The Introduction of Adaptive Social Decision-Making in the Mathematical Modelling of Egress Behaviour
(Volume II)

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A thesis submitted in partial fulfilment of the requirements of the University of Greenwich for the Degree of Doctor of Philosophy

January 2000

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NOMENCLATURE

Below is a list of commonly used terms and their description.

Symbol	Meaning
$\| \|_2$	Euclidean Norm
$[x, y]$	Positional Vector
$\sum$	Summation Of Indicated Terms
ρ	Density
ε	Random Variable
/m	Per Metre
A_i	Exit Attractiveness
A_{max}	Maximum Exit Attractiveness
CoHb	Carboxyhaemoglobin
CWT	Cumulative Wait Time (seconds)*
d	Distance (m)
D_i	Occupant Motivation *
D_{max}	Maximum Occupant Motivation *
f	Occupant Flow (p/m/s)
FED	Fractional Effective Dose
FIC	Fractional Irritant Concentration
FIC_{HBr}	Fractional Irritant Concentration For Hydrogen Bromide
FIC_{HCl}	Fractional Irritant Concentration For Hydrogen Chloride
FIC_{HF}	Fractional Irritant Concentration For Hydrogen Fluoride
FIC_{NO2}	Fractional Irritant Concentration For Nitrogen Dioxide
FICO	Fractional Incapacitation Dose For Carbon Monoxide
FIC_{Org}	Fractional Irritant Concentration For Organic Gases
FIC_{SO2}	Fractional Irritant Concentration For Sodium Dioxide
FIHCN	Fractional Incapacitation Dose For Hydrogen Cyanide
FIN	Fractional Incapacitation Dose For Nitrogen
FIO	Fractional Incapacitation Dose For Reduced Levels Of Oxygen
ft^2/per	Feet Squared Per Person
K	Extinction Coefficient (/m)
kW/m^2	Kilowatts Per Metre Squared
m	Metres
m/s	Metres Per Second
m^2/m^2	Metre Squared Per Metre Squared
m^2/per	Metre Squared Per Person
max()	Function Determining Maximum Value For Indicated List Of Variables
mg/l	Milligrams Per Litre

min	Minutes
min ()	Function Determining Minimum Value For Indicated List Of Variables
n_i	Nodal Connectivity
n_{max}	Maximum Nodal Connectivity
OD	Optical Density
per/ft/min	Persons Per Foot Per Minute
per/m/sec	Persons Per Metre Per Second
PET	Personal Elapsed Time (seconds)*
ppm	Parts Per Million
Q_i	Exit Quality *
s_i	Occupant Seniority *
s_{max}	Maximum Occupant Seniority *
t	Time (seconds, unless otherwise stated)
t_{conv}	Time To Incapacitation Due To Convective Heat (seconds)
TET	Total Evacuation Time *
t_{rad}	Time To Incapacitation Due To Radiative Heat (seconds)
v	Velocity (m/s)
VCO_2	Multiplicative Factor Which Measures Increased Uptake Of CO And HCN Due To CO_2 Induced Hyperventilation
W_a	Actual Width (m)
W_e	Effective Width (m)
x'	Derived Value

* term used in either release or prototype version of buildingEXODUS

CHAPTER 5 THE IMPLEMENTATION AND VERIFICATION OF PROPOSED BEHAVIOURAL FEATURES.

The validation cases analysed have demonstrated that the buildingEXODUS model has an impressive flexibility in representing evacuation conditions. It is able to simulate a variety of conditions, reflecting the changing circumstances of the occupant population at an individual level. These conditions include low and high population densities, motivated and placid populations, complex and simple geometries and different knowledge levels amongst the occupant population. It has also been shown to be sensitive to the provision of new data. This is important as it allows crude preparatory representations to be made utilising reduced data-sets. Under these conditions it is incumbent upon the engineer to detail the inadequacies of the data-set and the subsequent results.

Most striking is the quantitative accuracy of the model, which suggests that in the examples investigated that the model was capable of simulating the events relatively accurately. However, this may not be the case in more complicated scenarios such as those exhibited in the Beverly Hills Supper Club incident [52], the Summerland incident [53] or the World Trade Centre evacuation [106]. During these events sophisticated and localised occupant responses were evident.

In comparison with the other models examined in Chapter 3 the buildingEXODUS behavioural model provides an array of features. However, when this capability is compared to the detailed analysis in Chapter 2, a number of deficiencies are evident.

It is not suggested that the buildingEXODUS model is in any way unique within evacuation modelling. Indeed, the model shares several underlying features with a number of other models [8], such as a nodal network, a distance mapping system and an individually described occupant population. The proposed behavioural developments would therefore equally benefit a variety of the existing evacuation models. Obviously implementational details may differ between models, but the principles on which the algorithms are based and the functionality that they provide would extend the capability of nearly all of the models examined.

The buildingEXODUS model is seen as a useful arena in which to test the proposed developments. By doing so it enables the behaviour to be assimilated into a pre-existing framework that has a comprehensive physical model as well as the basis for a sophisticated behavioural model. The fact that a significant proportion of the model already exists allows a greater degree of concentration upon the proposed behavioural developments. The validation process detailed in Chapter 4 enables a greater degree of confidence in the existing components of the behavioural model.

The process of implementation is invaluable for a more detailed understanding of the proposed algorithms themselves as well as forcing a systematic analysis of the influences to which they are susceptible and the consequences of their implementation upon other aspects of the evacuation model.

In the following sections the proposed behavioural developments are outlined. The features will be grouped according to their sophistication and the dependence of other features upon them.

These developments are the culmination of the analysis of the available literature concerning expected occupant behaviour. The algorithms developed are original work. Where they have been influenced by other researchers this has been acknowledged and referenced. The algorithms have been developed independently of any computational framework. Their implementation has attempted to faithfully represent these algorithms. Where compromises have been made they are acknowledged and explained. They have also been shaped by the general requirements suggested through the analysis of currently available evacuation models as well as the specific requirements of the buildingEXODUS model.

The nature of the proposed behaviour is dependent to a large degree upon the existence and the availability of relevant data. As identified previously, the field of evacuation modelling is a relatively new field that is starved of data. However, this absence of empirical data should not prevent the generation and testing of modelling techniques in readiness for the eventual provision of supporting data. It does mean that the techniques produced in the absence of a detailed data-set are based on more *anecdotal* evidence and are far more difficult to verify. The concepts being addressed still need preliminary analysis, concerning the coherence and consistency of the resultant behaviour. In these examples, the *concept* of the inclusion of such a behaviour representation within the overall evacuation model is demonstrated, in addition to a comparison against the evidence that is available. Where the evidence is available, a conceptual demonstration is still conducted, although this is accompanied by detailed verification.

Chapter 5 describes a number of the less complex proposed features. This section describes those features that are unable to be verified in isolation. These tend to be internal occupant attributes or simplistic occupant capabilities. As such only a brief description is made, which is expanded upon in later sections, where they are examined in conjunction with other behavioural factors.

In Chapter 6-8, the analysis of more complex proposed behavioural implementations will be produced, being described in separate sections, each comprising of a number of component subsections. The proposed behavioural features are addressed individually for a number of reasons. Firstly, the complexity of the behavioural developments warrants detailed analysis. This would be difficult if the behavioural implementations were collected together. Secondly, it would be impossible to compare either the accuracy of the proposed behaviours or the success of their integration into the buildingEXODUS model, if they were combined prior to their implementation. It would also be a much simpler task to camouflage any shortcomings in the details of the developments. Although a piecemeal solution, the proposed behaviours are subject to greater scrutiny in isolation. Ideally, these behavioural implementations will be combined into a single behavioural engine. This is outlined in Chapter 10.

In Chapter 6, the interaction of the occupant with a number of external features is examined. These features represent a more sophistication perception of information by the occupant and an ability to internalise and react to this information. In Chapter 7, the dynamic response to the external conditions are examined, crediting the occupant with experiential processes that are not simply based on stimulus-response actions [8]. Instead they are sensitive to the surrounding environment, according to the identity, history and location of the individual concerned. Finally, in Chapter 8, the occupant is seen as a decision-making engine that organises and engineers their response to the environmental conditions according to analysis and estimation, as well as to the provision of new information.

In Chapter 6-8, the expected occupant behaviour addressed is initially described. Although previously the general principles of the new behaviour will have been addressed in Chapter 2, a more specialised description of the behaviour and any relevant new evidence will be included.

The ability of the present buildingEXODUS model to represent this behaviour is then described, identifying any shortfalls in this representation. This is to allow for a clearer comparison of the proposed developments, describing in detail the shell in which the proposed behaviour will be examined and the possible restrictions that the buildingEXODUS model provides for the proposed algorithm.

The proposed method of representation is then described in some detail. This includes the principles and assumptions on which the behaviour is based and the actual form of the algorithm incorporated.

This proposed algorithm, the assumptions on which it is based and the manner in which it will be incorporated into the buildingEXODUS model is then described. This effectively uses the buildingEXODUS model as a shell, which can examine the mathematical implementation of sociological and psychological principles. Most importantly, the proposed behaviour is then 'verified' using this shell.

A number of other behavioural models exist [8]. These may be based on experimental or field-work that have then lead to theoretical models. These models are rarely, if ever, verified, through their application. Of fundamental importance then, given the extraction of the behavioural features from the appropriate literature in Chapter 2 and the development of a behavioural model, is the ability to apply them and identify their strengths and weaknesses.

If actual data is available this will be used in the verification process. The sophistication and extent of this process is therefore dependent upon the evidence available. Irrespective of this availability the purpose of this process is to:-

- Demonstrate that the proposed behaviour performs the tasks described
- Rule out the occurrence and existence of anomalies due to the introduction of the proposed behaviour
- If possible compare the proposed behaviour against available evidence, including real-life evidence, experimental evidence, trail-run experiment, anecdotal evidence and finally evidence extracted from other fields of knowledge.
- Compare and contrast the findings with the present buildingEXODUS behavioural model, allowing the nature of the development demonstrated clearing.

Once these tasks have been performed it is possible to determine whether the proposed behaviour provides a *quantitative* and *qualitative* advantage over the present representation.

The absence of quality data-sets against which to compare the behavioural developments has forced the process from a one of *validation* to one of *verification*. Although a weaker analysis of the proposed features, it still provides evidence and insight into either their future development or adoption.

None of the behavioural features described will be without difficulties. The nature and complexity of the algorithms prohibits this. Any potential weaknesses in the proposed behaviour will suggest a number of *future developments*, which may again be addressed in some detail.

Finally, each section is concluded, describing the overall accomplishments of the proposed behaviour.

5.1 Occupant Attributes and Internal Developments

This initial section describes those features that cannot be tested directly. These features, whether they are new occupant attributes or other considerations, can therefore only be demonstrated in conjunction with other more complex behaviours that have a qualitative/quantitative impact upon the evacuation results. *These are 'enabling' features.* They are essential building blocks upon which the other more complex behaviours described in Chapter 6-8 are dependent.

These attributes will therefore be described briefly and less formally in this section, as their uses and the assumptions on which they are based will be more thoroughly examined in context with the more complex behavioural features described in Chapters 6-8.

5.2 THE REPRESENTATION OF SOCIAL RELATIONSHIPS

The existence of social structures and the occupant's position within these structures has, in the past two decades, been identified as having a significant impact upon the actions adopted by individual occupants [58,60]. These structures not only determine the adoption of specific roles [52,58,60], but will influence the choice of action, the occurrence of collective behaviour and the level of communication between occupants [1].

The relationships formed need not be static and will be dependent upon the social dependencies that the occupant brings to the event, as well as those that might emerge during the event [1,52,58]. The effect of representing the social structures within an evacuation in conjunction with the occupant's behavioural reaction is addressed in Chapter 9.

At present no means of representing the different roles and relationships that exist within the occupant population is available within the buildingEXODUS model [5-7,21-27]. Occupants are seen as isolated physical entities that, although are represented by complex physical processes, are not social beings. The introduction of an index to associate occupants is an attempt to remedy this omission.

In the proposed implementation of a social identity within buildingEXODUS, prior to the beginning of the simulation, the user has the option of attributing an occupant with a relational index, termed a *gene*. This represents the relationship between an occupant and those occupants who share an identical gene (and conversely also establishes the relationship that the occupant has with those occupants who do not share the same gene). Alternatively this can be randomly generated by an automatic mechanism, that allocates the population with an index derived from a finite set of integers.

The *gene* is represented by an integer. *Those occupants that share a common gene are deemed to be in a social relationship.*

Once the required occupant relationships have been accounted for, the model examines the occupant population to form social groupings. It does this by scanning the entire population and attributing each occupant with a list of the population members who have the same gene, thereby creating a list of occupants who are considered *socially significant.*

This information is assumed to be available to the occupant *prior* to entering the evacuation; therefore the occupant is aware of significant social relationships prior to any evacuation incident. This provides the occupant with a means of differentiating between the general population, with whom the occupant is making a new acquaintance and those with which a prior relationship has been established (be they familial, social, economic or otherwise).

This list is dynamic, therefore allowing occupants to be added/removed from the list according to a change in their circumstances. This may include the significance of an occupant increasing during an evacuation due to constant 'companionship' or difficult circumstances [58,163]. This ability is addressed in detail in Chapter 8.

The existence of an index that identifies the relationship between occupants forms the basis from which a more complex behavioural system can be developed. It allows the existence of a relationship to promote/prevent the performance of particular actions and therefore becomes a factor in the outcome of the evacuation; a factor highlighted in Chapter 8.

Although this system functions adequately, the flexibility of this system may be increased in two ways. Firstly, an occupant may be attributed with numerous *genes*. This would allow a number of social relationships to exist [1,52,58,163] reflecting the numerous social groupings that could exist in large geometries (see Figure 5-1).

This may represent an occupant who is accompanied by their family, a group of friends and a number of strangers.

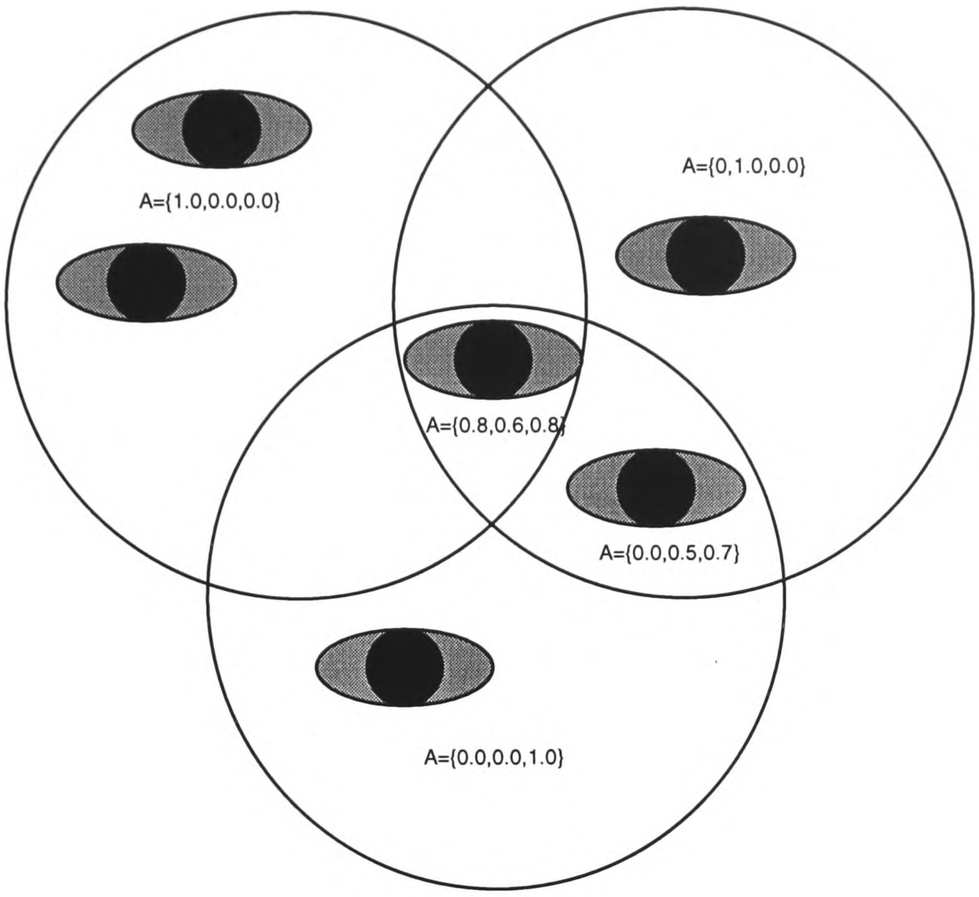


FIGURE 5-1: MULTI LAYERED ASSOCIATION. AN OCCUPANT MAY BE A MEMBER OF MORE THAN ONE SOCIAL GROUP. THE VECTORS ASSOCIATED WITH EACH OCCUPANT IDENTIFIES THE EXTENT OF THEIR MEMBERSHIP TO A GROUP (1.0 SIGNIFYING STRONG RELATIONSHIP, 0.0 NO RELATIONSHIP).

Secondly, a figure may be defined that represents the *strength of association* between occupants. This would be particularly important if the occupant could be attributed with more than one gene, allowing a level priority to be ascribed (see Figure 5-1).

Similar to the 'association index' seen in fuzzy logic, this ability would represent the extent with which the occupant was associated with a particular social grouping. This would enhance the previous feature allowing certain social groupings to dominate others, e.g. family ties might be considered stronger than ones created in the work place.

5.3 THE AUTHORITY OF OCCUPANTS

Once an attempt has been made to represent social affiliation, such as that in Section 5.2, the next logical step is to represent the hierarchical structure within particular social entities. These structures influence the behaviour exhibited and the roles adopted once an occupant of significance, or indeed a member of the general public has been encountered [52,58,97,163]. A representation of the occupant's status within the social group is required to determine their position. As Hollander comments,

"Status refers to the placement of an individual along a dimension, or in a hierarchy, according to some criterion of value" [198]

Once an occupant is encountered, their perception according to their social authority will not only impact upon the priority given to any communication but the likelihood of that information being acted upon. Numerous examples of this were examined in Chapter 2, including the Beverly Hills Supper Club and King's Cross incidents, where the perceived authority of individual occupants significantly influenced the interpretation of the information imparted [52,58,97].

These social hierarchies are not accounted for in the present buildingEXODUS model, due to its inability to account for any social factors or their influences upon occupant behaviour [5-7,21-27]. A static motivational index exists that represents the ability to occupy contested floor-space. However this does not represent the sociological importance of the occupants to each other as well as their position within a hierarchical social structure.

A *seniority index* has been devised to represent the authority with which a particular occupant may be associated and therefore the relative position of the occupant within their particular social grouping. In this formulation, the occupant's social position is dependent upon a number of existing occupant attributes. These are

- The occupant's *age,*(a_i)
- The occupant's *gender* (g_i)
- The occupant's motivation (represented within the buildingEXODUS model through occupant's *initial drive,* D_i)
- The occupant's *patience*(p_i).

These are crudely categorised according to the influence they have upon an occupant's authority. For instance, in Western societies, an adult male who is highly motivated is generally seen as having a higher level of authority than a young female, irrespective of her motivation . This is represented by equation (43)

$$s_i = \alpha a_i + \beta g_i + \chi D_i + \delta p_i \tag{43}$$

where $\alpha,\beta,$ χ and δ are coefficients determining the importance of the factors highlighted. These coefficients have been analysed and designed to reflect the influence of the factors in equation (44) such that

$$\alpha > \beta > \chi > \delta \tag{44}$$

The values attached to these coefficients purely reflect the relationship defined above and have no intrinsic value in themselves.

In this definition of social authority the default characteristics are male occupants being more authoritative than female, adult occupants being more authoritative than the young or elderly, the impatient being more authoritative than the patient, and highly motivated occupants being more authoritative than unmotivated occupants[52]. These categories are taken from the work of Stagdill, Rectan and Shaw and Berg and Bass [198] each of whom analysed the factors that influenced authority and seniority. The coefficients within the formulation reflect this prioritisation.

This calculation produces a dimensionless value that allows comparison between occupants as to who is the most senior. This is particularly important in the communication process. It is acknowledged that the assumption that these factors are additive is arbitrary. However, more sophisticated data is required for a more realistic representation of this phenomena .

Bales developed a similar system based on the ability of people to influence those around them. This was formulated in equation (45) such that

$$\frac{\bar{e}+_i}{\bar{e}+_i+\bar{e}-_i} \times \frac{E-}{E+} \times 100 \tag{45}$$

where e represents individual communication activity, E the group communication activity, + that the information was adopted, - that the information was rejected, a hat ($\bar{}$) represents that information was incoming and an absence of the hat represents outgoing information[199]. The equation therefore provided a ratio relating the individual communication activity to the group activity, based on the perceived communication levels of the individual.

Of course the user has the ability to override any automated calculation, enabling the description of female staff members, for instance, who would be perceived to be influential irrespective of the social norm.

Some fuzziness is maintained within the system to allow for variation and unusual or exceptional circumstances. Therefore irrespective of the factors highlighted above, it would be most unlikely that two occupants would have identical seniority levels, due to the noise within the system.

The crudeness of this system identifies both a weakness and a potential strength that may be addressed in future work. An obvious weakness is the arbitrary nature of the scale and the categories. Obviously, this may differ between and within social groupings according to the nature of the structure. Therefore in the future, *social modules* may be defined to represent the nature of the social environment and possible large-scale cultural differences (see Figure 5-2). For instance, in matriarchal societies, or in more structured societies, such as Japan.

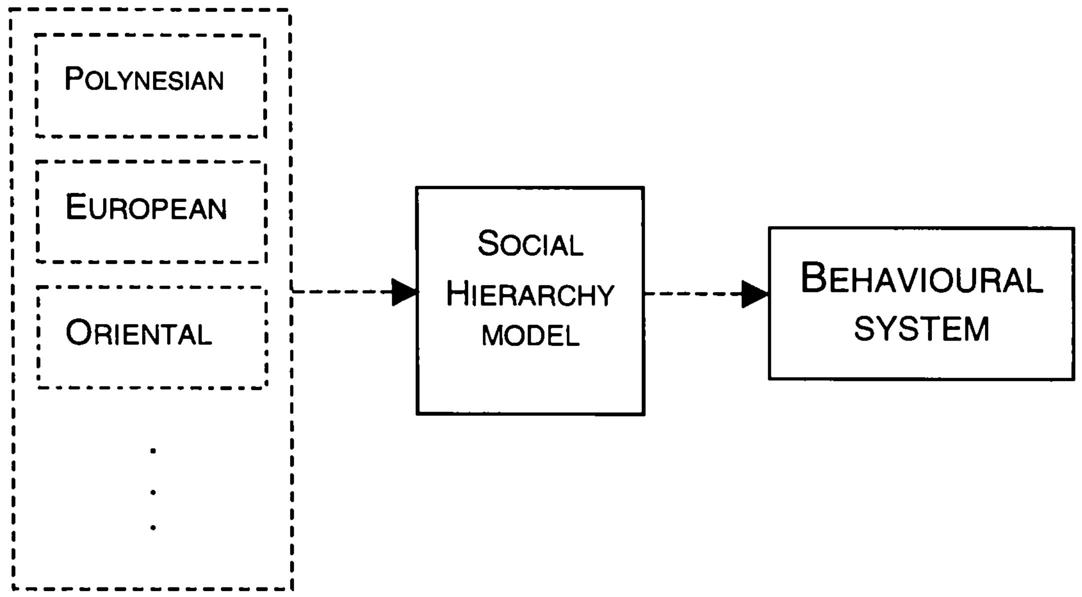


FIGURE 5-2: IMPACT OF THE INTRODUCTION OF DISTINCT SOCIAL HIERARCHY MODULES.

One idea to achieve this is to use this system in concert with pre-defined *GENES* (see Section 5.2) that would trigger different modules into action. A pre- defined gene could therefore not only identify the existence of a relationship between a set of occupants, but may also denote the 'cultural reference' to which the association is made (e.g. a family group exists and the family is Middle-Eastern).

Another enhancement that might improve the representation of the authority of the occupant is for the *occupant's authority to evolve* during the simulation. It would therefore be able to alter dynamically according to the occupant's character prior to the evacuation and it's development during the evacuation.

5.4 LINE OF SIGHT CALCULATIONS

The awareness of the occupant of their immediate surroundings is a vital component in their wayfinding capability [200,201]. It determines the occupant's ability to perceive information and therefore to adapt their behaviour accordingly. This will be affected by their *position within the enclosure*, *the environmental conditions*, the *sensorial and cognitive capabilities of the occupants* and *the existence of available data sources* [200,201,202].

The ability of the occupant to receive information according to visual access allows the transfer of information between the environment and the occupant population to be simulated. This provides a more accurate means upon which the simulated occupant can base their decision, instead of using globally defined information transfers or strictly local definitions. This form of system might then be used by the occupant in an array of analytical decisions for which the provision of information is essential.

At present in the buildingEXODUS model, the occupant is aware of the immediate surroundings. This is defined as the location occupied and those nodes connected to this present location. To some extent the occupant may also be said to be aware of the availability of the nearest exit as the occupant is able to determine whether the exit becomes unavailable. However, due to the rudimentary nature of the present representation of occupant familiarity, this may allow the occupant access to inappropriate levels of information.

