], MG [21], S [25–27], V [29, 30]} the entire floor space of the enclosure is usually covered in a collection of tiles or nodes. The size and shape of a node varies from model to model, for example EXODUS [7–12] typically uses 0.5×5 m square nodes, SIMULEX [25–27] uses 0.25×0.25 m squares, while EGRESS [5, 6] uses hexagonal nodes, of sufficient size to cater for a single occupant. The connectivity of the nodes also varies, in EXODUS [7–12] each node is connected to its eight neighbours, while SIMULEX [25–27] connects each node to its 16 neighbouring nodes and in EGRESS [5, 6] each node is connected to its six neighbours.

A large geometry, comprising of many compartments, may be made up of thousands of nodes. In this way, it is possible to accurately represent the geometry, and its internal obstacles, and accurately locate each individual at any time during the evacuation.

In the *coarse network* approach {C [2, 3], DE [4], E89 [18], E [19, 20], EP [13], ES [16, 17], EV [14, 15], PP [22–24], TF [28], WO [31]}, the geometry is defined in terms of partitions derived from the actual structure. Thus each node may represent a room or corridor irrespective of its physical size. Nodes are connected by arcs representing actual connectivity within the structure. In such a model, occupants move from segment to segment, and their precise position is less defined than in the fine network models. An occupant might therefore move from room to room instead of from one area inside a room, to another.

This presents difficulties when incorporating local movement and navigation including overtaking, the resolution of local conflicts, and obstacle avoidance. This is because the exact location of an individual is not represented, and therefore detailed calculations of individual movement, and the interaction between individuals cannot be made.

This limitation should be kept in mind when examining the behavioural models, especially those of EVACSIM [16, 17], CRISP [2, 3] and E-Scape [13], which claim to have sophisticated behavioural models.

In summary, fine networks are more able to accurately represent an enclosure than an equivalent coarse network. However, coarse networks have advantages in the ease of representation and the speed of computation. The difference between fine and coarse network models becomes increasingly indistinguishable when the evacuating population is treated as a homogenous ensemble (see Section 2.3).

2.3. Population perspectives

The enclosure population, as with the geometry, can be represented in one of two approaches: an individual or global perspective (Fig. 3). Most models allow for personal attributes to be assigned either by the user, or through a random device. These personal attributes are then used in the movement and decision-making process of that individual. This process is typically independent of other occupants involved in the simulation, and allows for the individual trajectories/histories to be followed. The models that are based on this *individual perspective* {BG [1], C [2, 3], E [19, 20], EG [5, 6], EP [13], ES [16, 17], EXO [7–12], MG [21], S [25–27], V [29, 30]} can then represent a diverse population, with different internal traits, whose evacuation, in some manner, relies on these traits. It is important here not to confuse independent decision-making with an inability to implement group behaviour. The definition of individual occupants does not preclude group behaviour, but examines each occupant individually, and then allocates an action, that might be a group behaviour.

Other models {DE [4], E89 [18], EV [14, 15], PP [22–24], TF [28], WO [31]} do not recognise the individual, but delineate a population as an homogenous ensemble (or a grouping), without different identities, thereby adopting a *global perspective*. These models represent evacuation details not on the basis of which individual escaped, but on the numbers of occupants who escaped. This approach may be beneficial in both the management and the speed of the models, but lacks much of the detail available to the individual perspective.

This approach presents difficulties in modelling the effects of events on individual occupants (the effect of toxic fire gases, for instance). Only a distributed, or average effect can be established throughout the population. This provides no indication, for example, of the survival rates of specific groups of individuals, such as the elderly or the disabled, but instead, only that of the proportion of the population that had been affected.

This problem would arise for a number of other evacuation factors including any individual attribute, communication, individual responses to cues, and the interactions of an individual or subgroup with the rest of the population. This deficiency may not be considered as serious in completely uniform populations, but in more conventional situations, it would seriously hinder an accurate understanding of the behaviour of the population.

