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# A Review of the Methodologies Used in Evacuation Modelling

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Computer based analysis of evacuation can be performed using one of three different approaches, namely optimization, simulation and 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 that are available has led to the development of some 22 different evacuation models. This review 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. Copyright © 1999 John Wiley & Sons, Ltd.

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## INTRODUCTION

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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. Increasingly, computer based evacuation models<sup>1–31</sup> are being used to address 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 along 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<sup>32</sup> and Fruin.<sup>33</sup> This research into movement capabilities of people in crowded areas and on stairs eventually led to the development of movement models such as PED-ROUTE.<sup>22–24</sup>

Evacuation research is somewhat more recent, one of the earliest published papers appeared in 1982 and concerns the modelling of emergency egress during fires.<sup>34</sup> Attempts to simulate evacuation essentially fall into two categories of model, those that only consider human movement and those that 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 'ball-bearing' model (also referred to as environmental determinism<sup>35</sup>) as individuals are treated as unthinking objects that automatically respond to external stimuli. In such a model, people are assumed to evacuate the struc-

ture, 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 that ignores the population's individuality altogether and treats their egress en masse.<sup>28</sup>

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.<sup>7–12</sup>

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 variety of these approaches 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.

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## EVACUATION MODELS

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A total of 22 evacuation models are described in this section. This includes 16 models that are currently available and 6 models known to be under development. The available 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, the method used to represent the enclosure, the population perspective adopted and the behavioural perspective used.

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

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

In addition to the above mentioned models, six other models are known to be at various stages of development at the time of writing.<sup>36-42</sup> 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.

### 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 optimization, simulation, and risk assessment. The underlying principles related to 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 those models that treat the occupants as a homogenous ensemble, therefore not recognizing individual behaviour. These models are generally termed *OPTIMIZATION* models (EV,<sup>14,15</sup> TF<sup>28</sup>).

Alternatively, designers might attempt to represent the behaviour and movement observed in evacuations, not only to achieve accurate results, but to realistically represent the paths and decisions taken during an evacuation. These models are termed *SIMULATION* models (BG,<sup>1</sup> DE,<sup>4</sup> E,<sup>19,20</sup> EG,<sup>5,6</sup> EP,<sup>13</sup> ES,<sup>16,17</sup> E89,<sup>18</sup> EXO,<sup>7-12</sup> MG,<sup>21</sup> PP,<sup>22-24</sup> S,<sup>25-27</sup> V<sup>29,30</sup>). The behavioural sophistication employed by these models varies greatly, as does the accuracy of their results.

*RISK ASSESSMENT* models (C,<sup>2,3</sup> WO,<sup>31</sup>) attempt to identify hazards associated with evacuation resulting from a fire or related incident and attempt to quantify the resultant risk. By performing many repeated runs, statistically significant variations associated with changes to the compartment designs or fire protection measures, can be assessed.

### 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. In each case, space is discretized 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,<sup>1</sup> EG,<sup>5,6</sup> EXO,<sup>7-12</sup> MG,<sup>21</sup> S,<sup>25-27</sup> V,<sup>29,30</sup>) 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<sup>7-12</sup> typically uses 0.5 m × 0.5 m square nodes, SIMULEX<sup>25-27</sup> uses 0.2 m × 0.2 m squares, while EGRESS<sup>5,6</sup> uses hexagonal nodes, of sufficient size to cater for a single occupant. The connectivity of the nodes also varies, in EXODUS<sup>7-12</sup> each node is connected to its eight neighbours, while EGRESS<sup>5,6</sup> connects each node to its six neighbours and SIMULEX,<sup>25-27</sup> while possessing variable connectivity, typically connects each node to its 16 neighbours. A large geometry, comprising 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. The fine network approach, taken to its logical extreme, would eventually encompass a coordinate based representation. Some models (e.g. SIMULEX) use a combination of both fine networks and coordinate systems; the coordinate system being used for some purposes (e.g. defining the building fabric) and the fine network being used for others (e.g. calculating travel distances).