A more accurate method of describing the possibility of receiving information would have to take into account the potential obstacles that exist within the occupant's immediate environment. To represent the ability of occupants to receive information *visually*, they are provided with *'line-of-sight'* information concerning neighbouring exits or nodal positions. This is initially quite a simplistic system as a realistic *'line-of-sight'* system, based around three-dimensional calculations, would be computationally expensive and complex to implement. To determine the potential impact of such a system, this rudimentary first step is produced.

The form of calculation proposed is two dimensional, relying upon the geometry used in the buildingEXODUS model rather than requiring specialised material. A more detailed three dimensional system would require a paradigm shift in the methods used in the buildingEXODUS model. This would possibly involve a movement towards virtual reality technology, which is at present used as a post-processor graphical interface (see Figure 5-3). Just as this assists the engineer to visualise the occupant movements, so it may enable the detailed data structures required for three-dimensional visual access calculations to be made.

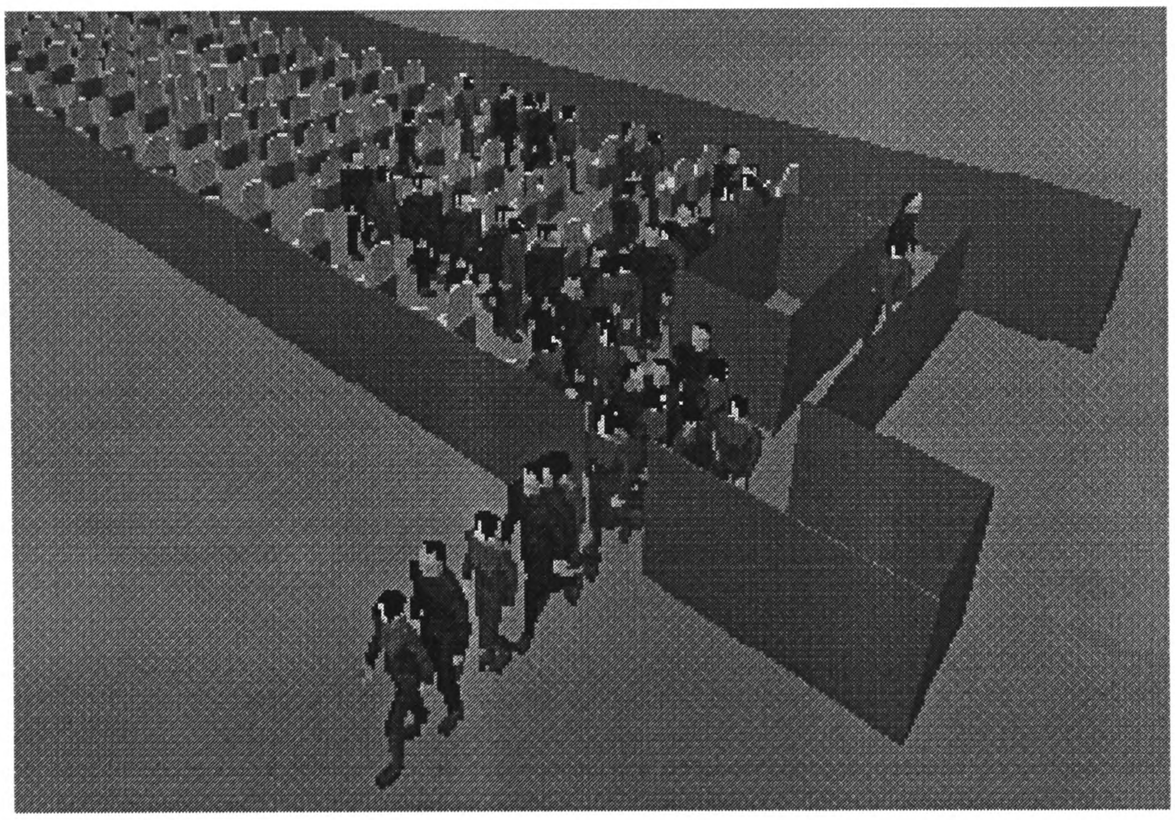


FIGURE 5-3: PROTOTYPE VR INTERFACE OF BUILDINGEXODUS.

Initially, the system implemented was based upon exit usage. This rested on the assumption that the occupant's attention would be centred around the target destination. This was achieved through grouping the exits according to which of them could be seen simultaneously. Therefore, if information became available concerning a particular exit, those exits that shared an identifying marker would also be visible and could be interrogated for information to a similar degree. The flaw with this system was that in large or complex systems, occupants might become aware of information that in reality would have been denied them due to geometrical obstructions.

A more refined system has been conceived to overcome these problems. A *nodal-based* representation is centred on the exact vantage-point of the occupant. This was the most refined means by which the occupant locations could be identified in the present incarnation of the buildingEXODUS model. Aligning visual *connectivity* to the buildingEXODUS nodal system restricts the accuracy of the system to 0.5m units. Obviously, the inclusion of this method is a significant improvement over the present representation. The system can be further improved once the buildingEXODUS nodal system is further refined.

Nodes are attributed with several indices, denoting their visual connectivity. These indices represent the visibility from and of that location. If two separate nodes share an identical index, then each node may receive visual information from the other; they are deemed to be *visually connected.* Each node has the capacity of storing three identifying indices enabling complex visual patterns to be constructed (see Figure 5-4). Ideally no limit would be enforced on the complexity of these patterns, therefore removing any potential restrictions.

These indices are represented by an integer that may take the value of any positive integer. No boundary exists upon the number of regions generated, other than any limit imposed by the technology used.

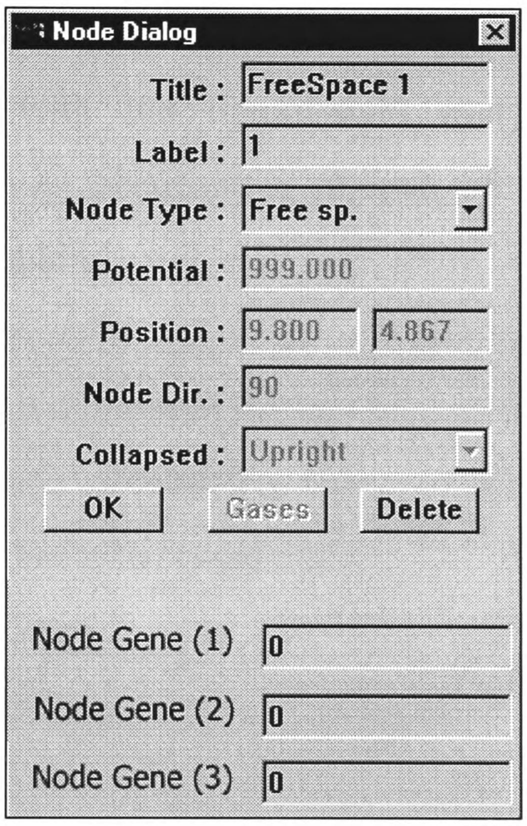


FIGURE 5-4: DIALOGUE BOX IN PROPOSED BUILDINGEXODUS MODEL DEFINING INDIVIDUAL NODES.

This nodal definition includes exits as well as any other type of node. The distance between the two locations is only a factor in the visual perception of the occupant, if the environmental conditions are such that they limit the visual capability of the occupant [9]. Under these situations, the visual capacity of the occupant is dependent upon the environmental impact as well as their vantage-point. Another factor that may impact upon the ability of the occupant to gain visual access, is the location of other occupants on adjacent nodes. In this crude representation, if either of the occupants involved in the calculation are completely surrounded by other occupants, then no visual access is achieved. This is described in greater detail in Chapter 8. Otherwise if two nodal positions have the same identifying index then an occupant located on one of these positions will have visual access to all of the information available.

This method requires the user to define the visual access, through grouping together nodes as shown in Figure 5-5. This requires a greater degree of user interaction with the model. It might also require an extended understanding by the user of both the model and the environment simulated. In this version of the algorithm, it is the user's responsibility to impose the visual access upon the geometry. This should reflect any potential obstacles within the geometry.

The system has been designed so that the user does not have to include the entire geometry in these calculations. It is possible to only include limited area of visual access, at which points the occupant utilises the algorithm defined previously (that is only a select number of nodes are attributed with a nodal gene). Elsewhere the behavioural model functions normally with the line-of-sight system automatically becoming redundant. This occurs once an occupant is situated on a nodal location that is not attributed with a identifying index.

This type of definition allows a number of distinct pieces of information to be transferred to an occupant located on a node calculated as being visually connected. This includes

- the population density at the interrogated node
- the environmental conditions
- the actions of occupants located on the visible nodes.

This allows the method to be used in a greater variety of behavioural scenarios, such as queuing, adaptive wayfinding and communication (see Chapter 8).

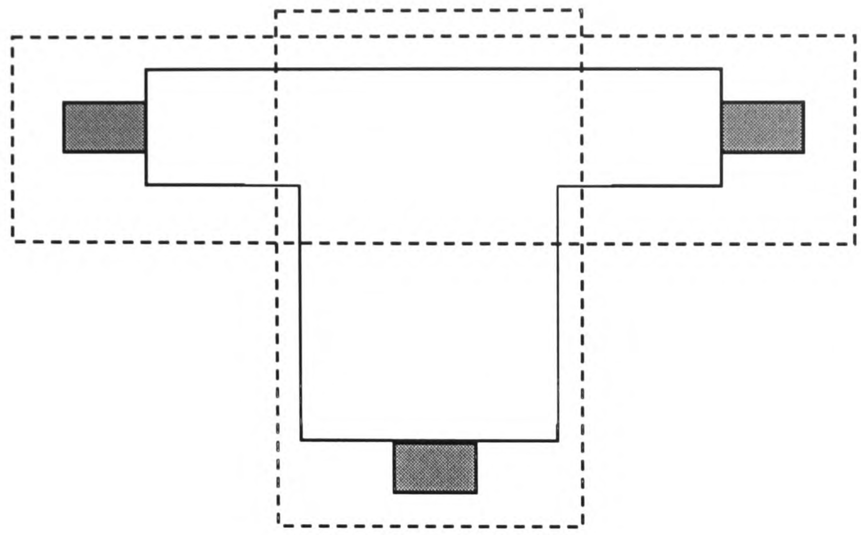


FIGURE 5-5: THE PROVISION OF VISIBLE ACCESSIBILITY. THE NODES GROUPED TOGETHER ARE ASSUMED TO HAVE VISUAL ACCESSIBILITY. THE OVERLAP PING AREA HAS ACCESS TO THE ENTIRE GEOMETRY.

The disadvantage of this system is that it is relatively computationally expensive, although given the developments in recent technology this should not necessarily prohibit its use. This is due to the behavioural features that this method enables rather than any detailed calculations made concerning the proposed behaviour itself. The main criticism is therefore that it is the foundation of so many other behavioural features. This method is also relatively time-consuming to configure, especially in large or complex geometries. The automation of this algorithm is left for future work.

5.5 CROWD ANALYSIS AROUND EXITS

In the present building regulations, occupants are assumed to evacuate according to their proximity to an exit (of which they are assumed to be aware) [1,203]. In a number of actual evacuations, occupants have been seen to analyse the situation according to the information available to them [1,52,53]. In reality, occupants are constantly adjusting their actions according to conscious or subconscious calculations. One of the most important external factors is the congestion perceived around potential exits. This will influence the occupant's adoption of an exit as a potential escape route.

There is a logical difficulty with the regulations as they implicitly adhere to the idea that crowd formations affect the occupant's egress in a physical sense, through attempting to minimise individual exit use [1,203]. However, the regulations ignore the psychological impact that these crowd formations can have upon the occupant decision making procedure [1,203].

In attempting to represent sensitivity to the existence of a crowd within the buildingEXODUS model, it is apparent that no means presently exists either to represent the size of a crowd as a defined unit around an exit, or for an occupant to interrogate a crowd's behaviour [24].

Imperative to a number of behavioural features including occupant redirective behaviour (see Chapter 8) is the ability of the occupant to receive information concerning the status of the occupant environment enabling estimations to occur [1,9,52,53,58]. Specifically, the ability of the occupant population to estimate the time it will take a high-density population surrounding an exit to pass through the exit. This will have an important affect upon exit selection. Given that the occupant is able to see the developments around an exit, their future behaviour may be affected upon their ability to calculate when specific exits become available [1,52].

A factor vital to the success of this feature is that the calculation conducted by the occupants should contain a degree of *fuzziness*. The occupant will not have time for arithmetic or accurate determinations concerning the movement of the exit populations but will instead base their calculations upon estimates and approximations, probably at a subconscious level.

The representation of such behaviour is achieved in a number of stages. Firstly, the crowd involved in the congestion around the exit is defined as those occupants who desire to leave via a particular exit and are within *a pre-defined distance from their target*. The algorithm only includes those occupants who are heading towards the exit in question. If an occupant is within an arbitrary distance threshold of 5m of the exit and is heading towards the exit in question, he is included in the calculation. This therefore excludes transient occupants who just happen to be within the perimeter of the crowd, but are in fact moving on towards another target and will not significantly effect the evaporation time. This also resolves the potential confusion that the algorithm may be subject to due to several exits being in close proximity.

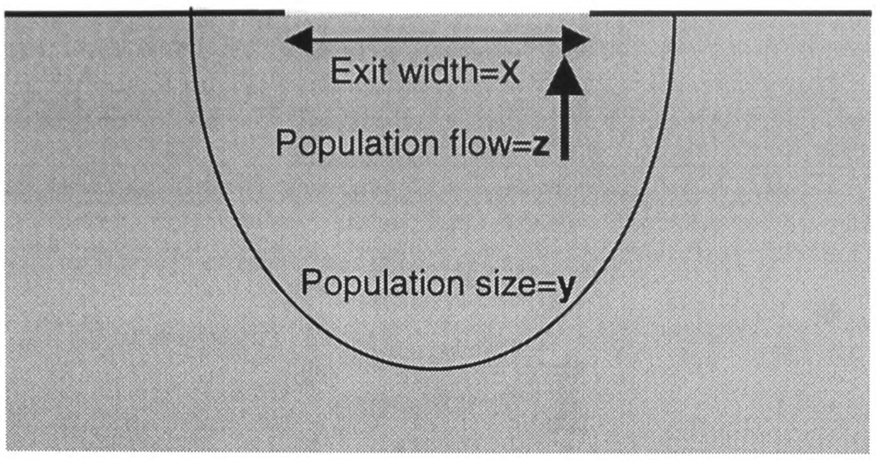


FIGURE 5-6: ESTIMATION CROWD DISPERSION TIME =Y / (X * Z)

Once this calculation has taken place, the estimation of how quickly the crowd will disperse can be made. This is largely based upon the size of the crowd (see Figure 5-6). It is assumed that the occupant is aware of the exit and its approximate width (as he is familiar with the exit), and can therefore make a rough estimate of the clearing time of the occupant population based on these factors, as well as the size of the crowd. It is not suggested that the occupants *actually* perform this task in this manner. In reality, this probably occurs at a more subconscious level.

The simulated task is enabled by the use of existing flow rates (HMSO [185] , Fruin [66], Hankin [156] etc.) and a combination of these rates to afford the occupant with a crude estimate of the queue time. The rates are used simply, because they are *accepted* rates and they are defined and implemented within the buildingEXODUS model. This provides a rough estimate for the occupants as to flow rates achievable given the conditions. Again, this is purely an internal mechanism for the occupant to perform the calculations rather than a model to represent the actual occupant decision-making process.

This behaviour is based on the assumption that the occupant is in visual contact with the exit (see Section 5.4) and that the occupant is familiar with the particular exit (see Chapter 7). Therefore the occupant will be aware of the dimensions of the exit. Given that the occupant has an estimate for the size of the crowd, the rate of the crowd's movement through the exit and the exit size, a calculation can be made to determine the time for the crowd to clear (see equation (46)):

$$t = \frac{P}{w * f} \quad \textbf{(46)}$$

where t is the time for the exit congestion to evaporate (in seconds), P is the perceived size of the population around the exit, w is the width of the exit in metres and f is the estimated flow rate of the crowd, in persons/metre/second. Upon this estimate, decisions may be made which alter or maintain the present position or course of action. Once the occupant has an understanding of how long it will take for the crowd to exit, the occupant may crudely approximate their own evacuation time through a particular exit.

For instance, given that the occupant location is a distance, d metres, from his target exit and that he is travelling at v m/s, his exit time, t_{exit} , can be approximated as being the time to cover this distance and the time for the congestion to evaporate around the target exit, such that

$$t_{exit} = \frac{\rho}{w * f} + \frac{d}{v} \text{ (IN SECONDS)} \qquad \textbf{(47)}$$

This provides a rudimentary understanding of the time for the occupant to exit. Obviously other considerations can be taken into consideration, including the results of conflict resolution, the different terrain types, etc. however, given that this method is applied consistently between targets, it is deemed not to distort the potential evacuation times disproportionately.

The inclusion of such considerations, as well as a greater reference to more internal occupant attributes (such as drive, patience, etc.) is left for future work.

5.6 Occupant Attributes and internal developments: Concluding Remarks

The attributes and capabilities outlined in this chapter form building blocks for the subsequent behavioural developments (see Table 5-1). Their implementation is therefore a vital component in any future behavioural advancement of the buildingEXODUS model. Their modular format is intentional, allowing their re-use and recombination into more complex and more flexible behavioural capabilities. This will facilitate a more sophisticated representation of occupant behaviour.

Table 5-1: Summary of the behavioural developments in this chapter.

Section	Development	Description
5.2	Social Relationship	Enables representation of social groups
5.3	Occupant Authority	Enables representation of social hierarchies
5.4	Line of Sight	Enables perception of information
5.5	Crowd Analysis	Enables calculation of crowd evaporation.

CHAPTER 6 ENVIRONMENTAL EFFECTS AS DISTURBANCES

In this section the impact of the proposed features can be directly examined and tested, rather than being restricted to a purely descriptive analysis, as in Chapter 5. These features are generally reliant upon the occupant population receiving and reacting to new forms of information. These features are relatively simple although they may have a significant impact upon the evacuation results generated. Most importantly, the introduction of the influences examined in this section enables the behaviour of the occupants to be more contextual, relating to the event around him, rather than being globally applied or assumed.

Where this introduction is reliant upon the unvalidated attributes in the previous section, references will be made. These features include:

- **6.1. THE OCCUPANT ABILITY TO NAVIGATE ACCORDING TO PROXIMITY TO THE ENCLOSURE**
- **6.2. THE IMPACT OF THE SURROUNDING POPULATION DENSITY UPON ROUTE ADOPTION**
- **6.3. THE DEVELOPMENT OF MECHANISMS TO DELAY OCCUPANTS ONCE THE EVACUATION HAS COMMENCED**

6.1 THE OCCUPANT ABILITY TO NAVIGATE ACCORDING TO PROXIMITY TO THE ENCLOSURE

6.1.1 EXPECTED OCCUPANT BEHAVIOUR

A vast amount of existing evidence suggests that occupant movement is conducted in respect to the surrounding geometry of the enclosure and that the bulk of occupant movement is conducted in a central segment of the floor-space. [56,66,177] The most influential of these works being that of Pauls [66,177] who identified that the *effective width* of corridors and passageways as being approximately 0.3m less than the *actual width*, such that

$$W_e = W_a - 0.3\,(\text{m}) \tag{48}$$

where W_e is the effective width and W_a is the actual width of the corridor (see Section 2.6.6, Chapter 2).

Fruin also identified a similar measure to represent the expected distance between occupant and the enclosure boundary, calculated as being between 1-1.5ft (0.305-0.457m). This distance was claimed to change according to the circumstances in which the occupant was situated. For instance, it might increase to 3ft (0.914m) whilst occupants are window-shopping. These figures were then used by Fruin to formulate a generalised model of occupant movement.

The importance of the occupant's proximity to the enclosure boundary may depend on a number of factors that are external to the occupant (terrain, population density, clarity of signage, etc) or may be internal and as such may involve dynamic calculations relating to the external factors highlighted. Obviously in some situations, given the physical description of the geometry and the existence of environmental impediments, the occupants will be compelled to adopt a position in close proximity to the enclosure boundary, irrespective of their wishes. Therefore the calculation of the occupant's position is based on *physical necessity* and *occupant choice.*

6.1.2 PRESENT BUILDINGEXODUS IMPLEMENTATION.

At present, in contrast to the evidence presented, the simulated occupant within the buildingEXODUS model makes navigational calculations without making reference to their proximity to the enclosure wall (see Figure 6-1). Although some space can be claimed to be maintained between the occupant and the enclosure wall, given that the nodal width is 0.5m and that the average occupant width is smaller [151], this distance would not generally be in the region of 0.3m.

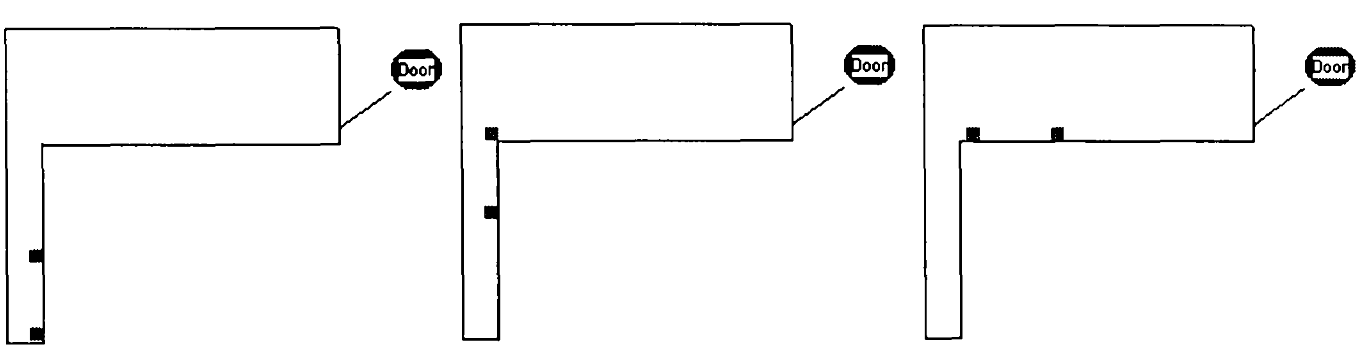


FIGURE 6-1: SIMPLE EXAMPLE DEMONSTRATING THAT IN THE PRESENT MODEL THAT THE OCCUPANT MIGHT ADHERE TO THE STRUCTURE BOUNDARY IRRESPECTIVE OF THE AVAILABILITY OF SPACE.

The experienced user, through the implementation of OBSTACLE nodes (see Section 3.1, Chapter 3) around the boundary of the enclosure [24], can approximate the relationship between the occupant and the enclosure boundary described. These nodes are less favoured by the occupants and will be avoided if another option exists. If OBSTACLE nodes are encountered by an occupant they will hinder occupant movement by reducing occupant speed. However, this implementation becomes tiresome when complex geometries are involved, where the number of adjustments may be vast and are also interpreted identically irrespective of the environmental and physical conditions. They are also treated by the occupant population in exactly the same manner, irrespective of the conditions or the occupant's experiences.

6.1.3 Proposed behavioural modification

The algorithm suggested accounts for the occupant attempting to maintain a distance between himself and the enclosure. It achieves this by allowing the occupant to examine a location within the enclosure and make a decision of movement according to the locations proximity to the boundary. The implementation of this development within buildingEXODUS allows the simulated occupant to impose an internal bias against moving towards the geometry boundary, without forcing the user to individually identify the nodes.

The method involves the occupant *interpreting* the environment and making decisions according to the *connectivity* of the nodes available; representing the number of options available to the occupant situated at the location in question. The likelihood of the occupant selecting a node to be their next location is dependent upon the occupant's interpretation of its connectivity.

Implicit within the proposed algorithm is the assumption that *the boundary of a structure can be approximated by nodal connectivity.* This is an implementational assumption, although one that is borne out through examining the meshing algorithm used in the buildingEXODUS model [24]. (Obviously if this algorithm was to be used in other models, then the exact nature of the nodal mesh would have to be established.) Those nodal locations that are adjacent to the boundary of an enclosure will have a lower connectivity than those more centrally positioned and will therefore be deemed less attractive by the occupant.

The occupant's view of their surroundings is constantly updated, so that the occupant analyses their position in relation to the boundary during each movement calculation (every 1/12th of a second). This method allows the changing environmental conditions to more readily be taken into account and therefore more accurately represent the individual reaction to the environment (see Figure 6-2). This is particularly important when the occupant is analysing the affect of their proximity to the enclosure boundary in concert in relation to other conditions such as the population density (see Section 6.2) and the environmental conditions (see Section 7.1, Chapter 7). Therefore the occupants appreciation of a situation is not solely governed by an individual factor.

This method does not involve the reduction in the speed of the occupant in relation to their proximity to the boundary, although it would be a trivial matter for this effect to be introduced. This effect is omitted to simplify the behaviour and enable a more detailed understanding of the impact of its introduction. The maintenance of this behaviour would also have required some justification. It is thought that the effective narrowing of the geometry caused by the proposed behaviour is sufficient a consideration.

It is intended that this behaviour will be developed to include a dynamic representation of the occupant's travel speed. The exact nature of this reduction may not be linear or uniform across the occupant population, nor across the geometry. This is left for further work.