2.4. Behavioural perspective

To represent the decision-making process employed by occupants in an evacuation, the model must involve an appropriate method to simulate occupant behaviour. Obviously, the behavioural perspective adopted, will be influenced by the population and geometry approaches taken, and as such is possibly the most complex of all the defining aspects.

Broadly speaking, the models investigated can be separated into the following five behavioural systems (Fig. 3):

- No Behavioural Rules—{EV [14, 15]},
- Functional Analogy Behaviour—{MG [21], TF [28]},
- Implicit Behaviour—{E89 [18], PP [22–24], S [25–27], WO [31]}
- Rule Based Behavioural System—{BG [1], C [2, 3], E [19, 20], EP [13], ES [16, 17], EXO [7—12]}
- Artificial Intelligence Based Behavioural System–{DE [4], EG [5, 6], V [29, 30]}.

Models that apply no behavioural rules {EV [14, 15]} rely completely on the physical movement of the population and the physical representation of the geometry, to influence and determine the occupant evacuation. In these models, decisions are made only on the basis of physical influences.

Functional Analogy Behavioural models {MG [21], TF [28]}, apply an equation, or set of equations, to the entire population, that completely governs the population's response. Although it is possible for the population to be defined individually in these models, all the individuals are affected in the same way by this function, and therefore will react in a deterministic manner to its influences, undermining individual behaviour. This function is not necessarily derived from real-life occupant behaviour, but is instead taken from another field of study which is assumed to be analogous to human behaviour, (e.g., the functions which drive the Magnetic model [21] were taken from Physics). Occupant movement and behaviour is then completely determined by this function, which may or may not have been previously calibrated with human movement.

Some models do not declare behavioural rules, but instead assume them to be implicitly represented through the use of complicated physical methods {E89 [18], PP [22–24], S [25–27], WO [31]}. These models might be based on the application of secondary data, which incorporates psychological or sociological influences. These models therefore rely upon the validity and accuracy of this secondary data.

Models which explicitly recognise the behavioural traits of individual occupants, usually apply a rule based system {BG [1], C [2, 3], E [19, 20], EP [13], ES [16, 17], EXO [7–12]}. This allows for decisions to be taken by occupants, according to pre-defined sets of rules. These rules can be triggered in specific circumstances, and in such circumstances, have an effect. For instance, a rule may be:

> If I am in a smoke filled room, I will leave through the nearest available exit.

A problem with this style of decision-making process is that in simplistic methods {E [19, 20]} the same decisions are taken under the same circumstances, in a deterministic fashion. This has the disadvantage of denying the possibility of natural variations in outcomes through repetition. Most of the rule-based models {BG [1], C [2, 3], EP [13], ES [16, 17]} are stochastic. However, Exodus {EXO [7–12]} incorporates a contribution of both deterministic and stochastic approaches, depending on the circumstances.

Recently, artificial intelligence has been applied to behavioural models {DE [4], EG [5, 6], V [29, 30]}, where individual occupants are designed to mimic human intelligence, or an approximation of it, in respect to the surrounding environment.

In general, the behaviour which can be expected in evacuations has a complex relationship with the surroundings. An individual may be involved in three types of interaction during an evacuation, all of which are associated with complex decisions. These encounters may be categorised as:

People–People Interactions—interactions with other occupants.
People–Structure Interactions—interactions with the enclosing structure.
People–Environment Interactions—interactions with the fire effected atmosphere, and possible debris.

These interactions effect an occupants movement, and therefore trigger the decision making process. This process is further complicated by the way in which this interaction takes place. This may occur on three levels:

Psychological—A response based upon the information available to an occupant given the profile and experience of the occupant. An interaction of this type under a fire threat, might entail an occupant rearing away from the fire, or the occupant's response to the call to evacuate
Sociological—A response based on the interaction of the occupant with other occupants. An interaction of

this type under a fire threat might cause an occupant to instigate a rescue, or alert other occupants

Physiological—A physical reaction to the surrounding environment which in some way affects the capabilities of the occupant. An interaction of this type under a fire threat may, result in intoxication due to narcotic fire gases or irritation to the sensory and respiratory organs due to the presence of irritant gases.