In the *COARSE NETWORK* approach (C,<sup>2,3</sup> DE,<sup>4</sup> E89,<sup>18</sup> E,<sup>19,20</sup> EP,<sup>13</sup> ES,<sup>16,17</sup> EV,<sup>14,15</sup> PP,<sup>22-24</sup> TF,<sup>28</sup> WO<sup>31</sup>), 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 one architectural construct to another, 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 the detailed calculation of individual movement, and the interaction between individuals are difficult to express. This limitation should be kept in mind when examining the behavioural component of the various 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.

### Population perspectives

The enclosure population, as with the geometry, can be represented in one of two approaches: an individual or global perspective. 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,<sup>1</sup> C,<sup>2,3</sup> E,<sup>19,20</sup> EG,<sup>5,6</sup> EP,<sup>13</sup> ES,<sup>16,17</sup> EXO,<sup>7-12</sup> MG,<sup>21</sup> S,<sup>25-27</sup> V<sup>29,30</sup>) 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,<sup>4</sup> E89,<sup>18</sup> EV,<sup>14,15</sup> PP,<sup>22-24</sup> TF,<sup>28</sup> WO<sup>31</sup>) do not recognize 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 serious in simple, homogenous populations, but in more realistic situations, it would seriously hinder an accurate understanding of the behaviour of the population.

### Behavioural perspective

To represent the decision-making process employed by occupants in an evacuation, the model must involve an appropriate method in determining 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:

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

Models that apply no behavioural rules EV<sup>14,15</sup> 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,<sup>21</sup> TF,<sup>28</sup> 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 might instead be taken from another field of study which is assumed to be analogous to human behaviour, (e.g. the functions which drive the Magnetic model<sup>21</sup> 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,<sup>18</sup> PP,<sup>22-24</sup> S,<sup>25-27</sup> WO<sup>31</sup>). 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 recognize the behavioural traits of individual occupants, usually apply a rule based system BG,<sup>1</sup> C,<sup>2,3</sup> E,<sup>19,20</sup> EP,<sup>13</sup> ES,<sup>16,17</sup> EXO.<sup>7-12</sup> 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<sup>19,20</sup> 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,<sup>1</sup> C,<sup>2,3</sup> EP,<sup>13</sup> ES<sup>16,17</sup> are stochastic. However, Exodus EXO<sup>7-12</sup> incorporates a contribution of both deterministic and stochastic approaches, depending on the circumstances.

Recently, artificial intelligence has been applied to behavioural models DE,<sup>4</sup> EG,<sup>5,6</sup> V,<sup>29,30</sup> where individual occupants are designed to mimic human intelligence, or an approximation of it, in respect to the surrounding environment. This allows the more accurate representation of the decision-making process, but removes a degree of user-control over the simulated occupants.

In general, the behaviour that 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 categorized as:

**People-people** interactions, i.e. interactions with other occupants.

**People-structure** interactions, i.e. interactions with the enclosing structure.

**People-environment** interactions, i.e. interactions with the fire effected atmosphere, and possible debris.

These interactions affect an occupant's behaviour, and therefore trigger the decision making process. This

process is further complicated by the way in which the occupants interact with their surroundings. 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 veering 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 effects 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. However, several models have attempted to incorporate a number of these behavioural interactions. The models discussed in this paper have been categorized according to the approaches adopted to represent the geometry, population and occupant behaviour. For a more thorough discussion of the behavioural perspective, interested readers are referred to Gwynne and Galea.<sup>43</sup>

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## DISCUSSION

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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 that currently appear most promising in accurately describing evacuation behaviour, employ a fine node network, and are capable of identifying individual members of the population. 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 'accurate' evacuation times while not 'realistically' predicting the behaviour of the occupants. A graphical run-time interface or post-processor visualizer 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. The variability of human behaviour compounds this problem 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.<sup>11,12</sup>

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 paper is a summary of a more detailed report<sup>44</sup> produced by the authors.

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## CONCLUSIONS

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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

emergency evacuation situations and in our attempts to model this response. This paper has been an attempt at compiling and examining the available evacuation modelling strategies. As such, the paper contains a discussion of some 22 evacuation models. Any omissions that 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 optimization, simulation, and risk assessment. The underlying principles associated with each of these approaches influence 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 paper can be separated into one of five behavioural systems. However, irrespective of the behavioural model implemented, no evacuation 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.

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