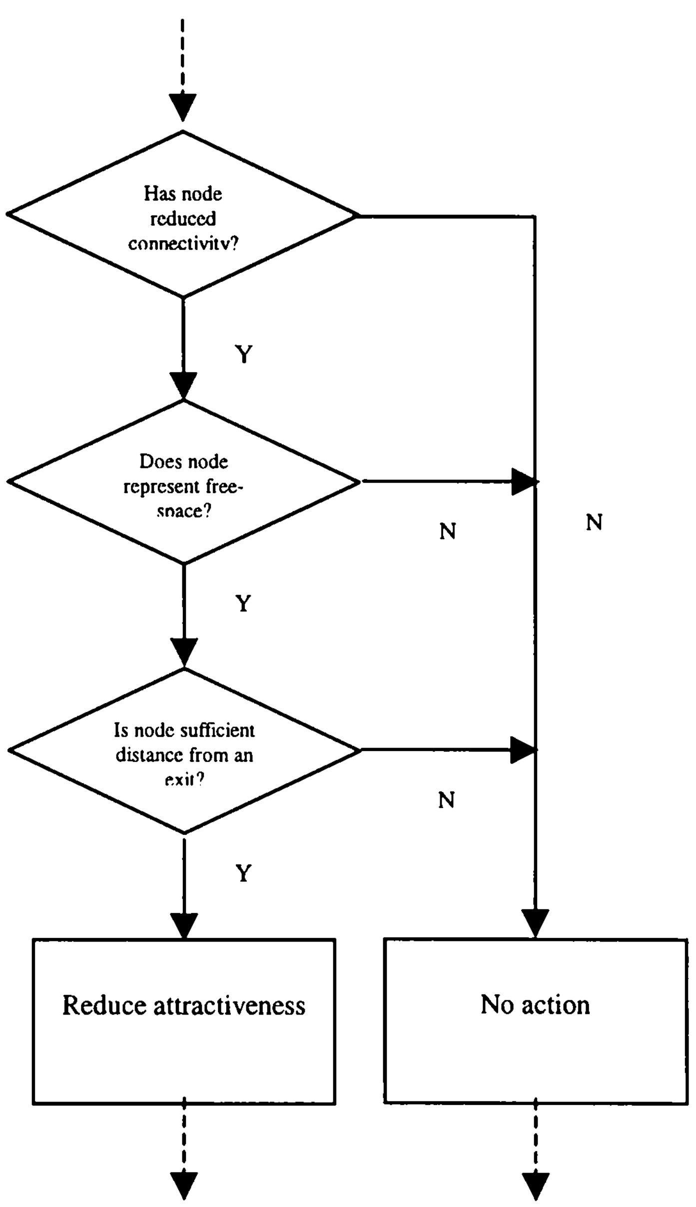


FIGURE 6-2: FLOW CHART REPRESENTING OCCUPANT REACTION TO BOUNDARY PROXIMITY.

The introduction of this algorithm into the buildingEXODUS model forces the occupant to consider the *exact* nature of the desired location prior to its adoption. The likelihood of occupying a nodal location will be biased according to its connectivity, i.e. the choice of a node will be biased in favour of those nodes that are more connected, reflecting their more central position within the geometry. Therefore the avoidance of such nodes, where possible, reflects the occupants general propensity to avoid locations in close proximity to the enclosure boundary, as described in the previous sections.

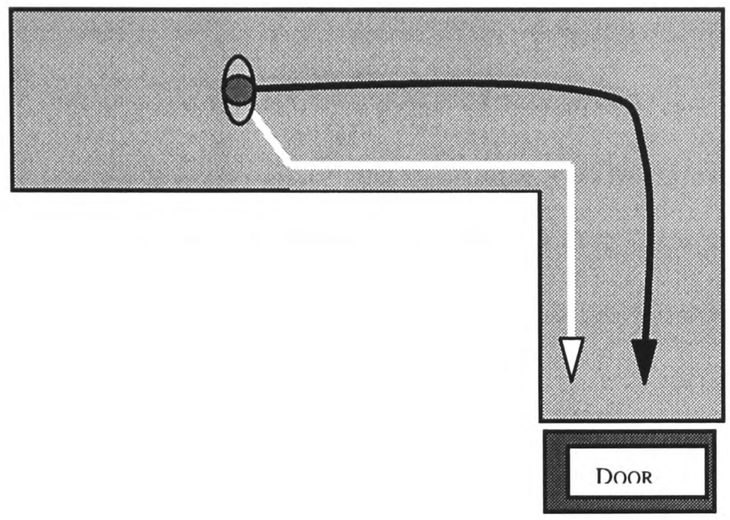


FIGURE 6-3: PATHS THAT ARE ADOPTED BY AN OCCUPANT GIVEN THE PRESENT METHOD (WHITE LINE) AND THE PROPOSED METHOD (BLACK LINE).

To prevent the possible absence of nodal options, the calculation in relation to nodal connectivity only affects those nodes that are *nearer* to the occupant's target than their present location. The quality of a nodal location is proportional to its connectivity. Therefore, the lower the nodal connectivity, the lower the additional biasing will be. Given that P, Q and R represent the three locations examined such that

$$P = [x_{exit}, y_{exit}], Q = [x_{target}, y_{target}], R = [x_{present}, y_{present}] \tag{49}$$

then the following relationship must be satisfied to allow the connectivity of the proposed node to be considered.

$$\|Q - P\|_2 \leq \|R - P\|_2 \tag{50}$$

where the Euclidean Norm , denoted by $\| \ \|_2$, represents the straight line distance between the two points examined. Once this function is satisfied, the attractiveness of a nodal location, A_i, is calculated according to

$$A_i = (\|R - P\|_2 - \|Q - P\|_2) + (\Lambda - \frac{n_{\max} - n_i}{n_{\max}}) \tag{51}$$

where $\|Q - P\|_2$ is the distance of the proposed node from the occupant's target exit, $\|R - P\|_2$ is the distance between the present node from the occupant's target exit, Λ is an arbitrary internal constant reflecting the additional desirability of a position due to its connectivity, n_i is the nodal connectivity and n_{max} is the maximum nodal connectivity (set to 8 within the buildingEXODUS model).

It is important to integrate this algorithm into the system with other elements of the behavioural model, such as the effect of the population density (see Section 6.2) and the environmental conditions (see Chapters 7 and 8). As mentioned previously, all of these proposed systems require the individual to constantly interact with the environment, receiving information and interpreting this information individually. During conditions of high population density or smoke, the unattractiveness of the nodes calculated as being close to the boundary may be ignored or become dominated by other conditions. Therefore although still an important factor the impact of the occupant's position in relation to the boundary is given a lower priority than these other conditions.

6.1.4 VERIFICATION

Hypothetical and real-life cases will be examined to demonstrate the qualitative improvements that can be gained through the implementation of the behaviour, especially involving individual geometrical cases (see Table 6-1). This involves

- 6.1.41 Examining the impact upon simplistic structures of relatively low population density
- 6.1.42 Observing the impact upon more complex validation cases such as the Tsukuba Pavilion evacuation in Chapter 4. The scenarios generated during this case allow examination of high and low-density situations as well as examining the interaction of the algorithm with a variety of terrain types.

These cases should both demonstrate the quantitative and qualitative impact of the proposed behaviour as well as highlighting any potential shortcomings.

TABLE 6-1: VALIDATION CONDITIONS

Scenario	Geometry	Population
6.1.41	Hypothetical 20m x 5 m, single free flow exit 1.5m	120 default occupants, instant response, randomly located
6.1.42	Tsukuba (see Chapter 4)	500 occupants, instant response, positioned in seating arrangement

CASE 6.1.41

A hypothetical geometry with a *relatively* low-density population movement is examined. The geometry is filled with 120 occupants that generates an average population density of 1.2 p/m^2, within the geometry of 20m x 5m. A single exit of 1.5m in width is provided, towards which all of the occupants move. The occupants are generated using the Population Panel system (see Section 3.1, Chapter 3), generating a distribution of occupant attributes. However, to maximise the possible influence of the proposed behaviour, all of the occupants respond instantly.

This hypothetical verification investigates the results produced through the use of the present model in scenario 6.1.411 and the differences that might be produced through the introduction of the proposed behaviour in scenario 6.1.412. The simplicity of the geometry is intentional to minimise any uncontrolled variables within the simulation.

RESULTS- CASE 6.1.41

There was no anomalous behaviour encountered during the simulations in case 6.1.41. This would have included unrealistic path adoption or the absence of route options outlined earlier and the subsequent locking of occupant movement that would have ensued. This is demonstrated through examining the shape and similarities of the evacuation curves described in Figure 6-4. These would be expected to show significant differences in shape or position if anomalies had occurred.

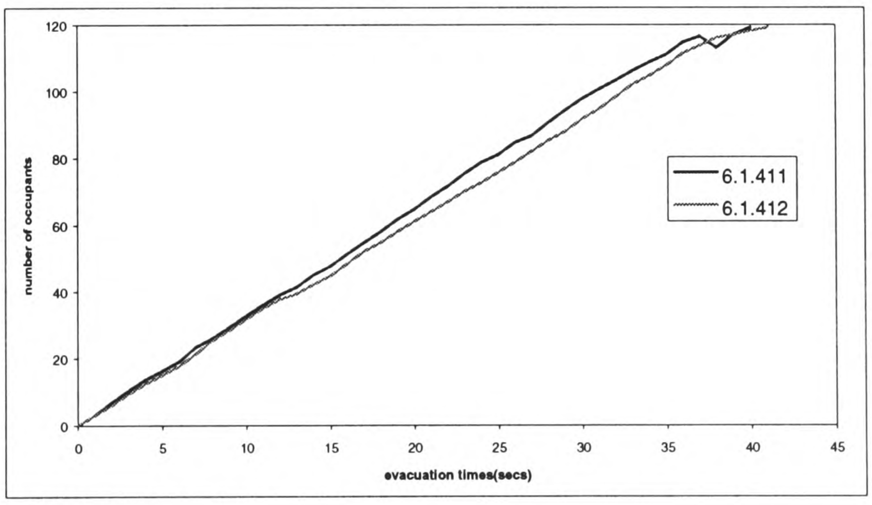


FIGURE 6-4: AVERAGE CUMULATIVE ARRIVAL GRAPHS GENERATED FOR 6.1.41.

The quantitative results generated during this validation provide evidence that *the introduction of the proposed behaviour does not greatly (or adversely) affect the simulation times generated* under the low-density conditions examined (see Table 6-2). Indeed, the discrepancy produced through the introduction of the proposed model over the present behavioural model is only 3.8%. This was due to the effective narrowing of the geometry, as the nodes in close proximity to the boundary were, where possible, avoided by the occupant population. As well as the average evacuation time produced being similar, a similar evacuation time distribution is also produced (see Table 6-2)

TABLE 6-2: OVERALL EVACUATION TIMES GENERATED IN 6.1.1, WHILST IMPLEMENTING THE DIFFERENT BEHAVIOURAL MODELS.

Behavioural Model	Evacuation times (secs)
Present 6.1.411	37.8 [36.1-40.3]
Proposed 6.1.412	39.3 [37.4-40.3]

The impact of the boundary effect is not seen to dominate the other considerations of the model, such as the resolution of conflicts. *According to these results, the introduction of the proposed behaviour under low-density conditions (1.2p/m^2) presents qualitative advantages with only modest changes in the quantitative results, that may been specific to this scenario.*

CASE 6.1.42 THE TSUKUBA PAVILION CASE

The Tsukuba Pavilion Population Movement [194] is presented to examine a more complex geometry and the occupant's interaction with the enclosure boundary under such conditions. Due to the more complex nature of the geometry, the conditions that the occupant's experience will fluctuate allowing a more general set of results to be established (see Figure 6-5).

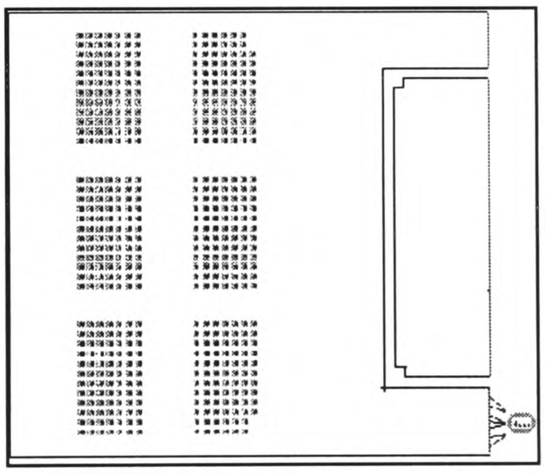


FIGURE 6-5: THE TSUKUBA PAVILION GEOMETRY.

However, the case involved a number of external influences (including inclement weather conditions [194]) and omissions from the original data-set (e.g. occupant response times [194]). This is discussed in detail in Chapter 4. In an attempt not to mask any inaccuracies that may occur due to the introduction of the proposed behaviour, the weather conditions that were present during the original event are not simulated. Therefore, in scenarios 6.1.421-6.1.422, no attempt is made to restrict the flow through the external exit, in an attempt to represent the weather conditions. In scenario 6.1.421, the results of the present model are provided to create a control case. In scenario 6.1.422 the proposed algorithm will be used to simulate the same conditions. (See Section 4.3, Chapter 4 for more details on the original simulations).

TABLE 6-3: DIFFERENT SCENARIOS EXAMINED IN CASE B1.3

Scenario	Behavioural model	External Conditions	Response Times (secs)
6.1.421	Present	Ignored	0, 0-90
6.1.422	Proposed	Ignored	0, 0-90

In both cases the response time distributions were varied between 0 and 0-90 seconds. This varies the level of congestion around the single exit and the congestion *en route* to the exit. For further analysis and explanation of this case, see Chapter 4.

RESULTS-CASE 6.1.42

The introduction of the wall proximity algorithm in 6.1.422 increases the overall evacuation times by 6.8% over the values produced by the present implementation in scenario 6.1.421 (see Table 6-4).

TABLE 6-4: THE RESULTS FROM THE TSUKUBA PAVILION, FREE FLOW

Scenario	Instant response	0-90 second response
6.1.421	95 [92-97]	144 [143-147]
6.1.422	105 [104-105]	150 [149-151]

This additional delay is caused by the constriction of the path between obstacles, forming narrower bottlenecks, through which the occupants had to pass. As expected, the results that are produced *converge* as the distribution of response times increases, due to the lower levels of congestion generated at the exit and the subsequent access of the floor-space. The increase in the evacuation times produced by the introduction of the proposed behaviour then falls to 3.8% (Scenario 6.1.422) (see Table 6-4).

The introduction of the proposed method did, however, demonstrate a qualitative improvement over the present method (see Figure 6-6), with the occupants maintaining a distance from the enclosure boundaries where possible. In the present model, the occupants are encouraged to maintain a path in close proximity to the boundary of the enclosure, given the positioning of the exit. Unless they reduce the distance to the occupant's target, the appearance of more central locations will have no effect upon the route available choice.

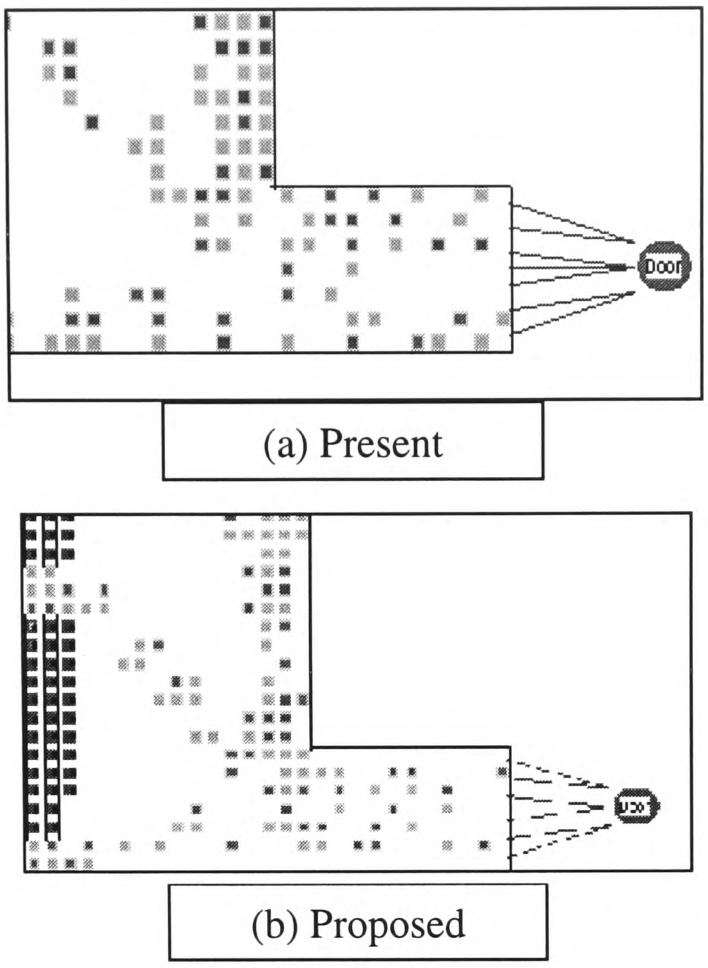


FIGURE 6-6: THE TENDENCY FOR THE OCCUPANTS TO VEER CLEAR OF THE EXIT BOUNDARY CAN BE OBSERVED IN (B). IN (A) NO ATTEMPT IS MADE TO OCCUPY THE CENTRAL RAFT OF THE CORRIDOR.

As can be seen from Figure 6-6 the qualitative changes are especially noticeable at low population densities where the option to select a location further away from the enclosure boundary is evident. *At higher population densities the occupants are forced into the limited space available to them, therefore reducing the qualitative differences between the scenarios.*

6.1.5 FUTURE WORK

A useful development would be to incorporate the occupant reaction to different forms of obstacles, such as furniture, walls, etc. and the impact that this had upon the occupant evacuation route. This would allow the occupant to maintain different distances according to the evidence provided by Fruin, Pauls [56,66,177].

It is also difficult to know the thresholds at which the occupant reaction to the boundary alters from being one of avoidance (under regular conditions, such as during daily use) to one of attraction (under more extreme conditions, such as smoke-filled environments [9]). A more realistic representation would require further analysis of the limited data available.

6.1.6 Conclusion

It is essential for the occupant to adjust their egress route according to the obstacle posed by the enclosure. To be consistent this should be applied at the macro level (long-term route adaptation), as well as at the micro level (maintaining distance from boundary surfaces). The long-term consideration is substantially catered for in the existing model (see Chapter 3) through the provision of the potential map system. Therefore the proposed behaviour is concerned with the short-term proximity considerations.

This process has been shown to adequately represent the ability of the occupant to analyse their path and maintain a distance based on the evidence available, without generating unforeseen occupant behaviour or anomalies in the simulation process.

The introduction is flexible enough to allow the occupant to adapt their route and therefore make choices upon their location according to the exact nature of their circumstances. It has been demonstrated that under certain conditions (for instance, a high-density population) the occupant may be forced into close proximity with the enclosure boundary. This option should always remain open to them.

Some differences were noticed in the quantitative results produced, especially under these high-density conditions. This is due to the effective narrowing of the enclosure and the subsequent increase in conflict resolution. However, the proposed behaviour introduces *local* differences into the occupant's navigational procedure that are dependent upon the surrounding conditions. These conditions will fluctuate according to the location and movement of individual occupants. This is important as any representation of occupant calculation that had a global effect would be inconsistent with the evidence available.

6.2. The impact of the surrounding population density upon route adoption

6.2.1Expected Occupant Behaviour

Mills comments that

> *"a state of crowding existed and is perceived as such by the individual, when the individual's demand for space exceeds the available supply of such space". [204]*

The importance of this definition is that it refers not only to the physical imposition of high-density populations but on the ability of the occupant to perceive such circumstances. In terms of evacuation, this occurrence might be directly related to the interruption of the occupant's egress route due to the close proximity of other occupants [1,66] as well as affecting route adoption.

Fruin found that occupant movement was directly related to the space available around each occupant [66]. Depending on the circumstances, the occupant expected different levels of space in which to move and adapted their movement patterns accordingly. He noted that, if possible, occupants attempted to maintain a '*no touch zone*' around themselves that allowed free movement and did not infringe upon what might be defined as the occupant's '*personal space*' [66] (see Figure 6-7). *The logical extension of this finding is that if space is available, that would allow free movement, and that the occupant desires to maintain their travel speed, that they would choose to move into that space, given that no other factors were influencing their decision.* .During this process, the occupant also attempts to maintain the zones identified by Fruin in their desire to move freely (see Figure 6-7).

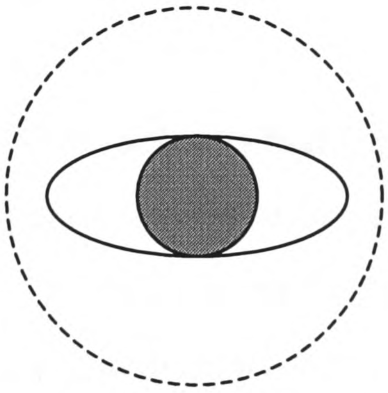


FIGURE 6-7: REPRESENTATION OF THE COMFORT ZONE DESCRIBED BY FRUIN [66]

The impact of the population is not purely physical. As noted by Stokols,

> *"Crowding is a psychological variable; the experience of crowding depends not only upon population density but also upon the circumstances under which the population density occurs". [204]*

Therefore the navigation procedure employed by the occupants will not simply be concerned with their ability to manoeuvre in relation to the other occupants, but will also take into account the psychological needs of the occupants involved.

The occupant therefore will react to the presence of other occupants when they are in close proximity and when they are impinging upon their ability to move to a desired location.

6.2.2 PRESENT BUILDINGEXODUS IMPLEMENTATION

At present, occupant movement is only affected by other adjacent occupants who act strictly as physical barriers. This not only allows the high-density populations to adhere to the potential map, but also, in less dense populations, allows evacuating occupants to approach slower/static occupants very closely, prior to overtaking them.

6.2.3 PROPOSED BEHAVIOURAL MODIFICATIONS

The method suggested to represent the behaviour described is the implementation of a localised *density function.* This calculates the *desirability* of the location available to the occupant according to the distance of the occupant from their target and the population density of the target location and its surrounding area .

This should not be confused with the use of density-flow calculations used in some of the more simplistic evacuation models outlined in Chapter 3. In the proposed behaviour, the population density *affects* occupant speed, whereas in these models population density *determines* occupant speed.

In the proposed algorithm only those locations that are closer to the eventual goal of the occupant are included in the population calculation (as in Section 6.1). In keeping with the rest of the buildingEXODUS model, occupants do not continually attempt to move away from a target to lower their population density. This is demonstrated in Figure 6-8, where the nodes given a thick border will be those considered in the calculation (those that are hatched might be considered according to the distance calculation). It would be a trivial matter to extend this behaviour to include all of the surrounding nodes but would require extensive testing and is therefore left for future work.

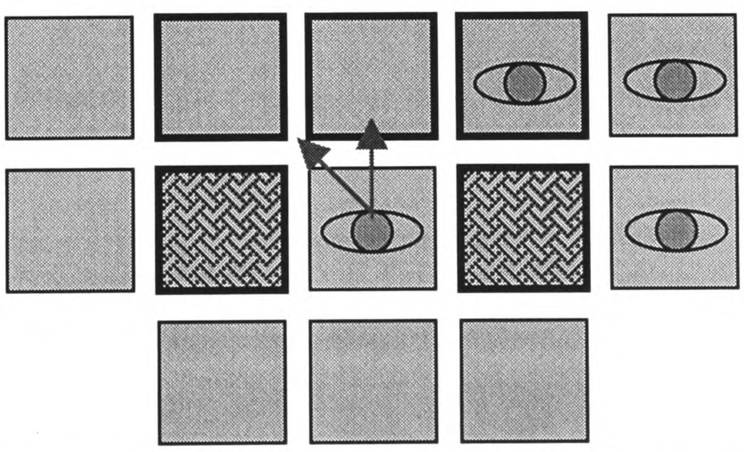


FIGURE 6-8: PROPENSITY OF THE OCCUPANT TO MOVE AWAY FROM A MORE CROWDED REGION OF THE GEOMETRY. ANALYSIS CONCERNS NODES WITH DARK EDGE AND POSSIBLY THOSE HASHED.

Within the buildingEXODUS model, the node's potential is increased inversely with the population density recorded at each node. Therefore given that *P*, *Q* and *R* represent the three locations examined such that

$$P = [x_{exit}, y_{exit}], Q = [x_{target}, y_{target}], R = [x_{present}, y_{present}] \quad (52)$$

then the following relationship must be satisfied to allow the connectivity of the proposed node to be considered.

$$\|Q - P\|_2 \leq \|R - P\|_2 \quad (53)$$

representing the locations of the proposed node and present nodes in relation to the target exit. Once satisfied, the attractiveness of the nodal location according to the population density is calculated as being

$$A_i = (\|R - P\|_2 - \|Q - P\|_2) + (\Delta - \frac{\rho_i}{\rho_{\max}}), \text{ where } 0<\rho_i\leq 1 \quad (54)$$

where A_i is the attractiveness of the node in question, $\|Q - P\|_2$ is the distance to the target exit from the target node, $\|R - P\|_2$ is the distance to the target exit from the present node, ρ_i is the population density of the node, ρ_{max} is the maximum density achievable at that nodal position and Δ is an arbitrary internal constant representing the additional desirability of a position due to its low population density.