As identified earlier, human behaviour is the most complex and difficult aspect of the evacuation process to simulate. No model to date fully addresses all the identified behavioural aspects of evacuation. Furthermore, not all these behavioural aspects are fully understood, or quantified. For a more thorough discussion of the behavioural perspective, interested readers are referred to [43]. However, several models have attempted to incorporate a number of these behavioural interactions. The models discussed in this article have been categorised according to the approaches adopted to represent the geometry, population and occupant behaviour. Figure 3 is a graphical representation of this categorisation.

3. Discussion

It has become apparent during this examination, that there is a trend towards models which include greater behavioural detail. The impact of these developments is strongly dependent upon the methods employed by the models to represent both the enclosure, and the population perspective.

The success of those models employing extensive behavioural features are tempered by the use of a coarse network, or through the representation of the population as a homogenous group. Both approaches make the description of the effect of events on members of the population far more vague, and more difficult to analyse. Those models which currently appear most promising in accurately describing evacuation behaviour, employ a fine node network, and are capable of identifying individual members of the population (e.g., building EXODUS [7–12], Egress [5, 6], Simulex [25–27]). By doing so, they are able to produce sophisticated behaviours, and are then capable of distinguishing where these behavioural events take place, and which members of the population are involved.

In terms of software usability, the development of graphical interfaces has vastly improved the ability of the user to fully understand the activities of the model population, as well as simplifying the process of developing evacuation scenarios. The ability to view the simulation reveals qualitative features of the evacuation which otherwise would be lost. Furthermore, it may be possible to generate 'correct' evacuation times while not 'correctly' predicting the behaviour of the occupants. A graphical run-time interface or post-processor visualiser allows these features to be examined. In addition, the specification and design of the evacuation scenario will be greatly assisted through a well designed graphical interface. However, irrespective of the level of sophistication of the graphical user interface, the evacuation model is only a tool to be used to aid the engineer in exploring the dynamics of the evacuation scenario. It does not replace good engineering practice.

The overall usefulness of the evacuation model to design engineers is also dependent on the computational cost of performing the simulations. As each scenario is typically run several times and many scenarios may be considered, the simulation speed limits the number of cases that can effectively be performed. Often information concerning typical model run-times is not provided. If this in an oversight, it is unfortunate as this is an important consideration for a potential user.

A number of evacuation models omit a comprehensive description of occupant behaviour or limit the model to a small number of people. The justification used by several developers concern the limitations of computer technology. However, with the increase of processor power and the memory capacity of modern PC computing, models are now available which can simulate large populations, and include complex behavioural attributes which begin to address the complex interactions of structure, environment, human behaviour and procedures. Another fundamental problem with a number of models, related to this, is the inconsistency with which they treat areas of the evacuation process. A number of the models give a disproportionate amount of weight to one particular area of the evacuation process, to the detriment of others. For models to be effective, it is important that they are consistent in their treatment of evacuation factors, and utilise the available technology to its greatest effect.

The single most important feature which all of the models examined lack is a convincing battery of validation comparisons. For the most part this is due to a general lack of data suitable for validation purposes. To a certain extent this problem is shared with another branch of fire safety engineering, that of fire modelling.

The problems associated with developing an evacuation data base suitable for validation purposes are many. Evacuation performance is dependent on many parameters including:

- Physical nature of the enclosure (size, number of rooms, number of floors, number of exits size of exits, presence of obstacles, presence of stairs, etc.),
- Function of the enclosure (offices, hospital, prison, school, theatre, etc.),
- Nature of the population (number of people, age/gender distribution, inter-relationships, physical attribute distribution, familiarity with structure, roles, etc.),
- Nature of the environment (night/day, seasonal, debris, signage, smoke, heat, toxic gases, irritant gases, etc.).