The population density is calculated according to

$$\rho_i = \frac{\sum_{i=1 i\neq j}^{n} \sum pers + \sum_{i=j} pers}{n} \quad (55)$$

which determines the number of occupants situated on the node presently occupied (node j) plus the number of occupants on the adjacent nodes. This is then divided by the total number of nodes involved in the calculation. The density will always be greater than zero as the occupant determining the population density is included in this figure. *Therefore nodes which are attributed with low population density calculations will be considered relatively favourable.*

In the present model a similar attractiveness calculation is made, except that no reference is made to the population density, such that

$$A_i = (\|R - P\|_2 - \|Q - P\|_2) \tag{56}$$

Therefore the remaining distance to the exit from each of the nodal locations available, strictly controls the occupant movement. It should be remembered that in both cases the A_i value of individual nodes has no intrinsic value other than as a comparison against other nodes.

The population density is only a factor during the traversal of particular terrain types. For instance, on a stairwell or in seated arrangements, the exact population density may not be as great a consideration as in a more conventional terrain, where it would have more of an effect (see Figure 6-8). The proposed behaviour is only considered if the occupant is located on a horizontal empty surface, instead of a stairwell, seat, etc.

This calculation is discarded as the occupant approaches an exit. This provision is again included to prevent unnecessary and inappropriate occupant diversions away from their intended target, where the occupant's desire to exit the enclosure would supersede any reticence that the occupant may have in crowding. Therefore the results of the calculation are not included once the occupant is within 2.5m of the exit, allowing the occupant sufficient time to readjust their path towards the desired exit (this distance was chosen in line with existing buildingEXODUS thresholds [24]).

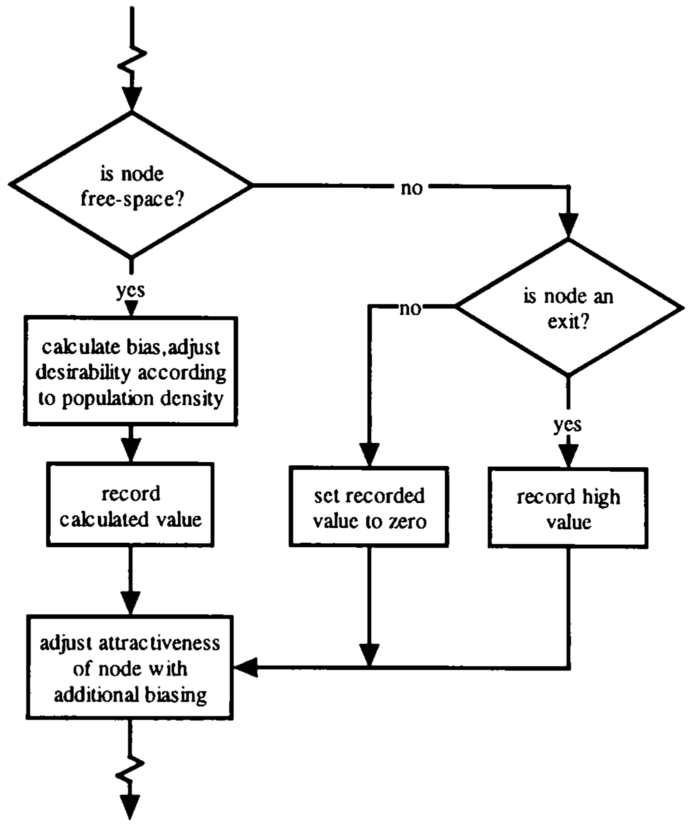


FIGURE 6-9: FLOW CHART REPRESENTING OCCUPANT REACTION TO POPULATION DENSITY

The importance of the imposition of the population density as a factor in route calculation reflects an important point that is evident throughout this dissertation and which is a fundamental principle in the buildingEXODUS models. A number of models (see Chapter 3) determine occupant speed according to the flow rate calculations from the density of the occupant population. The proposed algorithm and the buildingEXODUS model, assume that calculations are made at an individual level rather than being calculated according to macroscopic structures.

As well as this theoretical assumption, buildingEXODUS relies upon the resolution of conflicts between individual occupant vying for particular locations. Conflicts reduce the effective travel speeds of the occupant by providing small delay periods in their progress. The extent and number of these delays are dependent upon the motivation of the occupant involved (see Section 3.1, Chapter 3 and Chapter 4). Through the inclusion of the behaviour outlined in this section, not only are the occupants in conflict over particular locations, but are also attempting to minimise the number of conflicts arising, allowing for occupants to adapt their paths according to the availability of alternative routes. Although the occupants may travel an increased distance in attempting to reduce population density, this will be compensated for in the reduced number of conflicts experienced. These alternatives are truly short-term and the occupants will return to their 'optimal' path as soon as is practicable.

6.2.4 Verification

Similar to the effect of the proximity of the enclosure boundary (see Section 6.1), the proposed behaviour should be tested at low and high population densities and in a number of different scenario types. The cases are therefore designed to examine

- 6.2.41 The impact of the algorithm upon low-density populations, particularly examining the qualitative impact upon occupant path adoption where space is available
- 6.2.42 The consequences of the occupant population attempting to maximise their space given high-density conditions. These will then be compared against actual experimental data derived from the Stapelfeldt case (see Section 4.1, Chapter 4).
- 6.2.43 The introduction of the algorithm into a more complex environment that allows comparison with Tsukuba Pavilion results [194]. This allows the algorithm to operate under varying conditions.

TABLE 6-5: VALIDATION CASES USED TO EXAMINE THE IMPACT OF THE PROPOSED BEHAVIOUR.

Scenario	Geometry	Population
6.2.41	20mx5m	120 occupants (1.2 p/m^2)
6.2.42	Stapelfeldt (8.5mx3m)	100 occupants (3.9 p/m^2)
6.2.43	Tsukuba Pavilion (Irregular)(see Chapter 4)	500 occupants

All of these cases will be examined implementing the proposed behaviour and the present buildingEXODUS model for comparison.

CASE 6.2.41

The impact of the behaviour upon a low-density population is examined within a simple, hypothetical geometry. In 6.2.41, a rectangular geometry of 20m x 5m is randomly populated by 120 default occupants who head toward a single exit of 1.5m. These occupants respond instantly to allow unidirectional free-flow movement. This scenario should allow us to examine the impact of the proposed behaviour upon relatively low population densities (1.2 occupants per metre squared). The present model is examined in scenario 6.2.411 while the proposed model is examined in scenario 6.2.412.

RESULTS-6.2.41

From **Table 6-6** very little *quantitative* difference can be seen from the introduction of population density as a factor in determining egress routes, with a difference of 3% between the average times. This is important as if the introduction of the proposed algorithm in Scenario 6.2.412 produced a more realistic representation of the occupant distribution, the benefit in doing so would be negated by the changes in the quantitative results that have been previously shown to be relatively accurate (see Section 4.3, Chapter 4).

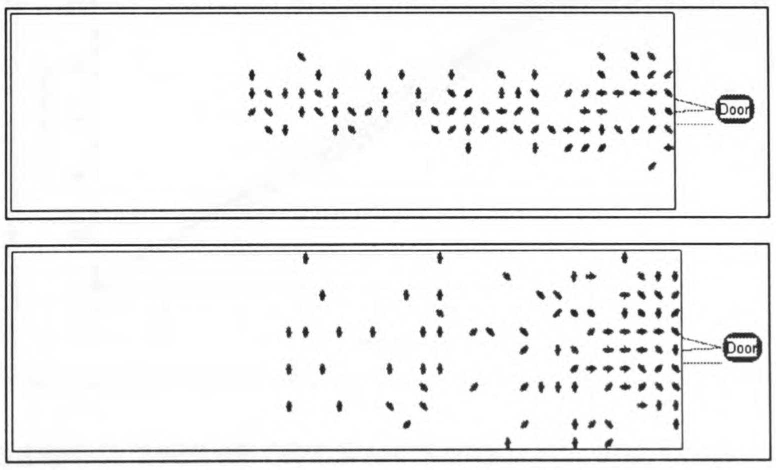


FIGURE 6-10: SNAPSHOT OF THE POPULATION MOVEMENT GENERATED THROUGH THE USE OF THE PRESENT (TOP) AND THE PROPOSED (BOTTOM) BEHAVIOURAL MODELS.

Instead of being limited to the central area of the geometry, seen in the present buildingEXODUS implementation, due solely to the production of the potential map, the occupants are forced to consider the more extreme reaches of the geometry, as they approach the exit (see Figure 6-10). The occupants are therefore seen to disperse over a larger area of the geometry.

Interestingly the proposed behaviour described in this section and that described in section 6.1 have approximately opposite effects upon the occupant population. The coincidence of these behaviours will be dependent upon the proximity of the occupant to the enclosure wall and the population density at the precise moment.

TABLE 6-6: EVACUATION TIMES PRODUCED IN 6.2.411 AND 6.2.412

Density behaviour implemented	Evacuation Times For Individual Populations (secs)
	Avg
Scenario 6.2.411 (Present)	**38.7** [36.7-40.4]
Scenario 6.2.412 (Proposed)	**37.5** [35.6-39.3]

However the qualitative differences are not reflected in the quantitative results in Table 6-6 and Figure 6-11, where there are obvious similarities between the occupant arrival behaviour.

If anomalies in the occupant behaviour were introduced by the new behaviour, then it would be expected that these would generate unusual evacuation curves. From examining Figure 6-11 this is not seen to be the case, as the curves generated have a high degree of similarity.

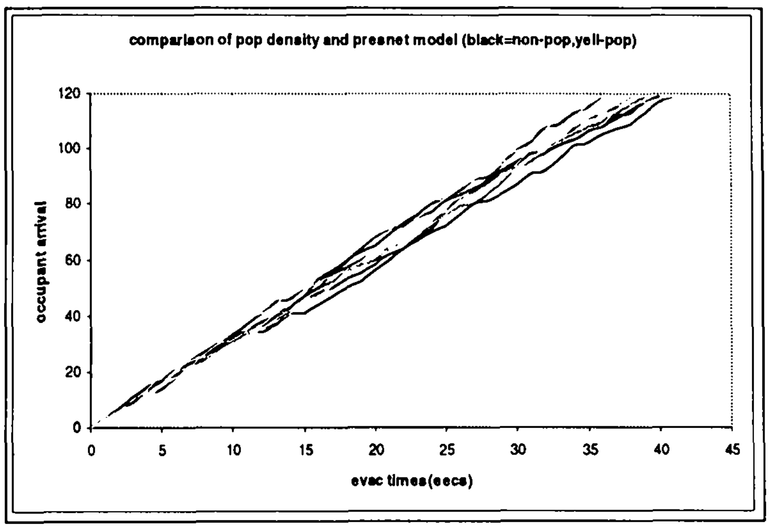


FIGURE 6-11: TYPICAL ARRIVAL TIME OF OCCUPANTS IN 6.2.41. THE LIGHT DATA POINTS REPRESENT SCENARIO 6.2.412. WHILE THE DARK DATA POINTS REPRESENT SCENARIO 6.2.411.

A closer examination can be attempted through the analysis of the distances travelled by individual occupants during the simulations. It was expected that during the introduction of population density as an influence in navigation, that the occupant would travel further during the simulation, due to more circuitous nature of their route in avoiding other members of the population and maintaining free space.

As can be seen in **Table 6-7**, the distances travelled by the occupants are similar with, if anything, a slight *decrease* in the distance travelled, when the population density is a consideration (with a reduction of approximately 4%). Importantly, this demonstrates that the expected increase in occupant travel distances due to the introduction of the proposed behaviour might be compensated by the increased availability of space due to the more distributed nature of the population.

TABLE 6-7: AVERAGE DISTANCE (IN M) TRAVELLED BY EACH OCCUPANT

Density behaviour implemented	Avg. Distance (m)
Scenario 6.2.411 (Present)	**12.6** [12.5-12.7]
Scenario 6.2.412 (Proposed)	**12.1** [11.8-12.2]

This trend is confirmed through examining Figure 6-12, where the distances travelled by each occupant would be expected to be related to the model implemented, if the occupants experienced greater travel distances. If this were the case, under the proposed model, the occupants would be expected to travel a greater distance, to avoid areas of high density. Instead of this a reasonable distribution of results between all of the simulated occupants are visible. Again, it is the local conditions of the individual rather than the overall effect that seems to dominate these results.

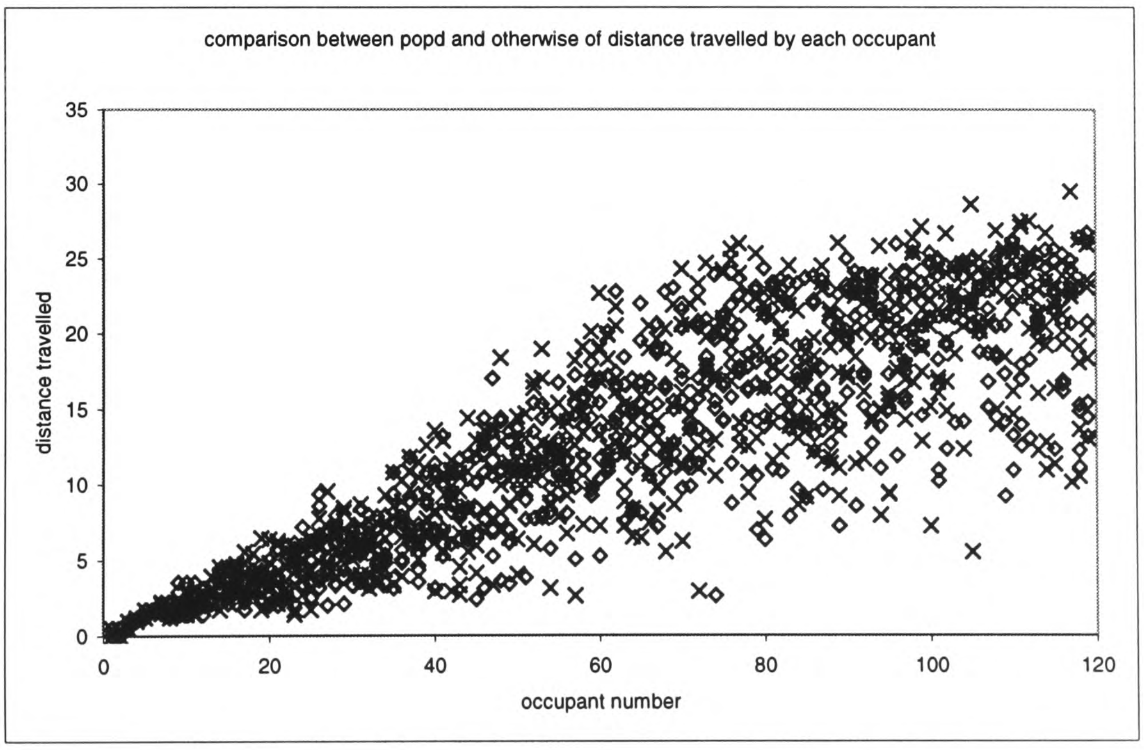


FIGURE 6-12: COMPARISON BETWEEN THE DISTANCE TRAVELLED BY OCCUPANTS IN 6.2.412 (CROSSES) AND 6.2.41 (DIAMONDS).

In this low-density example the qualitative advantages produced have therefore not been at the expense of the quantitative accuracy of the overall model.

CASE 6.2.42

In 6.2.42 a near saturated real-life incident is simulated (see the Stapelfeldt simulation in Section 4.1, Chapter 4). The high population density allows the impact of the behaviour to be traced under high-density conditions and compared against real-life observations. The scenario is produced to represent the validation case as closely as possible, whilst implementing the 40% drive distribution (one of the original cases). At present, the drive distribution has no impact upon the occupant's response to the population density, although it might be considered for future work. The present model is represented in 6.2.421 while the proposed model is represented in 6.2.422.

RESULTS- 6.2.42

During the introduction of the proposed behaviour in 6.2.422, as the population began evacuating through the single exit, an increased level of movement around at the rear of the population arch could be seen. This is due to the occupant's *appreciating* the existence of space and taking this into consideration when selecting their next location (see Figure 6-13).

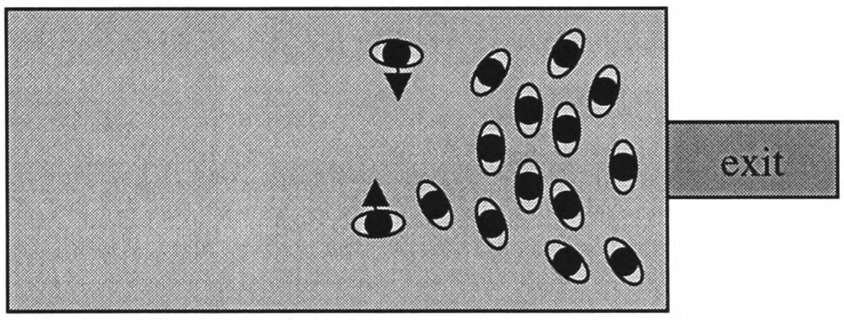


FIGURE 6-13: ARCHING BEHAVIOUR EXHIBITED WHILST IMPLEMENTING PROPOSED MODEL.

However, although this again allows for a more realistic representation of the arching phenomenon, it is not a dominant influence on the overall evacuation time. The overall evacuation time is substantially dependent the exit width, the drive distribution and the population saturation levels described. The introduction of the proposed behaviour in 6.2.422 only produced an increase of less than 2% over the results in 6.2.421 (see Table 6-8).

TABLE 6-8: COMPARISON OF THE STAPELFELDT RESULTED WITH/WITHOUT THE INFLUENCE OF POPULATION DENSITY.

Density behaviour implemented	Population
6.2.421 **(Present)**	30.0 [28.8-32.3]
6.2.422 **(Proposed)**	30.8 [28.1-33.3]

Again, no anomalies in the occupant movement or arrivals are evident in the curves generated (see Figure 6-14). Under both behavioural models the occupant arrival curves generated are almost linear, being dependent upon the occupant crowding around the exit.

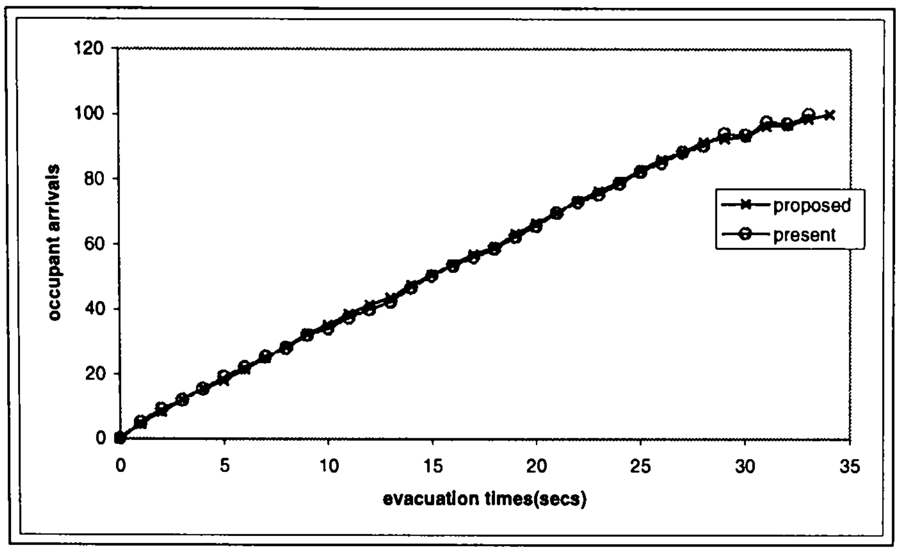


FIGURE 6-14: COMPARISON OF THE OCCUPANT ARRIVAL CURVES GENERATED.

The production and maintenance of high-density conditions demonstrate that occupants attempt to minimise the surrounding population density, rather than automatically ignoring areas of high-density.

CASE 6.2.43

In 6.2.43, the impact of the introduction of the behaviour is examined in context with a more complicated geometry; that of the Tsukuba Pavilion (see Section 4.3, Chapter 4). This allows the examination of the introduction of the proposed behaviour upon a fluctuating population density, as well as upon a more complex and less uniform geometry. The 500 occupants are assumed to respond instantly or over a period of 90 seconds. The occupants not only have to cope with an irregular geometry but also have to contend with a seating arrangement that prevents direct access to a single exit, which is attributed with free-flow conditions.

The impact of the present model is examined in 6.2.431 while the proposed model is examined in 6.2.432.

RESULTS-CASE 6.2.43 TSUKUBA PAVILION

Examining the quantitative impact of the proposed behaviour in 6.2.432, a number of observations can be made. In Table 6-9 a similar trend to that observed in section 6.1.422 can be seen; as the exit becomes less congested so the impact of the proposed behaviour becomes less significant. This reduction in congestion is due to the increase in the response time distribution, forcing the arrival of the occupants to occur over a greater period of time.

TABLE 6-9: THE TSUKUBA PAVILION CASE WITH A FREE-FLOW EXIT ATTACHED.

Scenario	Response Time Distribution	
	Instant Response	0-90 second
6.2.431 (Present)	95 [92-97]	144 [143-147]
6.2.432 (Proposed)	103 [100-107]	138 [136-142]

A contradictory pattern of results emerges, as the response times are altered. Once the occupants are assumed to respond instantly, the use of the proposed model causes a slight *increase* in the overall evacuation times (an 8.5% difference in the results). This is caused by the greater ability of the occupants to navigate around potential obstacles that might not have been possible if occupant navigation was entirely dependent upon the potential map (including the build up of occupants at bottlenecks or navigating around seating arrangements). This then caused greater congestion *at the exit*, as the occupants were subjected to fewer delays and therefore arrived in less time.

This impact of the proposed behaviour is reversed when the distribution of response times is applied, where a *reduction* of approximately 4.3% in the evacuation times is recorded. This is due to the same increase in navigational capabilities highlighted previously, except that the hindrance previously provided by occupant congestion distant from the exit has been removed, as the occupant response is not simultaneous. Therefore occupants arrive at the exit more quickly and on their arrival the build up of occupants is far less extreme (due to the distribution of response times), allowing smoother individual evacuation.

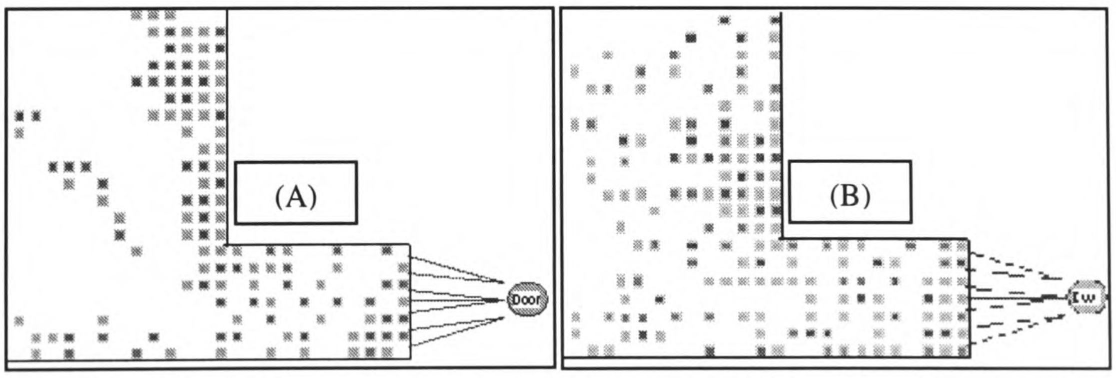


FIGURE 6-15: COMPARISON BETWEEN THE 6.2.431(A) AND 6.2.432 (B).

Even more significant are the differences present in the qualitative results. As already mentioned the imposition of the proposed behaviour allowed the occupants to have greater access to available floor-space. This might have occurred between seating areas, around crowd formations, etc. Generally, the occupants were able to maintain a more realistic distribution across the geometry floor, occupying a larger degree of the enclosure and not adhering strictly to the potential map. In Figure 6-15 the distribution of the occupants can be seen in relation to available free-space, whereas the more linear movement of the occupants under the present model is apparent in Figure 6-16, in comparison to the proposed model.

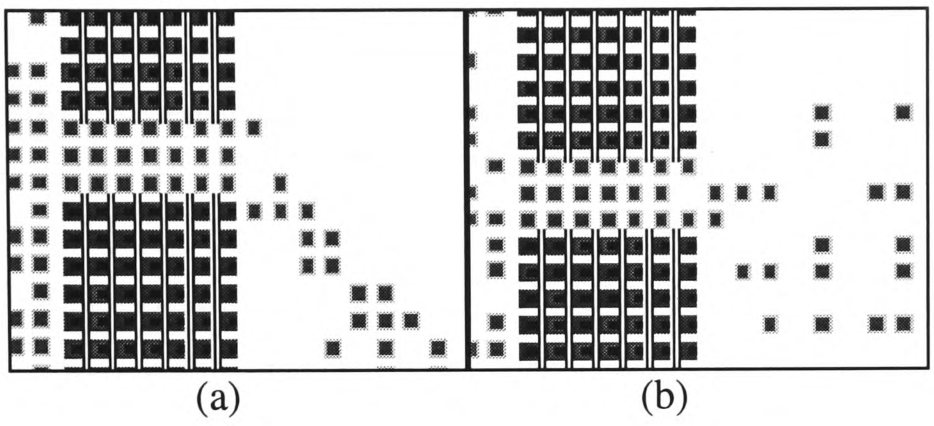


FIGURE 6-16: INTERACTION BETWEEN OCCUPANTS AND SEATING AREA. IN (A) THE PRESENT MODEL IS REPRESENTED WHEREAS THE PROPOSED MODEL IS REPRESENTED IN (B).

6.2.5 FUTURE WORK

In some circumstances, the identity of the surrounding occupants [163, 198] may impact upon the size of 'buffer zones ' [66] around the occupants. For instance a mother and child may be expected to maintain a closer proximity than two complete strangers. This might be taken into consideration, through examining the identity of the occupants involved and the severity of the surrounding conditions. These influences will also be influenced by the cultural and social context in which they occur. This type of behavioural representation will require substantial data.

Particularly motivated occupants may have an increased impact upon the surrounding occupants, so that extra biasing could be afforded to them, further discouraging the occupants from adopting a location nearby. This would coincide with our previous assertions from the findings of Fruin. Those occupants who are travelling in different directions (being attributed with different target exits) may also be particularly avoided, preventing the creation of small contra-flow systems.

The population density algorithm may be extended to include all of the surrounding nodes, not just those ahead of the occupant. This would promote a greater dispersal of occupants. The influence of the population may be made more sophisticated, according to the direction that the occupant is travelling, so that a *cone* is formed representing the occupant's visual awareness.

As populations move towards an exit the fluctuation in the crowd movement can cause a staggered effect on the movement of individuals (see Figure 6-17).

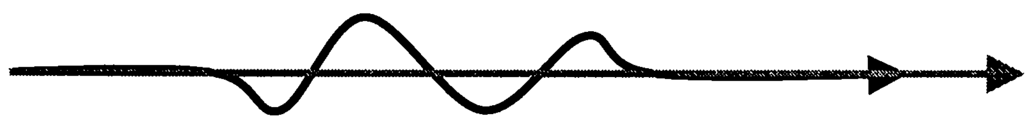


FIGURE 6-17: EXAGGERATED STAGGERING OF NEW FEATURE SHOWN IN BLACK WHILST ORIGINAL PATH SHOWN IN YELLOW

This is due to the short-term nature of the route calculation, so that as occupants move off the population density may change drastically. This problem may be resolved through a more long-term decision-making process or through a more intelligent analysis of the population density.

6.2.6 CONCLUSION

Similar to the considerations of the impact of the boundary, it is important for the occupant to take decisions concerning their immediate egress route based upon their perception of the surroundings. A fundamental part of these surroundings will be the occupant population.

The verification cases provided here demonstrate the importance of the proposed behaviour upon the qualitative behaviour of the occupants as well as correcting possible anomalies and difficulties within the present behavioural model. The implementation of the proposed behaviour within the buildingEXODUS model did affect the overall evacuation times produced. However this effect was noticeable once high-density populations had been formed and may have been exacerbated by the nature of the scenario geometry.

6.3 EVACUEE DELAY MECHANISM

6.3.1EXPECTED OCCUPANT BEHAVIOUR

During an evacuation, particular occupants may come to a halt for a brief period of time, for a variety of reasons. [205]. This might include window-shopping [66], observing a piece of information/signage [153, 202], or traversing particularly difficult terrain.

Although some of these examples may be associated with non-evacuation activities they may be equally performed by occupants who are unaware of the existence of an evacuation, or those that do not perceive the severity of the situation. Therefore, occupants who are delaying their movement for non-evacuation purposes may hinder those attempting to evacuate.

A different form of delay is caused by the occupant performing an action *during* an evacuation. This may include examining the surrounding conditions, fighting the fire, gathering information, etc. In reality, the outcome of the action will be the most important aspect to the engineer. However, the delay incurred by the occupant due to the performance of the action and the potential subsequent congestion may also have an effect upon both the individual and the surrounding evacuating population.

The implication of the occupant(s) becoming stationary may be significant, especially in narrow corridors, or if the occupants are positioned near to a functioning exit. Their presence may adversely affect the passage of other more mobile occupants, while obviously affecting their own egress time.

6.3.2 PRESENT BUILDINGEXODUS IMPLEMENTATION

In the present buildingEXODUS there is no *dedicated* mechanism to represent the delaying of an occupant once he has begun to evacuate. The only recommended method of delaying/preventing occupant movement is though increasing the *initial* response time. This provides a means to represent occupant delay. This is especially the case if the delaying effect being portrayed is localised, due to an impact of the terrain or through internal factors.

The manipulation of the geometry through extending the distances to be traversed by the occupant can have the effect of delaying the occupant's movement. However, this method is inappropriate as it uses the manipulation of an entirely unrelated factor (the physical distance to be covered) to represent the effect of a behavioural action.

A number of other methods may also be adopted, including the manipulation of the obstacle values attached to the arcs connecting specific nodes. This would be a localised effect. However, for this to affect occupants individually, the attribute that relates to this particular effect, *AGILITY*, would also have to be adjusted (see Chapter 3). This action would also affect other aspects of the occupant evacuation.

The halting of an occupant differs fundamentally from delaying an initial movement, which can be represented through increasing the occupant's *response time* (see Chapter 4). The occupant's initial response time already takes into consideration a number of factors vital to the accurate representation of the evacuation process (time to recognise the event as potentially serious, the time to decide upon an appropriate action, time to move off [1,4]). The response time cannot therefore simply be interpreted as accounting for any subsequent delays.

Occasionally, the two forms of delay (due to a delayed initial response or halting) might coincide, e.g. if the occupant's initial position coincides with an area that delays the occupant. This can at present be produced in the model through delaying the occupant's *initial* response to the evacuation. This would, however, not generally be the case. Superficially the two non-mobile occupants may appear to be acting in the same fashion but are in fact responding in two distinct ways.

6.3.3 PROPOSED BEHAVIOURAL MODIFICATION

The implementation of a delay area will allow the user to halt a section of the population as they arrive at a specified area. This will increase the flexibility of the model in simulating a range of occupant behaviour, without compromising the model or requiring unsubstantiated distortions of the model.

Within buildingEXODUS the unit of the delay area is the *node*. Therefore, the creation of a delay area will be constructed from collections of nodes (labelled *delay nodes*) that are defined as presenting the possibility of delaying further progress (see Figure 6-18).

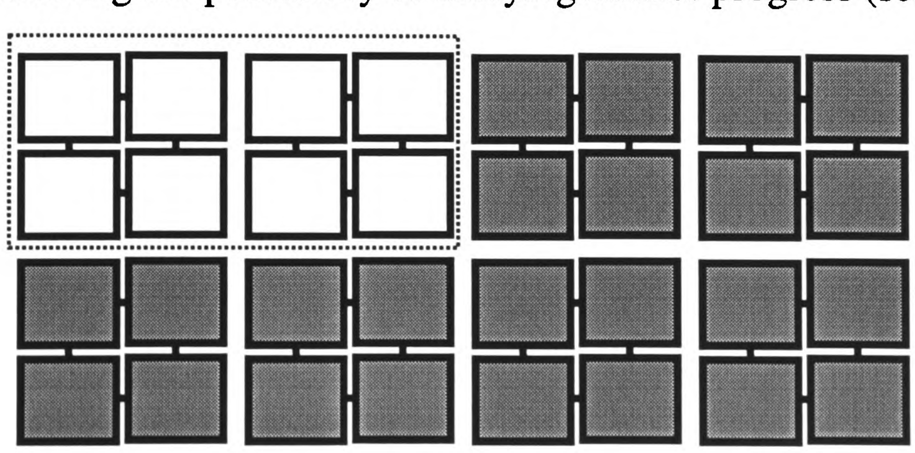


FIGURE 6-18: NODES ARE GROUPED TOGETHER TO FORM DELAY AREAS.

The likelihood of this event is dependent upon the motivation of the individual. This is initially based upon the assumption that occupants who are highly motivated will be less likely to delay their movement. In certain circumstances, such as if the user is attempting to represent the delay caused by fighting the fire, this assumption may not be sound. This problem may be addressed by either having the reason for the delay associated to the node, or having a more sophisticated dependence upon the occupant's attributes and the context of their actions or by having the conditions of delay open to user control. However, occupant motivation is deemed sufficient for demonstrating the concepts involved in the proposed behaviour and as an initial attempt at representing the occupant likelihood of delaying. To represent all of the contextual factors that may influence the halting of the occupant (identified in the previous section) would require a more detailed analysis and is left for further work. Therefore in this initial stage the simulation of the occupant's immediate reaction towards the hazard, although capable of being addressed, is not specifically dealt with.

The delaying of an occupant is calculated according to (57).

$$\frac{D_i}{D_{\max}} + \varepsilon \leq r_{delay} \qquad (57)$$

where D_i is the occupant's motivation, D_{max} is the maximum occupant motivation, ε is a random number between 0 and 1.0 and r_{delay} is the probability of delay. Therefore the lower the occupant motivation in relation to the maximum achievable, the *more likely* it is for the occupant to come to an halt. The user is able to determine the exact likelihood of delay (therefore setting the value of r_{delay} manually) or may (if the relevant information does not exist) allow r_{delay} to be produced internally (arbitrarily set to 1.0). This is based on the assumption that an occupant, who is fully aware of the emergency and becomes highly motivated, is less likely to delay movement. As highlighted previously, it is recognised that this is simplistic and that the decision should be taken in context with the situation and the occupant's previous actions.

The occupant is prevented from continually delaying their movement. This is achieved through the occupant having a memory of previous instances of delaying. If an occupant has previously delayed due to a delay node, he will be prevented from doing so again. This is important as the occupant who is continually delayed could be interpreted as continually performing the same action or influenced by the same factor. Means are required to prevent or control this process.

This is achieved by crediting the occupant with a memory of their previous delays. This arbitrarily limits the number of delays to a single instance. This restricts the behaviour especially in enclosures where a number of areas are deemed to cause delays. However, a more detailed examination of the impact of previous actions upon the likelihood of being delayed is left for future work.

As well as being able to control the probability of halting, the user can also control the extent of the delay provided by the delay area. In reality, the extent of the delay may be influenced by the events occurring in a particular area, including the time taken for a passenger to examine a timetable, for an examination of a particular shop window, the time taken to traverse unusual terrain, etc (see Figure 6-19). Information relating to this event can be supplied by the user who supplies an expected delay time, t_{user}, providing a estimation of the delay times expected.

$$t_{delay} = t_{\min} + (t_{\max} - t_{\min}) * r \qquad (59)$$

where t_{delay} is the calculated delay time, t_{min} is the minimum delay time, t_{max} is the maximum delay time and r is a random number between 0 and 1.0. If t_{min} and t_{max} are equal then the delay is constant.

If the user has no appropriate information concerning the expected delay times, then a default position is adopted with t_{user} set to 5.0 seconds. This is suggested as a default position and has no empirical basis.

Once on a delay node, the occupant remains motionless for an amount of time influenced by their *drive*, the *delay time attributed to the node* and possibly *the activities of other occupants*. Once this time has exhausted, the occupant moves off.

In general, the occupant stopping on a delay node will only occur under the NORMAL behaviour regime, based on the assumption that if the occupant is EXTREME he has been made aware of the emergency or has experienced extreme conditions and will not therefore stop on routine business (see Section 3.1, Chapter 3 and Chapter 4). In future this might be dependent upon the *exact nature* of the delay node or of the context in which it occurs. For instance, an occupant may be fighting a fire, opening a window, etc., all of which would occur under extreme conditions. This could be determined manually or could be automated. Therefore if the occupant has experienced hazardous conditions, is situated near to the fire and is delayed, then he could be assumed to be fighting the fire. Under these circumstances he could delay and be EXTREME simultaneously. The extension of this feature in such a way is achievable but would require extensive analysis and is left for future work.

The halting of a number of occupants may be significant, in that depending on the exact position of the population build up, significant blockages may form. The implementation of these nodes might then allow the user to determine the most effective position for such blockages to take place, to minimise the interference caused to the evacuating/mobile population. This would then represent a tool that would assist in the design of enclosures.

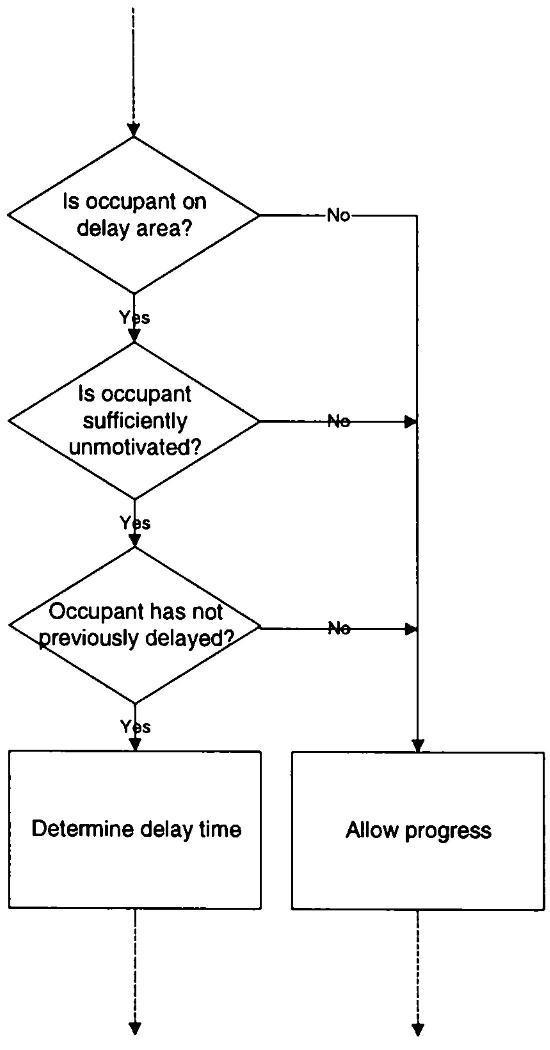


FIGURE 6-19: FLOW CHART REPRESENTING THE IMPLEMENTATION OF THE PROPOSED BEHAVIOUR

The actions of a group of occupants who are members of the same social group (see Section 5.2, Chapter 5 and Section 8.3, Chapter 8) arriving at a delay area is slightly different. These will be based around the activities of the most senior (see Section 5.2, Chapter 5) member of the group. These activities will be discussed in greater detail in Section 8.3, Chapter 8.

6.3.4 VERIFICATION

Several variables are examined to highlight the impact of delay nodes and the use of the proposed behaviour as a design tool (see Table 6-10). All of the scenarios are examined within a simplistic geometry so as to minimise the unknown variables and clarify the impact of the proposed behaviour.

- 6.3.41 The make-up of the population is varied to examine the impact of the occupant attributes upon the proposed behaviour.
- 6.3.42 The extent of the delay times attached to the nodes is examined. This feature allows potential users to include experimental data into the simulation process.
- 6.3.43 The representation of an actual event using the delay node mechanism is examined to determine the flexibility of the proposed system.

TABLE 6-10: VALIDATION CASES USED TO DEMONSTRATE THE IMPACT OF THE INTRODUCTION OF THE DELAY NODE.

Validation	Geometry	Population
6.3.41	20m x 5.5m 1m exit (free flow) delay nodes (7.5m x 1.5m) positioned Delay nodes positioned2.5m from exit	100 occupants, drive 5,10,15,20
6.3.42	20m x 5.5m 1m exit (free flow) delay nodes (7.5m x 1.5m) positioned Delay nodes positioned 2.5m from exit	100 occupants, drive constant at 10
6.3.43	Irregular hall, with desks	124 occupants with distribution of attributes and response times

CASE 6.3.41

A simple 20m x 5.5m geometry is implemented with a single 1m exit (see Figure 6-20). An area of delay nodes (4.5m x 1.5m) is positioned 2.5m from the exit so that that the occupants are forced to interact with them *en route* to the exit.

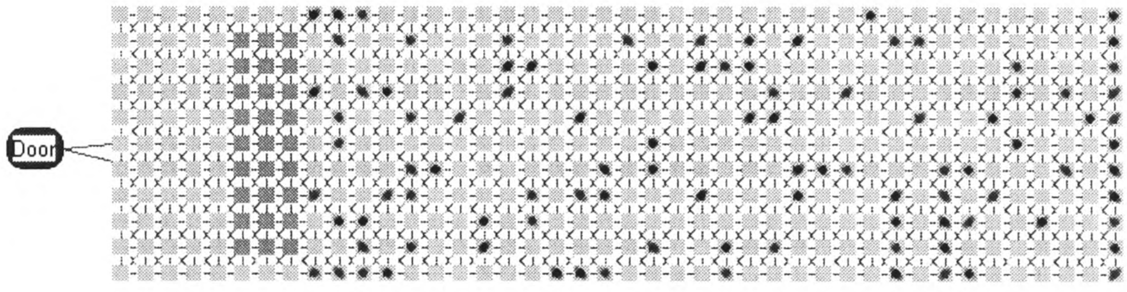


FIGURE 6-20: GEOMETRY USED IN THE VALIDATION OF THE DELAY NODES. THE DARK NODES REPRESENT THE DELAY NODES AS IMPLEMENTED IN 6.3.41.

Four occupant populations are examined. The drive levels of these populations range from 5 – 20 *motivational units* to examine the impact of the delay nodes upon the occupant movement, in conjunction with the occupant's motivation, this being the index that represent the likelihood of the occupant delaying their movement. All of these occupants are attributed with an instant response to provide a consistent basis from which the scenarios can be compared. The present model is examined in 6.3.411, whilst making no explicit attempt to delay the occupants at all. In 6.3.412, the present model is still utilised except that the geometry is deformed in an attempt to represent the delays experienced, whilst still using the present model. This is achieved by calculating the approximate average of the occupant speeds (given that they were taken from the Population Panel feature, see Section 3.1, Chapter 3) and therefore the additional distance that would be required to delay the occupants sufficiently to approximate the default delay period. The distance across the entire 'delay area' was therefore extended by 4m, given that an approximate average population speed of 1.3m/s).

Given that the delays simulated in the proposed model were of the order of 5.0 seconds, the manipulation of obstacle values attached to the arcs connecting the relevant nodes were not seen as capable of representing this behaviour.

The proposed model is examined in 6.3.413.

RESULTS-CASE 6.3.41

In case 6.3.411, where the present behaviour is in position without delay representation, no obvious influences can be derived from the alteration in the occupant motivation (see Figure 6-22 (a)) This is expected as no means to represent the delaying process is available that relies upon occupant psychological factors. The evacuation arrival curves produced all fall within a small area and maintain a similar shape, as there is no representation of the delaying mechanism.

During the distortion of the geometry in Scenario 6.3.412, some delay can be seen during the simulation. However, this was not dependent upon any psychological feature simulated within buildingEXODUS. It may have been possible to manipulate the occupant travel speeds to vary the occupant interaction with this geometrical deformation. However, this would not have been localised to the delay area. A more important impact of the physical distortion was the influence upon the path adopted by the occupants during the simulation (see Figure 6-21). The distortion of the geometry caused the occupants to divert around the 'delay area' as the potential map had been influenced. This minimised the impact of the delay mechanism. This problem may have been circumnavigated by the use of *ATTRACTOR* nodes (see Section 3.1, Chapter 3). However, it is not clear how this feature would respond in conjunction with manipulating the physical aspects of the geometry.

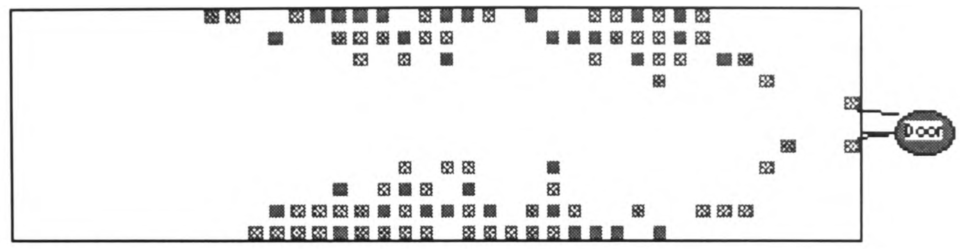
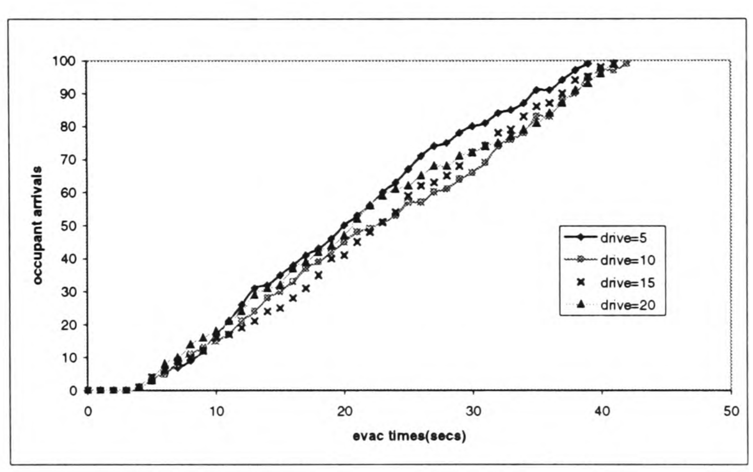


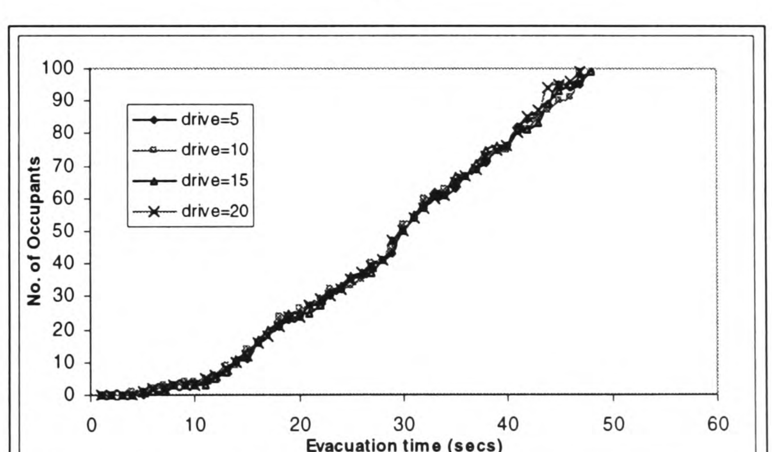
FIGURE 6-21: UNDER THE PRESENT MODEL, WHILST DISTORTING THE PHYSICAL SPACE, THE OCCUPANTS CAN CLEARLY BE SEEN TO AVOID THE DELAY AREA ALTOGETHER.

This highlights the difficulties in representing occupant delay within the present model, identifying the global influence of the mechanism across the population and the undesired impact upon the occupant path adoption (this process is also time-consuming).

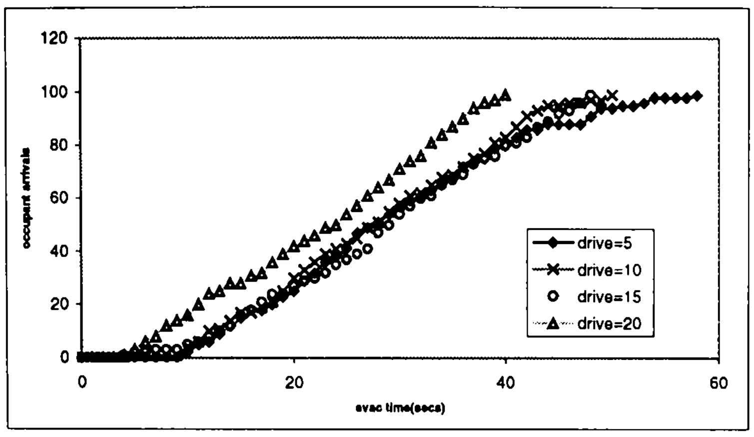
In contrast, when the delay nodes are introduced in 6.3.413, there are drastic changes in the results demonstrated by the cumulative arrival curves produced (see Figure 6-22(c)), due to the enforced delays. This was achieved without the accompanying difficulties highlighted in 6.3.412. During these simulations, the more motivated populations were seen to more often ignore the effect of the delay nodes and approach those of 6.3.411. These produce the faster overall evacuation time (see Table 6-11).



(a)



(b)



(c)

FIGURE 6-22: THE IMPACT OF OCCUPANT DRIVE UPON THE DELAY NODES IN 6.3.411(A), 6.3.412 (B) AND 6.3.413 (C).

From Figure 6-22 three distinct levels of delay are evident. In 6.3.411 (Figure 6-22(a)) no delay is evident, with the drive having no obvious bearing upon the arrival of the occupants. In 6.3.412 (Figure 6-22(b)) a reduced level of delay is evident, with motivation having no impact. Finally in 6.3.13 (Figure 6-22(c)), significant differences between the scenarios are evident, with an obvious trend existing in relation to the occupant motivation, as expected.

During the imposition of the proposed model, the occupant arrival curves formed are generally *parallel*, except at the initial and final stages. Initially it is apparent that the most motivated occupants (with a drive of 20) tended to ignore the existence of the delay nodes, therefore producing a steep arrival curve earlier in the simulation. Once the occupant flow stabilised, the arrival curves ran approximately parallel, as the occupant arrival tended to be more sporadic.

Towards the end of the simulation, the gradients and general shape of the curves changed according to the extent of the delays incurred by the occupants. Again, the extent of the delay was influenced by the occupant motivation.