The variability of human behaviour compounds these problems making repeatability of experiments an issue. It is thus vital that an understanding be developed of the role different forms of validation (e.g., qualitative, quantitative, functional) have to play in the general acceptability of these models [44].

Until a systematic and graduated approach to validation is adopted by the international fire safety community, this will remain the single most important issue impeding both the development and wide scale acceptance of evacuation models.

Finally, this article is a summary of a more detailed report [45] produced by the authors. For a more thorough description of the 22 models described in this article please refer to [45].

4. Conclusions

Since the first computer based evacuation model appeared some 17 years ago, great advances have been made both in our understanding of human response to emergence evacuation situations and in our attempts to model this response. This article has been an attempt at compiling and examining the available evacuation modelling strategies. As such, the report contains a discussion of some 22 evacuation models. Any omissions which may have occurred are due to the difficulty in obtaining relevant information, or through the appearance of information too late to be included in this publication. The authors apologise in advance for any such omission.

Broadly speaking, models that simulate evacuation tackle this problem in three fundamentally different manners, that of optimisation, simulation, and risk assessment. The underlying principles associated with each of these approaches influences the models' capabilities. Whichever approach is adopted, it is essential that the enclosure geometry, population and population behaviour be modelled. Each of these aspects can be modelled using one of several approaches.

The enclosure in which the evacuation takes place can be represented by one of two methods, namely fine and coarse networks. The enclosure population, as with the geometry, can be represented in one of two approaches using an individual or global perspective. To represent the decision-making process employed by the occupants, the model must incorporate an appropriate method for determining behaviour. The behavioural perspective adopted is influenced by the population and geometry approaches taken, and as such is the most complex of all the defining aspects. Broadly speaking, the models discussed in this article can be separated into one of five behavioural systems.

However, no model to date fully addresses all the identified behavioural aspects of evacuation. Furthermore, not all these behavioural aspects are fully understood, or quantified. This is not to say that evacuation models cannot be used in practice. As with any computer model, a thorough understanding of the principles upon which the model is based is required before any meaningful application can be attempted.

Acknowledgements

Mr Gwynne would like to thank the University of Greenwich for their financial support through the PhD Bursary programme. Professor Galea is indebted to the UK CAA for their financial support of his chair in Mathematical Modelling.

References

[1] Ozel F. Simulation modeling of human behaviour in buildings. Simulation 1992;June:377–84.
[2] Fraser-Mitchell JN. An Object-Oriented Simulation (CRISPII) for Fire Risk Assessment. In: Kashiwaga T. editor. Proceedings of the Fourth International Symposium of Fire Safety Science, 1994. pp. 793–804.
[3] Fraser-Mitchell JN. The Lessons Learnt During The Development of CRISPII, A Monte Carlo Simulation For Fire Risk Assessment. In: Franks C, Grayson S, editors. Proceedings of the Seventh International Fire Science and Engineering Conference, Interflam '96, 1996. pp. 631–9.
[4] Donegan HA, Pollock AJ, Taylor IR. Egress Complexity of a Building. In: Kashiwagi TL, editor. Proceedings of Fourth International Symposium on Fire Safety Science, 1994. pp. 601–12.
[5] Ketchell N, Cole SS, Webber DM. The EGRESS Code for Human Movement and Behaviour in Emergency Evacuation. In: Smith RA, Dickie JF, editors. Engineering for Crowd Safety, Elsevier, 1993. pp. 361–70.
[6] Ketchell N. Evacuation Modelling: A New Approach. In: Chow WK, et al., editors. Proceeding for the International Conference on Fire Science and Engineering, ASIAFLAM '95, 1995. pp. 499–505.
[7] Owen M, Galea ER, Lawrence PJ, The Exodus Evacuation Model Applied to Building Evacuation Scenarios. J of Fire Protection Engr 1996;8(2):65–86.
[8] Owen M, Galea ER, Lawrence PJ. Advanced Occupant Behavioural Features Of The building EXODUS Evacuation Model. In: Hasemi Y, editor. Proceedings of the fifth International Symposium IAFSS, Melbourne Australia, 1997. pp 795–806.
[9] Galea ER, Galparsoro JMP. EXODUS: An Evacuation Model For Mass Transport Vehicles. Fire Safety Journal 1994;22:341–66.
[10] Galea ER, Owen M. Emergency Egress From Large Buildings Under Fire Conditions Simulated Using The EXODUS Evacuation Model. In: Franks C, Grayson S, editors. Proceedings of the Seventh International Fire Science and Engineering Conference, Interflam '96, 1996. pp. 711–20.
[11] Gwynne S, Galea ER, Lawrence PJ, Owen M, Filipidis L. Further Validation of the building EXODUS Evacuation Model Using the Tsukuba Dataset. CMS Press, Paper No. 98/IM/31, 1998.
[12] Gwynne S, Galea ER, Lawrence PJ, Owen M, Filipidis L. Validation of the building EXODUS model. CMS Press, Paper No. 98/IM/29, 1998.
[13] Reisser-Weston E. Simulating Human Behaviour in Emergency Situation, RINA, International Conference of Escape, Fire and Rescue, 19/20 Nov 1996.
[14] Kisko TM, Francis RL. EVACNET+: A Computer Program to

Determine Optimal Evacuation Plans. Fire Safety Journal 1985;9:211–20.

[15] Taylor IR. A Revised Interface for Evacnet+. In: Franks C, Grayson S, editors. Proceedings of the Seventh International Fire Science and Engineering Conference, InterFlam '96, 1996. pp. 1010–17.

[16] Poon LS, Beck VR. EVACSIM: Simulation Model of Occupants with Behavioural Attributes in Emergency Evacuation of High Rise Buildings. In: Kashiwagi TL, editor. Proceedings of Fourth International Symposium on Fire Safety Science, 1994. pp. 681–92.

[17] Poon LS. Numerical Modelling Of Human Behavour During Egress In Multi-Storey Office Building Fires Using Evacsim—Some Validation Studies. In: Chow WK, et al., editors. Proceedings for the International Conference on Fire Science and Engineering, ASIAFLAM '95, 1995. pp. 163–74.

[18] Fahy RF. An Evacuation Model for High Rise Buildings. In: Cox G, Langford B, editors. Proceedings of the Third International Symposium on Fire Safety Science, Elsevier, London, 1991. pp. 815–23.

[19] Levin B. EXITT, A Simulation Model of Occupant Decisions and Actions in Residential Fires. In: Wakamatsu T, Hasemi Y, Seizawa A, Seeger P, Pagni P, Grant C, editors. Proceedings of the Second International Symposium on Fire Safety Science, 1989. pp. 561–70.

[20] Levin BM. EXITT-A Simulation Model of Occupant Decision and Actions in Residential Fires: User's Guide and Program Description. NBSR 87-3591, National Bureau of Standards, Gaithersburg, MD, 1987.

[21] Okasaki S, Matsushita S. A Study Of Simulation Model For Pedestrian Movement With Evacuation And Queuing. Engineering For Crowd Safety. In: Smith RA, Dickie JF, editors. Elsevier, 1993. pp. 271–80.

[22] Barton J, Leather J. Paxport—Passenger And Crowd Simulation. Passenger Terminal '95 1995:71–7.

[23] Bulman E, Clifford P. Customer Service. Interchangeable? Passenger Terminal World 1995:18–23.

[24] Buckmann LT, Leather JA. Modelling Station Congestion the PEDROUTE Way. Traffic Engineering and Control 1994;35(6):373–7.

[25] Thompson P, Marchant E. A Computer Model for the Evacuation of Large Building Populations. Fire Safety Journal 1995;24:131–48.

[26] Thompson P, Marchant E. Simulex; Developing New Computing Modelling Techniques For Evaluation. In: Kashiwagi T, editor. Proceedings of the Fourth International Symposium on Fire Safety Science, 1994. pp. 613–24.