TABLE 6-11: EVACUATION TIMES PRODUCED IN 6.3.411-13

Scenario	Drive			
	5	10	15	20
	Evacuation times (secs)			
6.3.411 (Present)	37.7 [34.8-43.1]	40.8 [36.3-45.9]	41.2 [38.6-43.3]	39.7 [37.3-42.4]
6.3.412 (Present)	45.6 [42.1-49.6]	44.2 [41.8-47.5]	46.3 [42.2-48.5]	46.1 [43.1-47.6]
6.3.413 (Proposed)	56.4 [54.8-58.6]	50.8 [46.9-57.1]	47.3 [45.8-49.6]	39.4 [36.1-41.3]

From Figure 6-23 and Table 6-11, an interesting consequence of the imposition of delay nodes can be seen.

In 6.3.11, no discernible pattern or delaying effect emerges. In 6.3.412, no pattern emerges other than the evacuation times being consistently higher than in 6.3.411. These delays were insensitive to the attributes of the occupant population.

Examining 6.3.413, when the occupant population is highly motivated, the delay nodes provide no hindrance to the evacuation time. This is because the arrival of occupants is more staggered than in the present model and therefore provides some relief to the congestion situated around the exit. This occurs while still allowing a steady flow of occupants through to arrive at the exit. This mimics the prevailing idea behind the implementation of procedures in large buildings and may point to another use of the delay node for instance, phased evacuations. As the motivation of the population decreases, so a greater proportion of the population delays, causing congestion to occur later on in the simulation.

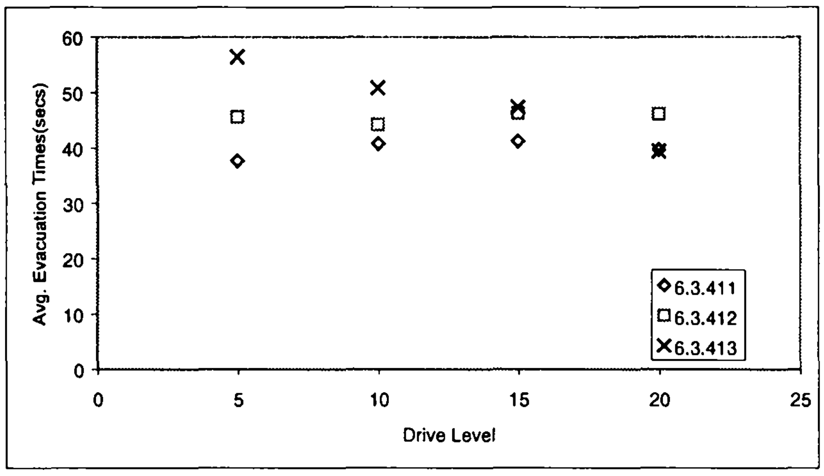


FIGURE 6-23: GRAPHICAL COMPARISON OF 6.3.411 , 6.3.412 AND 6.3.413.

CASE 6.3.42

In case 6.3.42, the geometry from 6.3.41 is implemented (20m x 5.5m), with the delay nodes positioned in an identical position. However in this case, the delay times applied are user controlled, ranging from 10 to 50 seconds. These are kept constant within each scenario, with the delay times being incremented between scenarios. This is to examine the impact of possible experimental data representing a variety of influences on the population. It is assumed that this data relates to the expected delay times imparted by the delay nodes, provided by the user. This might, for instance, represent a signage system offering different levels of information to the occupants who wait for varying periods of time to absorb this information (e.g. at a train station).

One hundred occupants, that are again produced using the Population Panel system, populate the geometry (see Chapter 3). The occupant motivation, already demonstrated as having an important impact upon the simulation, is kept constant (at 10) to minimise its influence during these simulations.

The results of the present model are not included, as it has already been demonstrated to have a limited capability to represent such an effect, due to the insensitivity of the behaviour to this attribute.

RESULTS-CASE 6.3.42

From Table 6-12 several important results can be obtained. Firstly, an increase in the delay times associated with the delay nodes *increases* the overall simulation times. This increase does not, however, linearly reflect the increase in the associated delay time. Instead, it is a more complex process, being influenced by the increased conflict resolution that occurs between occupants due to the greater congestion around the delay area. It is also relevant to examine the distribution of the results produced, which increase proportionately with the increase in delay times. The distribution of the evacuation times increased from approximately 1 second for the 10-second delay nodes to 49 seconds for the 50-second delay nodes, reflecting the increased impact of the data relayed to the occupant. This is due to the increased significance of occupants' refusing/accepting the delay node information.

TABLE 6-12: RESULTS FROM THE IMPOSITION OF DIFFERENT DELAY LEVELS

	Delay Level(secs)				
	10	20	30	40	50
Evacuation times (secs)	60 [59-60]	92 [88- 99]	108 [97- 126]	118 [86- 128]	147 [111- 160]

The complexity in the results is reflected in the fit of the polynomial trend-line, in Figure 6-24, which denotes the non-linearity of the relationship between the delay times and the impact on the evacuation times generated. (It should be remembered that the data points used to generate this trend-line each represent the average of five separate simulation runs).

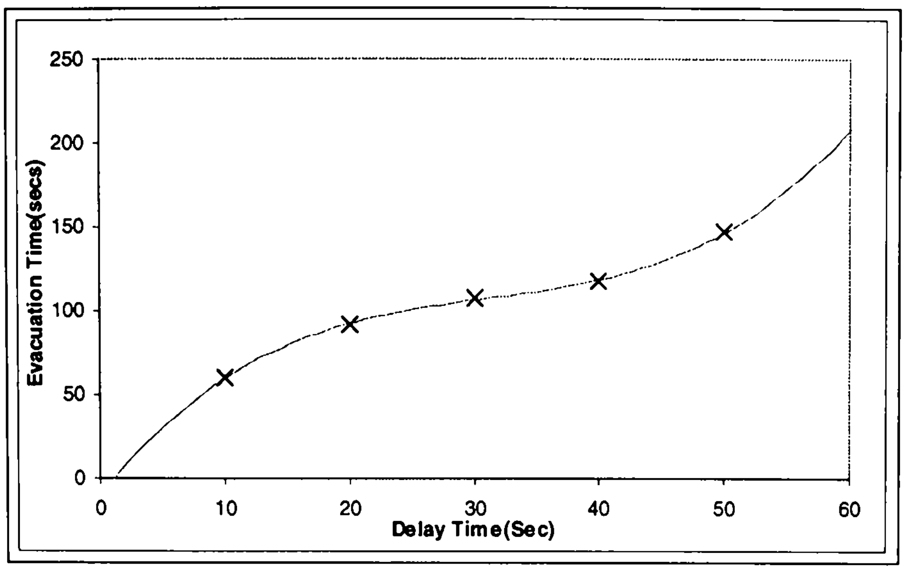


FIGURE 6-24: EVACUATION TIMES GENERATED GIVEN DELAY TIMES ATTACHED TO THE VIEWING AREA, WITH ACCOMPANYING NON-LINEAR TREND-LINE.

The importance of these results is to demonstrate that the effect of the delay area upon the evacuation times produced is not simply linear. As seen in reality [153], the exact response to delays and congestion are complex and can even, if monitored, accelerate the evacuation process.

The non-linearity visible in Figure 6-24 is due in part to the potential benefits to the overall flow through the single available exit provided by the delay nodes. As the delays imposed increases so this advantage declines, allowing a steeper rise in the overall evacuation times.

CASE 6.3.43

This case is based upon an actual population movement, measured whilst 124 students were leaving an exam hall. Their movement was staggered so as to minimise the congestion at the single exit.

The hall was 12m x 34m and contained 130 desks arranged in 9 columns. The hall had a single exit of approximately 0.5m. Other exits were available but were not used (see Figure 6-25).

The population was separated so that groups of the students left at specified intervals. These groups were formed from the columns of seats within the hall. The intervals between student movement were recorded at 60, 90, 150 and 180 seconds after the initial population movement. Before leaving, the students were required to collect their belongings from the front of the hall. This provided considerable congestion *en route* to the exit. On average the students were delayed for approximately 15 seconds, although a degree of variation existed between individual students. Unfortunately, due to limited resources available, the details concerning this distribution was not recorded. It was noted that some congestion occurred between the occupants irrespective of the staggering process.

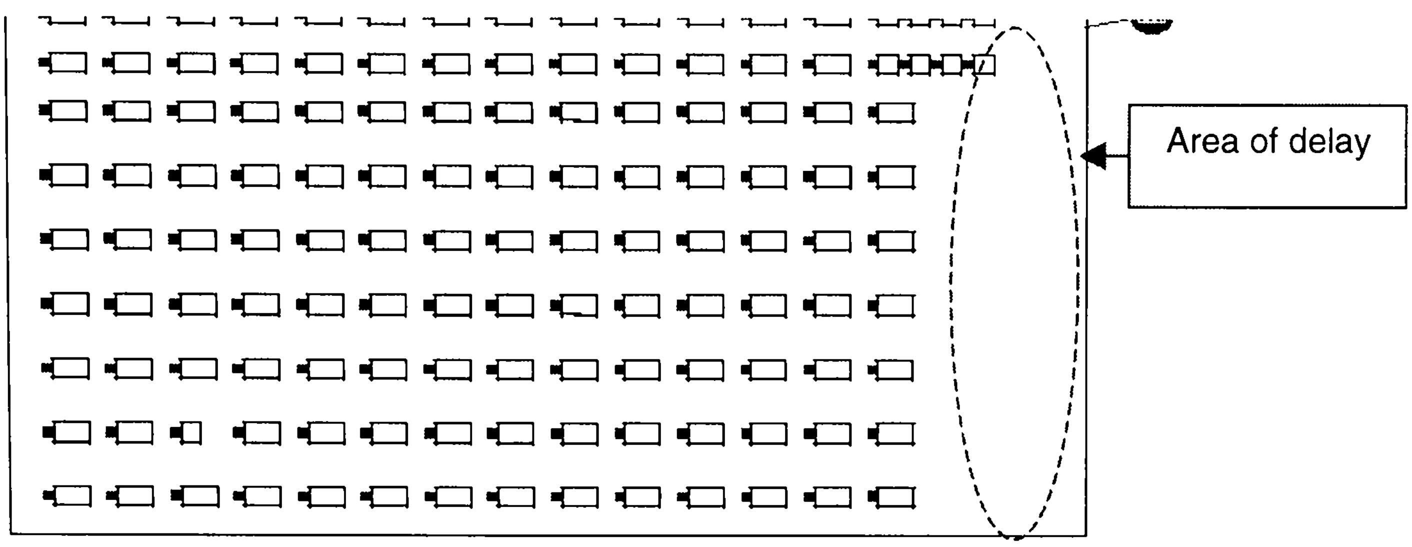


FIGURE 6-25: BUILDINGEXODUS REPRESENTATION OF THE SPORTS HALL.

The overall evacuation time was 270 seconds. Only one evacuation was examined, providing only one point for comparison. This obviously reduces the level of confidence in the results produced in this case.

To utilise this data, six scenarios will be examined. The occupant population is produced using the population panel mechanism (see Section 3.1, Chapter 3). The simulations were conducted under the normal behavioural regime, as no emergency conditions were evident to those involved.

In scenarios 6.3.431 and 6.3.432 the present model is used to examine how the evacuating occupants would be currently represented. In scenario 6.3.431 the occupants are attributed with an instant response time to provide a control case. In scenario 6.3.432 the response times outlined are attributed to the appropriate occupants to represent their staged response (e.g. 0 seconds, 60 seconds, 90 seconds, etc.). No representation of the collection of occupant belongings is made in either of these scenarios (see Table 6-13).

TABLE 6-13: DESCRIPTION OF THE SCENARIOS IN CASE 6.3.3.

Scenario	Scenario Description
6.3.431	Present Behaviour, Instant response
6.3.432	Present behaviour, Staggered Response
6.3.433	Proposed Behaviour Applied, Staggered Response, 10 second delay
6.3.434	Proposed Behaviour Applied, Staggered Response, 15 second delay
6.3.435	Proposed Behaviour Applied, Staggered Response, 20 second delay

In scenarios 6.3.433-6.3.435, the proposed behaviour is implemented. The delay nodes are positioned to represent the collection of belongings. The times attributed to the delay nodes are varied between 10, 15 and 20 seconds to examine the sensitivity of the evacuation times to the changing delay period.

The delay nodes are positioned around last 3m of the enclosure. Therefore, although the occupants are not attracted to the delay nodes, they will come into contact with them. Their reaction to them are then dependent upon the resolution of the equation provided.

RESULTS-CASE 6.3.43

Due to the relative free passage of the occupants to the exit in Scenario 6.3.431, the evacuation was largely dependent upon the exit conditions (see Table 6-14 and Figure 6-26). The evacuation times produced during Scenario 6.3.431 are significantly lower than the actual results as neither the delays nor the staggered response times are represented. The representation of the staged occupant movement within the present model in Scenario 6.3.432 alters the evacuation results significantly, producing a more accurate result. However, these results do not approximate the qualitative results. In the actual crowd movement, the occupants were seen to congregate some distance from the exit, around the points of luggage collection. The results produced during 6.3.431 suggest crowd congestion around the exit.

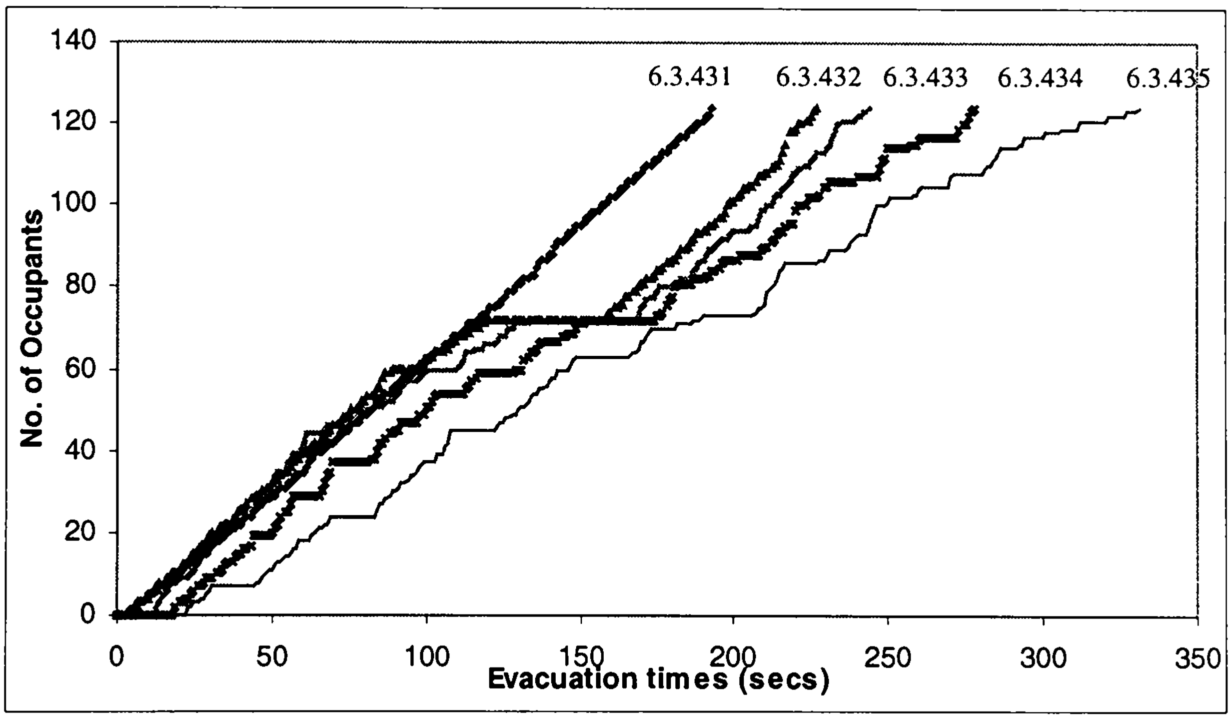


FIGURE 6-26: CUMULATIVE ARRIVAL CURVES FOR CASE 6.3.43

Once delay areas were introduced in scenarios 6.3.433-6.3.35 the evacuation results significantly altered. From Figure 6-26 the occupant arrival curves are less linear and generally more complex, due to increased number of variables affecting the outcome. As the imposed delay times increase, so the occupants become less dependent upon the exit conditions and more so on the impact of the staged movement and the effect of the consequent occupant blockages.

TABLE 6-14: RESULTS FROM CASE 6.3.3 (TET= TOTAL EVACUATION TIME, CWT= CUMULATIVE WAIT TIME AND PET= PERSONAL ELAPSED TIME)

Scenario	Avg. TET (secs)	Avg CWT times (secs)	Avg PET times (secs)
6.3.431	188 [183-192]	10 [10-10]	97 [93-100]
6.3.432	227 [221-228]	11 [9-13]	114 [112-116]
6.3.433	246 [240-253]	11 [9-13]	124 [122-126]
6.3.434	277 [273-281]	19 [18-21]	137 [136-139]
6.3.435	326 [316-332]	37 [34-41]	161 [157-164]

The individual occupant experience also changes dramatically, again in line with the increase in the imposed delay times (see Table 6-14). This is caused by occupants halting, due to the delay nodes, simulating the occupants collecting their belongings. *Importantly, this type of behaviour can now be represented.* This behaviour is deemed to increase the perceived occupant waiting time (the CWT) as they have begun to evacuate and are then faced with a delay. It is arguable as to whether there may be situations when the occupant stopping voluntarily may not be thought of by the occupant as being a delay. This is left for future work. In this instance however, the blockages caused to the mobile occupants by the other members of the population collecting baggage are definitely involuntary and should therefore be recorded as such.

Through the introduction of the delay nodes, the quantitative results represent the original results more accurately and do so through the introduction of appropriate influences. Due to the variation of the observed occupant delay times, scenarios 6.3.433-6.3.435 were included to examine the overall evacuation times. These scenarios produced times that were within 9.1, 2.0 and 20.8% respectively of the actual results. These generally present an improvement over the results from the present model, the best of which comes within 16.2% of the original data. However, the prediction made by the present model might be improved by engineering the occupant travel speeds or extending their response times to compensate for the extra delays. Both of these actions would, however, require justification.

A more qualitative examination of occupant behaviour demonstrates that not only do the times produced generally improve through the introduction of the proposed mechanism, but that the occupants were seen to behave in a similar manner. Therefore the occupants were seen to halt at a particular location and then possibly be subject to congestion due to other occupants coming to a halt.

6.3.5 FUTURE WORK

Generally the imposition of the delay node should be far more contextual. This could be achieved by analysing the experiences of the individual occupant. This could be compared to the location of the occupant in relation to other incidents, such as the seat of the fire, fire equipment, etc. In this manner, the model could then infer from the nature of the delay and the factors (such as occupant motivation) that might affect it. It should also be possible for the occupant to be attracted to specific nodes that then delay their passage.

As well as forcing the occupant to delay their movement, nodes may be constructed to pass information to the occupants, affecting other aspects of their behaviour. This information may relate to the need to respond (relating to the presence of an alarm system), or a change in direction (relating to the presence of signage).

The effectiveness of the alarm system is fundamental to the success of an evacuation (see Section 2.4.1, Chapter 2). This effectiveness is dependent upon the *clarity, believability* and *effectiveness* of the alarm system [1,64,66,82,83,117]. The effectiveness of an alarm system is vital in the occupant's perception and knowledge of the event.

As the size of the population involved in the evacuation from an unfamiliar enclosure decreases, so the necessity of signage increases to assist in the occupant wayfinding capabilities. Different forms of signage exist, from sophisticated, technologically advanced examples involving complex lighting systems and graphical screens, to more simplistic traditional methods [9,202].

In their reaction to alarm and signage systems, occupants initially have to *perceive* the imparted information prior to their interpretation of it. The clarity and effectiveness of the system is therefore an important factor in the acceptance of the information provided and will be dependent upon the environmental condition in which the sign is placed.

The algorithm would be dependent upon the use of nodes designed specifically to impart information. These would not signify the actual position of the system but the area within which information can be transferred. Once an occupant is situated in a specified area, he would be assumed to be either in visual contact with the sign or able to be affected by the alarm system and therefore may then receive new information. This information may take the form of new exit awareness or a reduction in the occupant's response time.

A probability could be assigned (either randomly or by the user) reflecting the likelihood of the occupant perceiving and believing the information. This probability would also incorporate a number of influences such as the effect of the environment upon the likelihood of perception according to the data derived by Jin [9] or the influence of the alarm type upon occupant response.

6.3.6 Conclusion

The development of the proposed behaviour has provided a number of distinct benefits. It enables the engineer to represent a relatively common occupant activity (that of delaying their movement), with a high degree of control and confidence. The results produced are sensitive to the occupant attributes as well as the conditions defining the delay area itself. The introduction does not only delay directly those occupants who are directly affected, but has a more complex impact, through the development of blockages and bottlenecks. This demonstrates how a relatively localised factor can feed through to influence a wider population. This type of facility therefore allows the engineer to examine the potential pitfalls of particular designs prior to their creation, in a flexible and appropriate manner.

6.4 Environmental effects as disturbances: Concluding Remarks

The developments in this chapter signify moderate progress in the simulation of occupant behaviour, through the simplistic interaction between the occupant and their surroundings (see Table 6-15). Although simplistic, this development does allow the occupant to react more appropriately to their immediate location according to the surrounding conditions, be they the proximity of the enclosure, the presence of other occupants or the prevention of free passage. The inclusion of these features have *desirably* affected the outcome of the simulations; in situations where no quantitative alteration was desirable, generally none occurred, while qualitative improvement was constant.

TABLE 6-15: SUMMARY OF THE BEHAVIOURAL DEVELOPMENTS IN THIS CHAPTER

Section	Development	Description
6.1	Navigation In Relation To The Enclosure	Enables more detailed representation of occupant movement
6.2	Navigation In Relation To The Surrounding Population	Enables more detailed representation of occupant movement
6.3	Evacuee Delay Mechanism	Enables the representation of localised blockages

CHAPTER 7 THE OCCUPANT AS A PSYCHOLOGICAL MECHANISM: THE IMPACT OF THE EVACUATION UPON THE OCCUPANT

The previous section proposed a number of simplistic changes to the occupant's ability to manipulate his behaviour according to external factors. This section represents a more advanced level of behavioural representation. The occupants perceive their surroundings and process the information available to them. The level of behavioural sophistication has increased within the model without introducing adaptive or complex decision-making processes. These representations include:

- **7.1. REPRESENTATION OF THE OCCUPANT MOVEMENT THROUGH SMOKE**
- **7.2. DYNAMIC BEHAVIOURAL REGIME REPRESENTATION**
- **7.3.THE LOCALISED REPRESENTATION OF OCCUPANT FAMILIARITY**

In 7.1 the movement of occupants through smoke-filled environments is developed. Instead of the occupants reaction to a smoke-filled environment being limited to an ability to maintain a constant speed, a reduction in the occupant's capacity to navigate is also represented. An individual representation of occupant familiarity is then described, enabling more sophisticated representation of the occupant's understanding of the geometry. Finally, the ability of the occupant to internalise their surroundings and experiences is developed. This allows the occupant to interpret the surroundings that will subsequently affect the occupant's motivation and therefore the behavioural response.

7.1. REPRESENTATION OF THE OCCUPANT MOVEMENT THROUGH SMOKE

7.1.1 EXPECTED OCCUPANT BEHAVIOUR

Jin [1,9-11], during his experiments involving volunteers moving through detrimental conditions (smoke-filled corridors), noticed that they demonstrated several behavioural features in response to the obscuration and irritation caused by the atmosphere (see section 2.5, Chapter 2). Firstly, the *occupant travel speeds were reduced* in response to the conditions [1,9-11]. Secondly, the occupants tended to *stagger* around their ideal path, rather than move directly towards their target. This was due to the difficulty in determining their present direction caused by the visual conditions, as well as the general irritability and physical problems caused by the presence of smoke. Thirdly, and in some respect attempting to compensate for the last effect, the occupants were seen to *move towards the enclosure walls*, to obtain guidance in their movement. This behaviour was also exhibited during the Beverly Hills Supper Club incident [52]. One occupant reported that,

> *"After the door was opened there was so much smoke you could hardly see then and so the only way I knew to leave was the spiral staircase and out the front door so I started*

towards the stairs and you just had to kind of feel your way along because the smoke had become really heavy.."[52]

Therefore not only is the occupant's speed diminished in response to the smoke, but the path adopted demonstrates a *qualitative difference* to that which would have been considered optimal.

However, for ethical and legal reasons Jin's experiments only extended to an extinction coefficient of approximately 1.5 l/m (an optical density of 0.65). These conditions may, however, be surpassed in an actual event [52, 145]. The physical configuration used in the experiment may have also significantly influenced the outcome. For instance, a wider geometry may have prevented the volunteers compensating for the smoke through the adaptive response of moving towards the enclosure wall. The fact that the experiment using isolated individuals would also have influenced the results.

7.1.2 Present buildingEXODUS implementation.

The quantitative impact of the environment upon the occupant progress is represented in the present model, with the increasing severity of the conditions reducing the occupant's mobility. This reduction is represented in the buildingEXODUS model through the inclusion of the Speitel [110-111] and Purser[108-109,112-113] fractional effective dose models. The smoke concentration experienced by the occupant will have a *physical* impact upon the travel speed of the occupant as the occupant's mobility is used as a coefficient of the occupant's speed (see Table 7-1).

Table 7-1: Present buildingEXODUS representation of the impact of smoke concentration.