[27] Thompson P, Wu, Marchant E. Modelling Evacuation In Multi-Storey Buildings With Simulex. Fire Engineers Journal 1996;November:7–11.

[28] Takahashi K, Tanaka T, Kose S. A Evacuation Model For Use In Fire Safety Design Of Buildings. In: Wakamatsu T, Hasemi Y, Seizawa A, Seeger P, Pagni P, Grant C, editors. Proceedings of the Second International Symposium on Fire Safety Science, Hemisphere, 1989. pp. 551–60.

[29] Still K. New computer system can predict human response to building fires. FIRE 84 1993;January:40–1.

[30] Still GK. Simulating Egress Using Virtual Reality—A Perspective View Of Simulation And Design. Paper 25, IMAS 94, Fire Safety on Ships 26–27 May 1994.

[31] Shestopal VO, Grubits SJ. Evacuation Model For Merging Traffic Flows In Multi-Room And Multi-Storey Buildings. In: Kashiwagi T, editor. Proceedings of the Fourth International Symposium on Fire Safety Science, 1994. pp. 625–32.

[32] Predtechenskii VM, Milinskii AI. Planning for Foot Traffic Flow in Buildings. Published for the National Bureau of Standards, Amerind Publishing Co., 1978, translated from the Russian publication which appeared in 1969, STROIZDAT Publishers, Moscow, 1969.

[33] Fruin JJ. Service Pedestrian Planning and Design. MAUDEP 1971, reprinted 1987.

[34] Stahl F. BFIRES-II: A behaviour based computer simulation of emergency egress during fires. Fire Technology 1982;18:49–65.

[35] Sime J. Human Behaviour in Fires Summary Report. CFBAC Report No.450, Portsmouth Polytechnic, 1992.

[36] Bradley GE. A Proposed Mathematical Model For Computer Prediction Of Crowd Movement And Their Associated Risks. In: Smith RA, Dickie JF, editors. Engineering for Crowd Safety, Elsevier, 1993. pp. 303–13.

[37] Court MC, Marcus JH. Use Of Object Oriented Programmming To Simulate Human Behaviour In Emergency Evacution Of An Aircraft's Passenger Cabin. AGARD-CP-587, Proceedings of NATO AGARD PEP 88th Meeting on Aircraft Safety, Dresden, October, 1996. pp. 34–1 to 34–7.

[38] Lo SM, Will B. An Approximate Analysis Method Of Perceptual Reaction For Emergency Behaviour. In: Chow WK, et al., editors. Proceedings for the International Conference on Fire Science and Engineering, ASIAFLAM '95, March 1995. pp. 151–62.

[39] Lo SM. Modelling And Simulation Of Wayfinding Process Under Fire Emergencies In Complex Buildings Using Systems Dynamics Approach. In: Franks C, Grayson S, editors. Proceedings for the Seventh International Fire Science and Engineering Conference Interflam '96, 1996. p. 721–30.

[40] Proulx G, Hadjisophocleous G. Occupant Response Model: A Sub-Model For The NRCC Risk-Cost Assessment Model. In: Kashiwagi T, editor. Proceedings for the Fourth International Symposium on Fire Safety Science, 1994. p. 841–52.

[41] Saunders WL. A Model Of Occupant Decision Making In Office Building Fire Emergencies. In: Chow WK, editors. Proceedings for the International Conference on Fire Science and Engineering, ASIAFLAM '95, March 1995. p. 139–50.

[42] Burns JR, Morgenson JD. An Object Oriented World-View For Intelligent, Discrete, Next-Event Simulation. Management Science 1995;34(12):1425–40.

[43] Gwynne S, Galea ER. Escape As a Social Response. CMS Press, Paper No. 97/IM/26, 1997.

[44] Galea ER. Validation of Evacuation Models. CMS Press, Paper No. 97/IM/22, 1997.

[45] Gwynne S, Galea ER. A Review of the Methodologies and Critical Appraisal of Computer models used in the Simulation of Evacuation from the Built Environment. CMS Press, Paper No. 97/IM/21, 1997.