Smoke concentration (l/m)	Occupant Mobility
0.0-0.1	1.0
0.1-0.5	1.0-0.5

This produces the overall impact upon the occupant described in Figure 7-1. Once the upper limit of the impact is reached, the occupant's mobility score defaults to 0.3 (stored internally as the *crawling speed* [24]). Any increase in the extinction coefficient after this stage does not further decrease the occupant's speed.

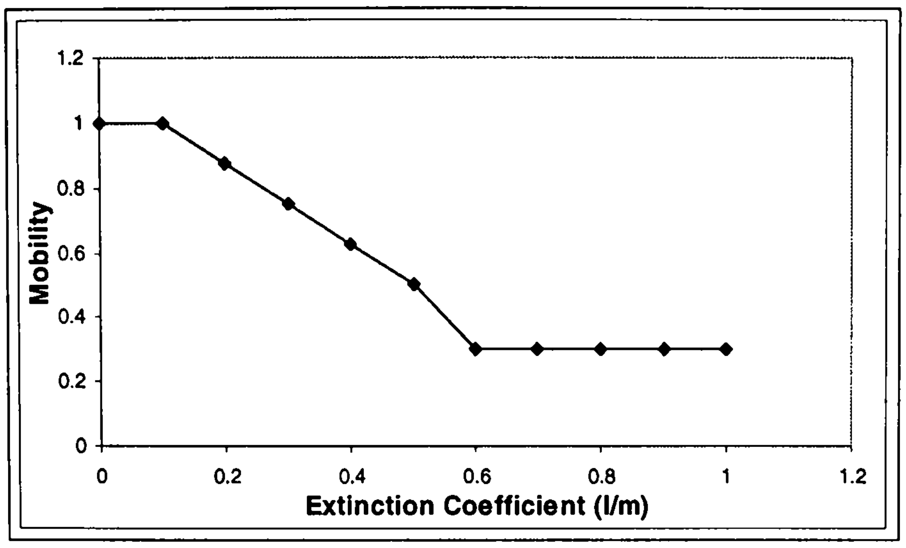


FIGURE 7-1: EFFECTIVE REPRESENTATION OF THE IMPACT OF THE SMOKE CONCENTRATION IN THE PRESENT EXODUS MODEL

The path chosen by the occupant population is not affected by the severity of the conditions, such that the usual considerations of the potential map and the occupation of node are paramount. Therefore, *irrespective of the environmental conditions*, occupants maintain their egress route.

7.1.3 PROPOSED BEHAVIOURAL MODIFICATIONS

The proposed features represent the two behaviours identified by Jin [1,9-11] and observed elsewhere [52]. The proposed behaviour therefore introduces an element of *inaccuracy* into the movement of occupants and a determination on their part that once the enclosure perimeter has been detected, that they will attempt to maintain contact with it and moving toward their desired goal (see Figure 7-2). Obviously, the occupant's desire to perform this task does not necessarily guarantee that it will occur.

It should be remembered that this movement assumes that the occupant is *engulfed* in a smoke-filled environment and has already made the decision to move through the smoke. The decision to initiate movement through a smoke filled environment is addressed elsewhere (see Section 8.4, Chapter 8).

Implicit in the proposed behaviour is the introduction of stochastic process into the occupant reaction to the environmental conditions.

At lower smoke densities, although the occupant is still capable of determining a general direction in which to travel, the accuracy of this determination is lowered to generate a ***stagger*** in the occupant's movement.

As the smoke densities increase, so the occupant's stagger becomes more exaggerated (see Figure 7-3). This would therefore be simulating a loss of awareness, a difficulty in focusing (caused by the irritant effects of the toxic environment) as well as numerous other symptoms identified [113].

The implementation of this algorithm within the buildingEXODUS model is based around the occupant's ability to *interpret* the potential map. The thresholds at which the different levels of inaccuracy in the interpretation of the potential map occur are dependent upon the individuals involved and generally reflect the experimental findings of the Jin experimental conditions [9,11].

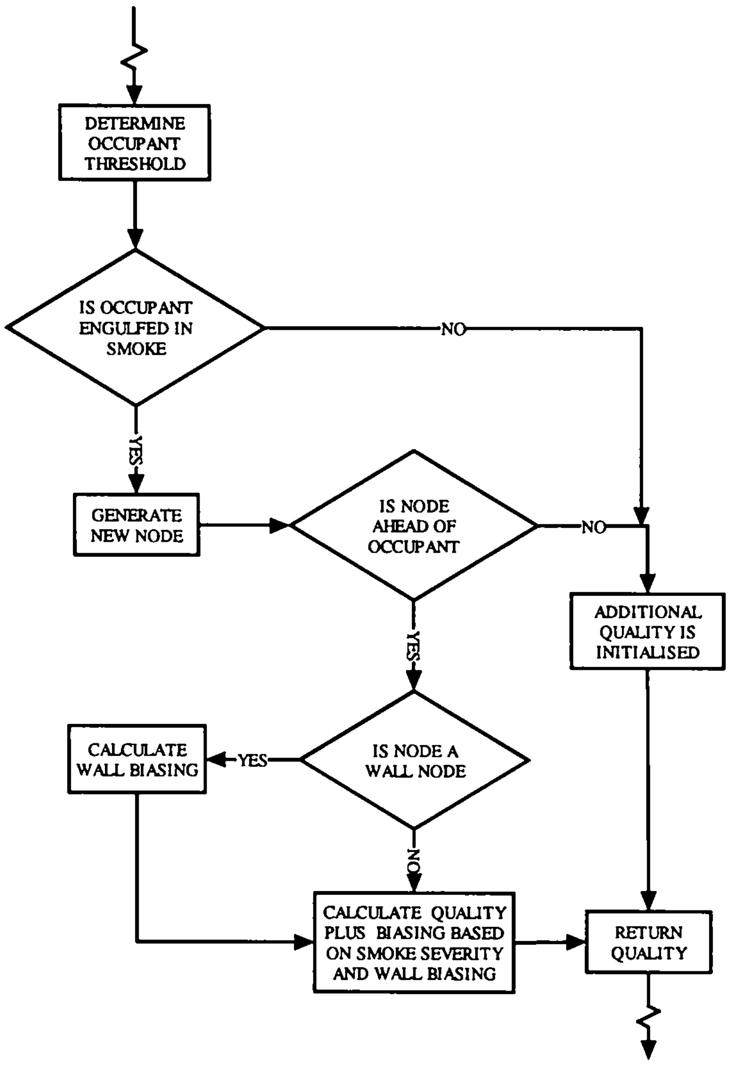


FIGURE 7-2: FLOWCHART OF THE PROPOSED BEHAVIOUR.

The representation of the occupant movement towards the boundary of the structure is less complex and is largely dependent upon the geometry of the enclosure. However, once in contact with a 'boundary', the occupant will be more able to navigate and will, in comparison with an occupant stranded in a smoke-filled environment, move more freely. The selection of this route is not guaranteed within the algorithm, as the choice of location includes some stochastic elements.

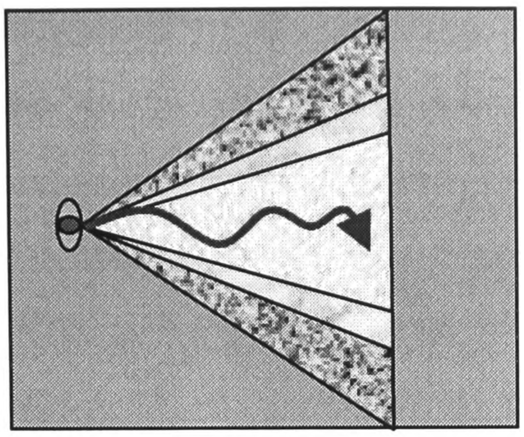


FIGURE 7-3: DIFFERENT LEVELS OF INACCURACY IN THE INTERPRETATION OF THE POTENTIAL MAP ACCORDING TO THE DENSITY OF THE SMOKE CONDITIONS.

The *staggering* algorithm is described by the following equation

$$A_i = \|P - Q\|_2 + (\Delta - r\rho(1 - \lambda\frac{n_{\max} - n_i}{n_{\max}})) \quad (60)$$

where A_i is the eventual attractiveness of the node examined, P is the position vector $[x_{present}, y_{present}]$, Q is the position vector $[x_{exit}, y_{exit}]$, Δ is an internal constant representing the advantage of a clear environment, ρ is the density of the smoke, r is a random number between 0.5 and 1, λ is a correcting factor stabilising the effect of the nodal connectivity , n_{max} is the maximum nodal connectivity and n_i is the actual nodal connectivity.

An extensive amount of sensitivity analysis was conducted to calibrate the constant Δ, so as to reduce anomalous results. From this equation it is clear that increasing smoke density decreases the attractiveness of the node, as does the increasing connectivity of the nodes, simulating the occupant's preference for the enclosure boundary [1,9,11]. It is also apparent that the influence of the smoke density and the enclosure boundary is subject to stochastic processes.

Once the attractiveness for individual locations is calculated they are then compared to determine which is the most likely to be adopted. The attractiveness associated to each nodal location, A_i, has no intrinsic use other than as a comparative index.

The wall adherence behaviour is less frequently observed than the occupant staggering, as it will only occur when an occupant is adjacent to the enclosure boundary. *This implementation includes no searching capability.* Although this might be claimed to model the difficulty in the occupant's visual abilities, in that they might not be able to determine the exact position of the enclosure walls under the severe environmental conditions, it is in fact due to the compromise involved in searching the immediate surrounding nodes. This compromise is entirely due to the nature of the implementation within the buildingEXODUS model.

7.1.4 VERIFICATION

With this form of behaviour, it is important to demonstrate that the qualitative advantages that are generated do not sacrifice the quantitative accuracy of the model already present. The validation cases are therefore an attempt at demonstrating the qualitative advantages provided, whilst testing the sensitivity to a number of variables and establishing the quantitative accuracy of the algorithm once implemented within the buildingEXODUS model (see Table 7-2). The verification cases are designed to examine distinct aspects of the proposed behavioural modifications including:

- Case 7.1.41- Examines the impact of the proposed behaviour upon the overall evacuation times given the worsening environmental conditions using the experimental conditions provided by Jin[1,9,11]
- Case 7.1.42- Examines the impact of the behaviour upon a larger population of occupants

TABLE 7-2: VALIDATION CONDITIONS.

Scenario	Population	Geometry	Environment
7.1.41	1 occupant velocities of 1.0/1.3/1.5m/s	20m x 1.5m	0.2-0.5 l/m
7.1.42	20 occupants, speed of 1.5m/s	20m x 1.5m	0.2-0.5 l/m

CASE 7.1.41

In case 7.1.41, the conditions of the Jin experiment are approximated using similar configurational and environmental conditions. The geometry of the enclosure used in the original experiment was 20m in length. The geometry is 1.2m in width and 2.5m in height as in his previous experiments [1,9,11]. As buildingEXODUS does not include a three dimensional representation of the floor-plan [24], only the length and width of the geometry are considered. These are approximated as being 20m x 1.5m. The width is rounded up due to the nodal representation used in the buildingEXODUS model [24], and to exaggerate the quantitative impact of the algorithm upon the results.

A single occupant is simulated as heading towards an exit, to examine the speed and geometry of the movement. The occupant will pass through an environment in which the extinction coefficient is varied between 0.2 and 0.5 l/m, although other forms of toxicity that may have been introduced into the original experimental environment is ignored.

The occupant speeds are examined to represent the reduction in occupant performance in relation to their original velocity. Occupant velocities of 1.0, 1.3 and 1.5 m/s are simulated to demonstrate the distribution of values that might be attained through changes in the occupant population. It should be remembered that the curve generated in the original Jin experiment can only be approximated through assuming the *same original occupant speeds.* It is expected that the results produced whilst assuming an occupant travel speed of 1.3 m/s will most closely reflect the results produced by Jin [1,9,11]. In the other cases, the same trends in the curve produced should be visible, rather than a replication to the Jin curve.

The present model is examined in Scenario 7.1.411, while the proposed implementation is examined in Scenario 7.1.412.

RESULTS-CASE 7.1.41

A general increase in the evacuation times through the introduction of the proposed behaviour can be observed from Figure 7-4. This discrepancy *increased* in relation to the density of the smoke. This is entirely due to the staggering of the occupant becoming more exaggerated as the conditions worsened.

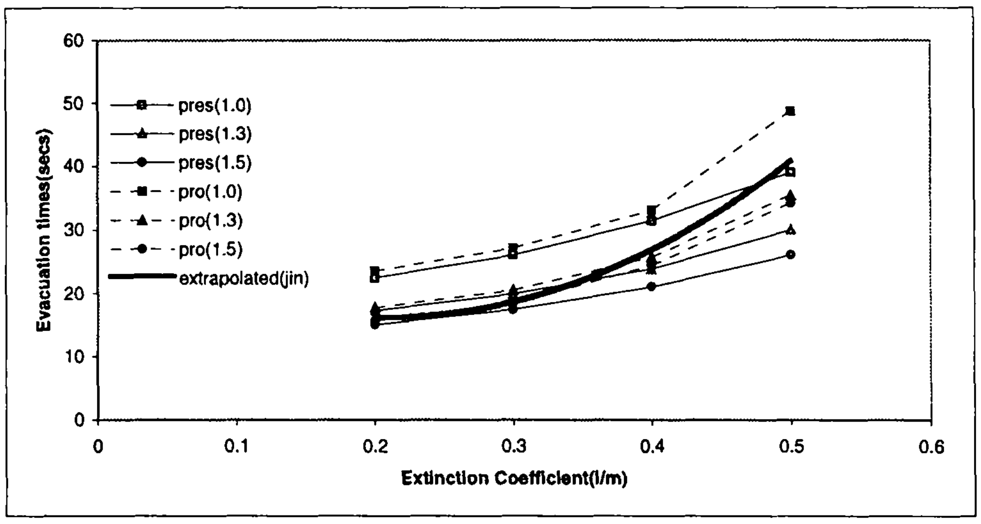


FIGURE 7-4:EVACUATION TIMES GENERATED THROUGH PRESENT AND PROPOSED MODELS

It is also apparent that the evacuation times that most closely resemble those derived from the Jin experiment are produced (in both the present and the proposed model) when the occupant is initially travelling at 1.3m/s. This is an important result, as it demonstrates an appropriate interaction between the algorithm (both present and proposed) and the individual attributes of the occupants involved.

From Table 7-3 another important difference between the two models can be seen. In the present model (Scenario 7.1.411), the results are *deterministic*, where no distribution is produced. The proposed model (Scenario 7.1.412) generates a distribution at the more extreme smoke densities. This is because the exact path chosen by the occupant involves random processes and may include subtle changes between runs. At the lower densities, the occupant is able to maintain almost an identical egress path to the present model. This is not *necessarily* the case, but the combination of factors and associated probabilities involved in these runs have generated this effect.

TABLE 7-3: EVACUATION TIMES OF THE REPLICATED JIN EXPERIMENT.

Ext. Coeff. (l/m)	Extrap. Jin Evac.times	Occupant Speed 1.0m/s		Occupant Speed 1.3m/s		Occupant Speed 1.5m/s	
		Scenario 7.1.411	Scenario 7.1.412	Scenario 7.1.411	Scenario 7.1.412	Scenario 7.1.411	Scenario 7.1.412
0.2	15.9	22.4	23.5 [22.4-24.1]	17.3	17.7 [17.3-18.5]	15.0	15.6 [15.0-16.5]
0.3	19.5	26.0	27.1 [26.0-28.4]	19.9	20.5 [19.9-21.9]	17.4	18.4 [17.6-18.9]
0.4	26.0	31.5	33.1 [32.1-35.3]	23.8	25.7 [24.4-28.1]	20.9	24.5 [21.7-27.3]
0.5	41.1	39.0	48.8 [42.3-51.1]	30.0	35.5 [32.1-38.1]	26.0	34.2 [27.3-37.1]

The discrepancies in the figures produced do not *necessarily* present difficulties in the verification process. This is due to the variation of the results produced in the original Jin experiments (Figure 7-5). It is difficult to accurately compare the results produced with the original Jin results, as the exact data points are not available for analysis. However, the trend-line generated by Jin is calculable and this is therefore used for comparison.

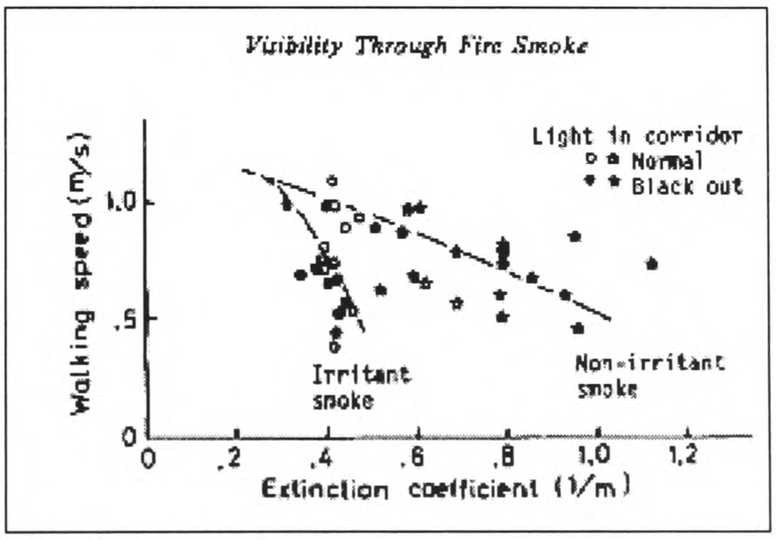


FIGURE 7-5: REPRODUCTION OF THE JIN EXPERIMENTAL RESULTS. REDRAWN FROM THE ORIGINAL [ ].

If we now convert the evacuation times generated into the average speed of the occupant throughout the simulation, some interesting comparisons can be made. Firstly, Scenarios

7.1.411 and 7.1.412 generate similar occupant speeds to those generated from the Jin experiments [1,9,11]. No obvious anomalies are detectable, although the comparison can only be made at relatively low extinction coefficients, due to the restrictions placed upon the original experiments [1,9,11].

More importantly, the predicted results (especially when using the proposed model) approximate the *results and the trends* produced by Jin, within the boundaries that Jin produced (0.1-0.5 l/m).

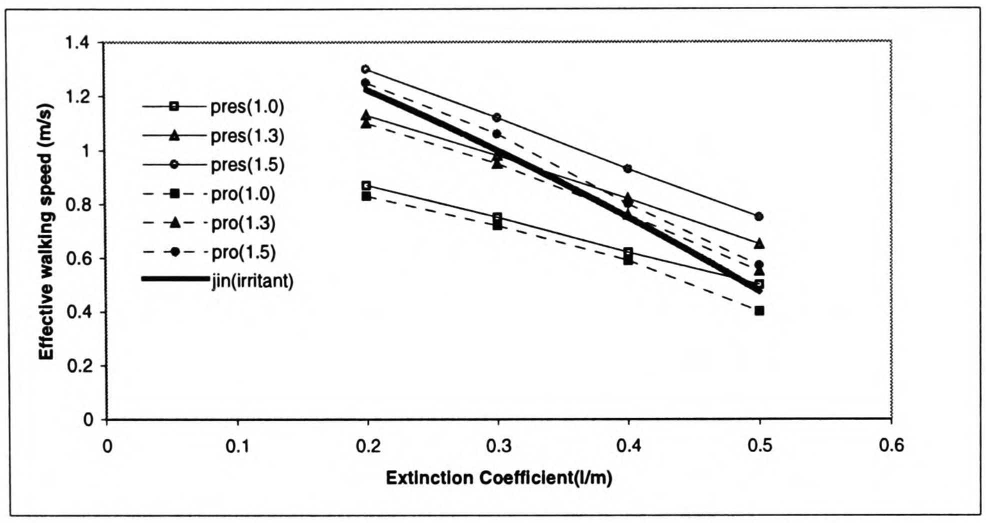


FIGURE 7-6: COMPARISON OF THE WALKING SPEEDS GENERATED IN COMPARISON WITH JIN.

At present the buildingEXODUS model implements a *linear* representation of the Jin data. The quantitative results have not been adversely affected through the introduction of the proposed behaviour. Indeed, the generation of a distribution of results may be seen as an improvement, as they more closely follow the curve produced by the Jin data. The qualitative impact is significant, with the occupant's movement becoming decreasingly optimal as the smoke density increase (see Figure 7-7). This is similar to the behaviour observed in the Jin experiments [1,9,11].

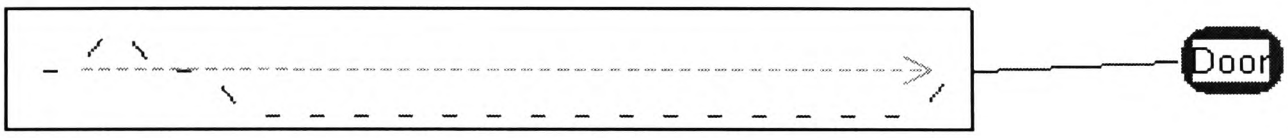


FIGURE 7-7: PATH ADOPTED BY SINGLE OCCUPANT IN SCENARIO 7.1.412. THE RED PATH REPRESENTS THE PROPOSED MODEL ,WHILE THE GREEN PATH REPRESENTS THE PRESENT MODEL.

Another aspect of the proposed behaviour is also demonstrated in Scenario 7.1.412. Due to the dimensions of the geometry, the occupant has an opportunity to come into contact with the boundary. Once the conditions have deteriorated, the occupants may use the boundary of the enclosure to assist in their wayfinding capabilities. This is clearly the case in Figure 7-7.

It should be remembered that due to the nature of the biasing system used, that the occupant's contact with a boundary node does not necessarily *guarantee* that he will maintain this contact. It does however, bias the future movement in favour of the continued proximity with the enclosure boundary. This allows for a greater variety in occupant movement. It would be a trivial matter to guarantee this tendency.

Some sensitivity analysis was conducted concerning the effect of increasing the width of the geometry upon the extent of the occupant stagger.

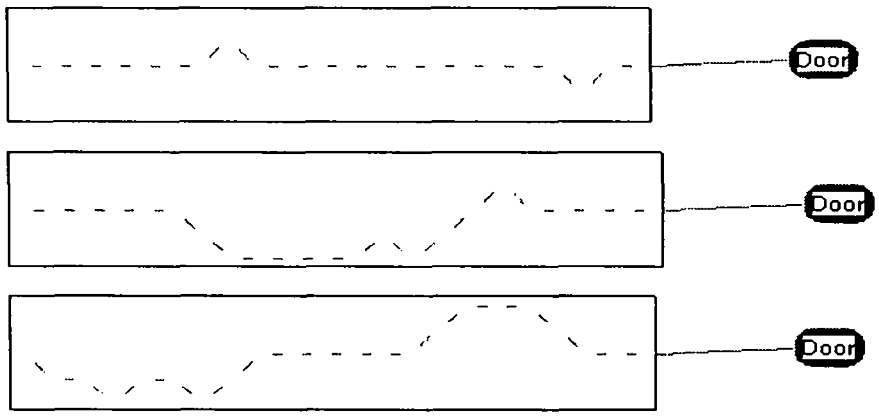


FIGURE 7-8: THE PATHS ADOPTED DURING A HAZARD OF 0.5,0.6 AND 0.7 L/M RESPECTIVELY. NOTICE HOW THE PATH BECOMES MORE EXAGGERATED AS THE EXTINCTION COEFFICIENT INCREASES.

From Figure 7-8 the increased variability that can be achieved in the occupant's path is apparent. As the environment worsens, so the occupant is able to stagger a greater distance prior to encountering a boundary, thus making an encounter with this stabilising influence less likely. Even this influence is not guaranteed, as they occupant may disengage from the boundary.

It is expected that this trend of increasing variability will be continued as the geometry is further widened.

CASE 7.1.42

In 7.1.42, the geometry from 7.41 is maintained, but the number of occupants in the geometry is increased to 20, to examine the cumulative impact upon the evacuating population of the 'staggering' effect. Although Jin did not examine this situation, it will still provide some insight into the reaction of the proposed behaviour to a higher density population. The population is made up of default occupants who react instantly. In this simulation the occupant travel speeds are kept at 1.5 m/s to limit the number of variables examined.

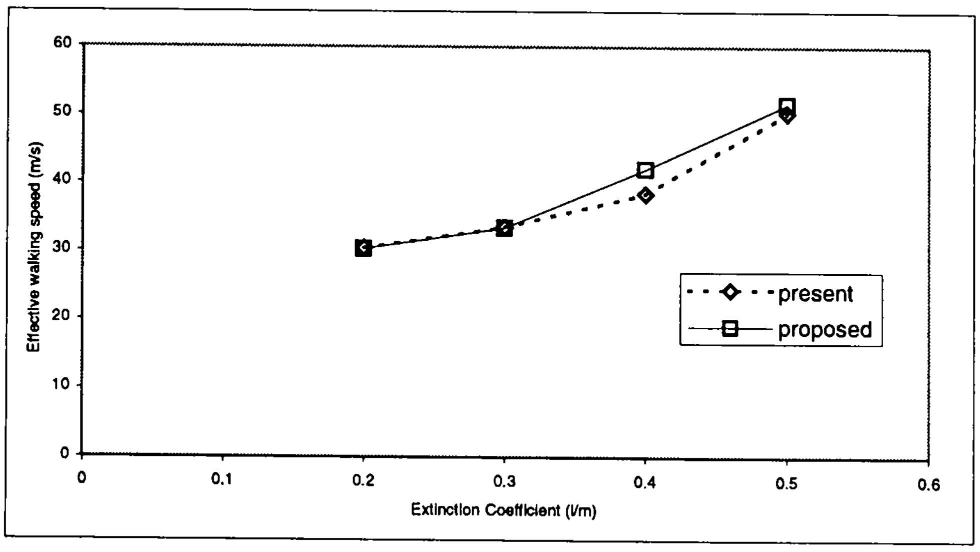
All of the other environmental considerations are maintained from the previous cases. The present model is examined in Scenario 7.1.421 and the proposed model is examined in Scenario 7.1.422.

RESULTS-CASE 7.1.42

Due to the population size increases in Scenarios 7.1.421 and 7.1.422, the relationship between the results becomes more complex. The evacuation times generated by the present and the proposed models are more similar than in the previous validation cases. It is also noticeable that both models generate a distribution of results. This is due to the resolution of conflicts, as well as the changing staggering patterns in the proposed model.

Examining Figure 7-9, the complex relationship between the two models is apparent. During those simulations in Scenario 7.1.422 conducted with a smoke density of less than 0.4 l/m, the proposed model produces *faster* evacuation times. This is due to the staggering of the occupants causing more space to be available and therefore fewer conflicts being resolved. While the smoke conditions are less severe, the resolution of conflicts is still the dominant factor.

As the extinction coefficient increases in Scenario 7.1.422, so does the occupant's inaccurate movement, therefore reducing any possible advantage that this behaviour may produce through the avoidance of conflicts.



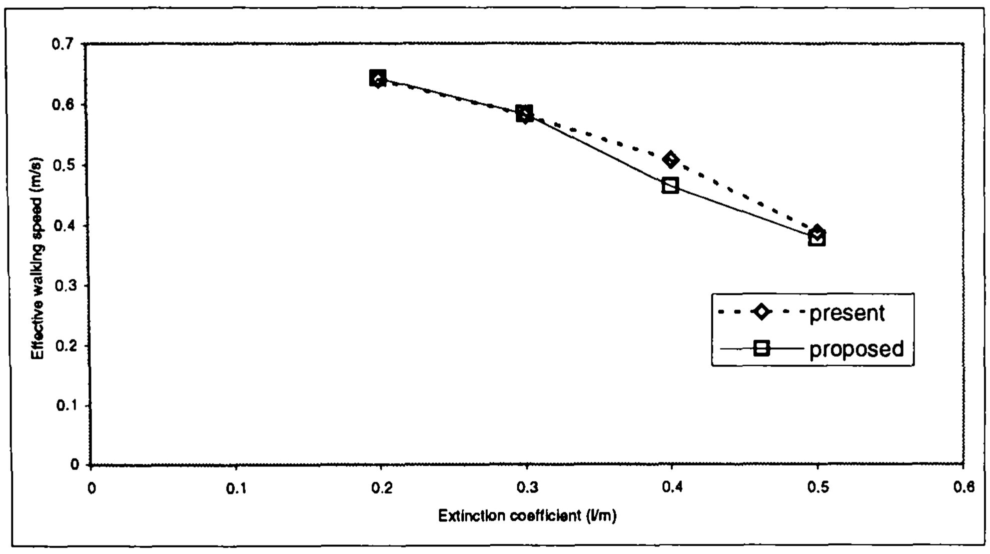


FIGURE 7-9: RESULTS PRODUCED FROM CASE 7.1.42.

Examining the travel speeds generated in Scenarios 7.1.421 and 7.1.422, they appear similar throughout the different cases (see Figure 7-9). At the lower levels of smoke density, the walking speeds generated reflect the impact of fewer conflict resolutions.

TABLE 7-4: TABULATED RESULTS FROM 7.1.42.

Extinction coefficient (l/m)	Present model (Scenario 7.1.421)	Proposed model (Scenario 7.1.422)
0.2	30.4 [28.1-34.4]	30.3 [29.4-31.6]
0.3	33.5 [32.9-34.6]	33.4 [31.1-36.7]
0.4	38.4 [37.6-38.9]	42 [39.3-47.4]
0.5	50.3 [48.8-52.1]	51.6 [47.1-54.1]

The Jin experiments provide limited information for this case as they were conducted with occupants in isolation. Drawing from other related areas of research [1], the complexity of the results generated once the population increases is completely appropriate, especially at low smoke densities. Due to occupant crowding, navigation and occupants blocking future passage, the impact of the proposed behaviour becomes less apparent. All of the flow problems and congestion that are observed under routine conditions are evident, but are compounded through the environmental conditions.

7.1.5 FUTURE WORK

One feature examined by Horiuchi [98] and Jin [1,9,11] is the ability of occupants to maintain their speed through smoke-filled environments when they are travelling in groups (see Figure 7-10). Their results implied that the maintenance of these groups may have been beneficial for the travel speed of the occupants in difficult environmental conditions.

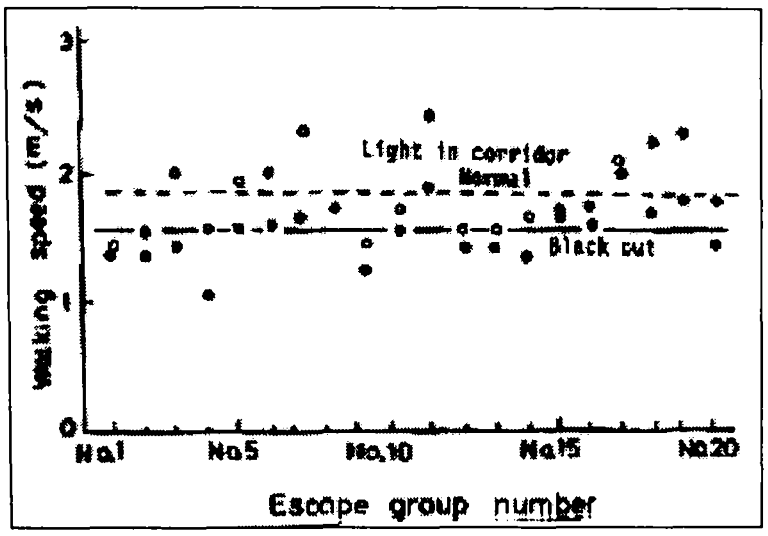


FIGURE 7-10: THE EXPERIMENTAL DATA OF HORIUCHI[ ]. THE OCCUPANTS IN THESE CIRCUMSTANCES MAINTAIN A MUCH HIGH TRAVEL SPEED THAN WOULD OTHERWISE BE EXPECTED. REDRAWN FORM ORIGINAL [11].

This might be incorporated in the proposed behaviour, in conjunction with the behaviour described in Section 8.4, Chapter 8, representing the communication process between occupants.

A possible deficiency in the proposed behaviour is that the randomised movement of the occupants, as well as the decrease in the occupant's mobility, may in effect be representing a reduction in the efficiency of the occupant movement twice. In this instance, this is limited as the serious reduction in the occupant's navigational capabilities is introduced *after* the boundaries used in the Jin experiment. However, this process requires more extensive testing, under a wider variety of conditions.

It is also important to introduce a more individual response to the data used, allowing the internal occupant attributes to have a greater influence over the ability to progress through difficult environmental conditions. However, the experimental data is not at present available on this topic.

7.1.6 CONCLUSION

The inclusion of the proposed behaviour introduces an important stochastic element into the calculation of occupant movement through smoke. It also still adheres to the findings of Jin [1,9,11] where appropriate. Of course the appropriateness of these results are dependent upon the acceptability of the original data. However, given the general acceptance of the original findings, the adherence of the simulated results to these original results is, in this case, desirable.

The qualitative variation of the proposed behaviour reproduced those occupant actions seen in the actual cases [1,9,11]. Importantly, this did not detract from the present buildingEXODUS implementation. The proposed algorithm therefore improved the physical representation of the behaviour (through the introduction of variability), whilst replicating a number of behavioural features identified in actual experimental conditions.

7.2. DYNAMIC BEHAVIOURAL REPRESENTATION

7.2.1EXPECTED OCCUPANT BEHAVIOUR

The occupant's motivation is a significant influence upon the decision-making process, as it is the culmination of a number of influential factors. The occupant's motivation to initiate and maintain evacuation behaviour is determined through their interpretation of the surrounding events, such as the existence and proximity of a hazard [52], the presence of significant others in the population [52,58,128]. As noted by Muir [142], Lewis [71] and Quarantelli [55], the motivation of an occupant has an important impact upon both the individual actions of the occupant and the overall outcome of the evacuation.

An occupant's motivation is largely dependent upon the events experienced. Obviously, the impact of this experience varies according to the event, the occupants involved and therefore the occupant's perception of the event. Unlike the majority of theorists in the first half of this century however, [72-74], *the occupant motivation is not only seen as determining the likelihood of **flight***, but is instead seen as an facilitator of particular actions.

Historically, humans under hazardous conditions were considered to adopt 'barbaric', anti-social tendencies, sacrificing the welfare of others for their own benefit [72-74]. During this process a complete shift in the behaviour exhibited by an occupant was expected. However, recent work suggests that instead of the occupant population being 'suggestible', reactionary agents [74], they were *instead information-processing units* [49-50,202,206]. These *units* act rationally according to the circumstances in which they find themselves, the information around them and the options available to them [206]. Therefore given the limiting condition supplied by the extraordinary circumstances, the number of options available may be restricted, forcing the hand of the evacuee. For instance, if the only viable options available to an occupant are to leap out of a 5^{th} storey window or to remain and perish, a normally bizarre and potentially fatal activity may be considered a rational option. This does not suggest a behavioural shift; rather an adaptive response to incredible circumstances.

A subtle example of the adoption of normally unusual behaviour could be seen in the Beverly Hills Supper Club incident. An occupant describes,

"... so my wife and I started moving back toward the entrance that we had come into the Cabaret from, went into the hallway, turned right and moved along that passageway until we came out into what is known as the garden area. As we moved down the hall, when I first came into the hall from the Cabaret there didn't appear to be any panic or large accumulation of smoke. But as I got closer to the exit that goes out into the garden, I looked back over my shoulder and there was a tremendous amount of smoke moving down the hallway toward that exit. At that point a man said, 'move faster, there's people back here and smoke around us, hurry up.' So then everybody started moving at a more rapid pace."[52]

Here, a previously unusual, although not necessarily anti-social activity (a couple accelerating towards a desired exit), is adopted in response to a rapidly changing environment. The occupants were sufficiently motivated, due to the perception of a cue that signified imminent danger, to adopt a behavioural action that might not normally be considered.

For the occupant to make a considered decision on the seriousness of the situation, they must be sensitive to the surrounding conditions. These conditions may alter during the evacuation. The occupant's interpretation of the evacuation will therefore develop according to the severity of these conditions. The occupant's motivation to perform specific actions must therefore reflect the dynamic environment surrounding them, as well as any personal traits that the occupant brings to the event.

7.2.2 Present buildingEXODUS implementation

At present in the buildingEXODUS model, occupant motivation is considered constant throughout the simulation. No external events or change in the physical/sociological condition of the simulated occupant infringes upon the occupant's motivation. *The occupant's determination to evacuate is therefore the same throughout the evacuation, irrespective of their experiences.*

This discrepancy has relatively little impact in a sparse population or in an evacuation that is relatively sedate. However, given that the resolution of conflicts within buildingEXODUS are solely dependent upon the occupant's drive (the representation of occupant motivation), one would expect that this ignorance of external events would significantly affect higher density populations especially those who have come into contact with life threatening situations.

Once the user has determined the motivation of the occupant population, the behavioural regime adopted by the occupant population is then determined. Once determined, the regime remains constant during the entire simulation, irrespective of the events and experiences of the occupant population. The behavioural regime applies to the entire population. All occupants initially start in the NORMAL behavioural regime, and, if the EXTREME regime has been specified will transfer to the EXTREME regime on becoming impatient [24]. Once the occupants have made progress towards their desired target, they return to the NORMAL behavioural regime.

The difference between the two regimes mainly lies in the ability of the occupants to adopt paths that are not immediately optimal [24]. Under the *EXTREME* regime, occupants who are not able to maintain their movement towards their chosen exit have the option to occupy a node that is more distant, instead of waiting for a closer node to become available. This difference although seemingly slight, can cause significant differences in the paths taken by occupants, as well as increasing the manoeuvrability of the occupant [24].

7.2.3PROPOSED BEHAVIOURAL MODIFICATION

The proposed behavioural developments are an attempt at introducing two new aspects to the model. Firstly, *the occupant's motivation will alter according to their experiences.* Secondly, *the static regime system implemented within the present model is replaced by a dynamic system that is dependent upon the occupant's motivation.* These factors are addressed separately.

The occupant's motivation plays a vital role within the buildingEXODUS model. As highlighted in Chapter 3, the ability of the occupant population to maintain a travel speed amongst a crowd is not directly determined by the population density-flow relationships as it is in numerous other evacuation models [24]. Instead it is calculated according to the *resolution of conflicts* concerning the occupation of nodal locations within the simulated enclosure. This resolution is dependent upon the motivational level of the occupants involved. Given that motivation in the proposed model now reflects the occupant experience, it is logical that it affects their future behaviour, including the maintenance of their travel speed.

A number of factors affect the occupant's motivation. These factors are perceived by the occupant and are distilled into a single motivational index, known as the *dynamic drive*. These factors relate to both internal occupant attributes and external information. They are prioritised according to the impact that they have on the motivation of the occupant, with the presence of smoke having the greatest impact, down to the distance that the occupant has travelled having the smallest effect. The factors considered in the proposed model, presented in decreasing levels of priority, are

1. the occupant's interaction with smoke *(internal attribute / external attribute ρ_i)*
2. the motivation of those around you *(external attribute, D_k)*
3. the time the occupant has spent waiting *(internal attribute, w_i)*
4. the initial demeanour of the occupant *(internal attribute, D_i)*
5. the surrounding population density *(external attribute)*
6. the time spent in the evacuation *(internal attribute, t_i)*
7. the distance travelled by the occupant during the evacuation *(internal attribute, d_i)*

It is conceded that other factors will certainly have an impact on the motivation of the occupant. However, the factors identified are already represented within the buildingEXODUS model and by using the factors available, we are therefore able to demonstrate the concept of dynamic motivation without further engineering. The inclusion of new factors is therefore left for further work.

These factors are combined into a single index, D_i' , through a number of composite functions. These functions reflect the order of priority identified above. The dynamic drive is updated every 1/12th of a second, as the occupant updates their perception of the environment. *With the introduction of the dynamic drive, the occupant's motivation will therefore fluctuate according to experience.*

To facilitate the use of the dynamic drive facility it was necessary to impose lower and upper limits upon the drive achievable, for computational purposes. In this case the limits were arbitrarily set as lower limit was 1 and the upper limit was 20. This also provides a scale against which the individual occupants may be compared.

The functions used in the dynamic drive facility take a number of forms. An example of one of these composite functions, $\alpha_i()$, represents the impact of the time that the occupant has spent waiting (w_i) upon the motivational index. This function is represented by,

$$\alpha_i(w_i) = \min(\max(0, \frac{w_i - \frac{P_i}{2}}{10P_i + 1}), \Delta) \tag{61}$$

where Δ is an internal coefficient that limits the impact of this factor upon the motivational index and P_i is the patience of occupant i (see Section 3.1, Chapter 3). Therefore once the occupant has waited beyond a threshold of impatience (arbitrarily defined as $P_i/2$), the act of waiting starts to impact upon the occupant's motivation. *Effectively the occupant begins to become concerned over the amount of time that spent waiting, given that the occupant has responded to the evacuation.* This effect will rise until the threshold (Δ, equal to half the maximum drive) is reached at which point the effect is achieved.

The denominator is increased by a factor of ten to control the impact of this factor. The addition of 1 to the denominator is required to remove a potential division by zero that will occur if the occupant is deemed to be impatient (i.e. has a patience of 0). The use of the minimum and maximum functions initially prevents negative values affecting the occupant's motivation and then places an upper boundary upon the effect, thus containing its potential impact.

This function can be compared to the function describing the occupant's interaction with smoke

$$\phi_i(\rho_i) = \frac{\max(\rho_i - \frac{D_i}{D_{\max}} J_\rho, 0)}{\rho_i - \frac{D_i}{D_{\max}} J_\rho} . D_{\max} \tag{62}$$

where ρ_i is the most severe extinction coefficient encountered to that point of the evacuation, J_ρ is the threshold at which smoke affects the occupant according to a coefficient derived from the work of Jin [1,9,11] (approximately representing when the smoke begins to impair the occupant's visibility), D_i is the occupant's motivation and D_{max} is the maximum achievable occupant motivation (arbitrarily set to 20 motivational units). Once the extinction coefficient of the surrounding environment reaches a sufficient level, the occupant becomes *fully* motivated (effectively set to D_{max}). This is to reflect the importance that an interaction with smoke has upon the occupant's perception of the severity of the emergency.

As can be seen from comparing the two functions, the impact of encountering smoke is far more influential than the amount of time that the occupant has spent waiting, in line with the available evidence such as that provided by Feinberg et al [207]. He reported the comments of an occupant during the Beverly Hills Supper Club incident, who recalled that,

"I immediately alerted (the) ... employees and their wives (or) husbands and I said, 'I see smoke, let's go'". [207]

implicitly recognising the significance of the perception of a smoke cue. Once an occupant encounters smoke above a specific threshold, their motivation immediately increases to a maximum level, rather than incrementally rising according to a prolonged experience, as in the case of the occupant waiting.

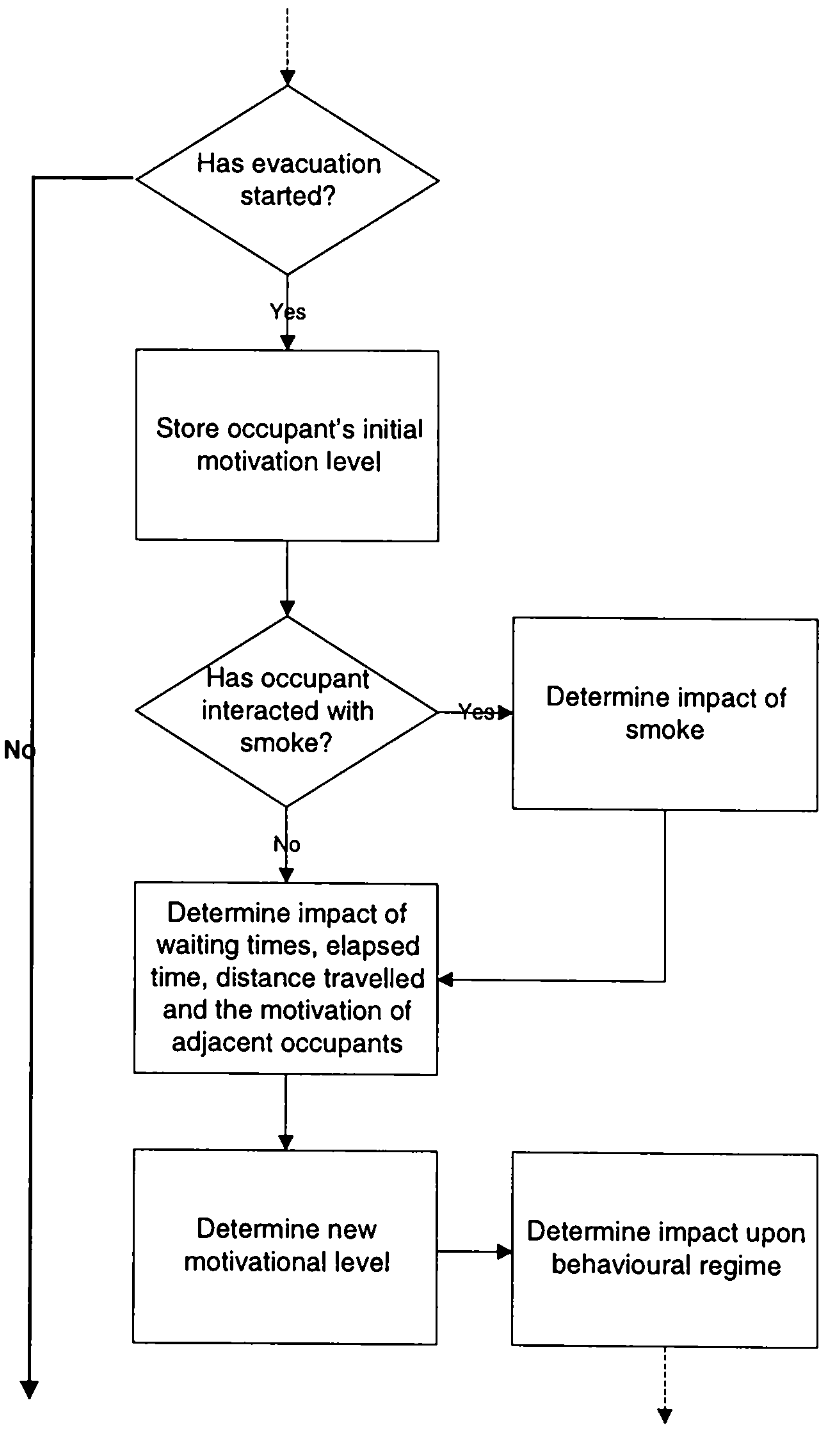


FIGURE 7-11: FLOWCHART REPRESENTING THE CALCULATION OF THE DYNAMIC DRIVE

Although seemingly arbitrary, the functions have been analysed for the sensitivity of their impact upon occupant motivation, as well as examining the appropriate literature for supporting evidence where appropriate [1]. However, a great deal more work is required to refine and research the nature of these functions.

The motivation of the occupant, as well as impacting upon the behaviour described in the present model, now *influences* a number of other proposed occupant behaviours. The set of behaviours influenced is now greatly extended in comparison to the present model. The behaviours influenced are now:

- The occupant's ability to redirect their egress route
- The communication of information between occupants and the perception of this information.
- The reaction to external cues, will be effected by the behavioural regime

The dynamic individually-based behavioural system now has a larger scope of influence upon the occupant's behavioural actions than the static globally defined system presently in use.

The second aspect of behavioural development addressed in this section is the movement between the behavioural regimes. At present the capacity for the occupant to alter their behaviour is determined *prior* to the simulation. The likelihood of the occupant doing so is entirely dependent upon the amount of time the occupant has spent waiting in relation to their patience level (see Section 3.1, Chapter 3).

This present method is replaced by a system where the movement between behavioural regimes is dependent upon the dynamic drive index. Given that the dynamic drive facility represents such a wide variety of the occupant experience, it is an ideal choice for determining the proposed flexible implementation of the behavioural regime.

The proposed behaviour represents the dynamic nature of the behavioural process. Instead of the behavioural regime being determined by the user prior to the simulation, it is dependent upon the previous, present and potential conditions surrounding the occupant. This information is stored within the occupant in the form of the dynamic drive index. *The eventual actions of the occupant will be dependent upon the conditions, experiences and the perception of the information supplied by the environment.*

Due to the regime-system implemented within the buildingEXODUS model, some compromises were required during the implementation of the proposed algorithm. One of the conditions of the proposed behavioural developments was that it should not remove the present functionality of the model, but instead should co-exist with it. Therefore instead of a completely continuous system deemed to be the most desirable representation, the occupant's behavioural state switches between two distinct positions [23]. This then maintains the functionality of the present model, allowing the user the same level of control over the proceedings, if required.

The movement between regimes is now dependent upon the *individual* experience and attributes of the occupant, reflected in the motivation. This is calculated according to the immediate surroundings. The changes in these attributes are then examined to determine the appropriate behavioural response. This is important as if the present behavioural mechanism is used, then occupants may *never* become aroused irrespective of their individual experiences. The behavioural regime of the occupant signifies their recognition of the potential hazard provided by the incident.

In the present model the movement between behavioural regimes mainly affected the ability of occupants to occupy particular nodal locations (see Section 3.1,Chapter 3). In the proposed model the movement between the behavioural regimes has been aligned to the achievement of a particular threshold of motivation, reflecting the increased likelihood of the performance of specific behavioural actions (such as redirection). This occurs at 75% of the occupant's maximum motivational score. At this point, the occupant is_labelled as having changed behavioural regime, identifying them as more actively seeking evacuation; at this point they become *EXTREME*. This does not represent a complete transformation in the occupant's behaviour. Instead it highlights that the occupant has received enough environmental cues to support the belief that the environment poses a threat and that the action chosen should reflect this hypothesis. *In a sense, the transition between behavioural regime is a descriptive representation of the occupant's perception of the severity of the situation.*

Once the occupant has an elevated motivation and has become *EXTREME*, having identified the potential threat to their safety, the next factor that must be addressed is the *length of time* that the occupant will stay at this new state. That is, when will the probability of performing the set of actions available to the occupant return to (or near to) their initial positions? This will again be affected by the occupant's drive and the particular conditions that have been experienced by the occupant as well as by random processes. This therefore reflects the return to the original condition of the occupant.

In accordance with the available data [52-53] once the occupant has encountered dense smoke the seriousness with which the incident is perceived increases. Therefore once the occupant has encountered smoke perceived as posing a significant threat, the occupant will maintain a heightened state of awareness for the rest of the evacuation. The time spent in the heightened state, t_e, is therefore

$$t_e = \phi t_\infty + \frac{D_i'}{D_{\max}}(x + r) \qquad (63)$$

where ϕ is a Boolean coefficient that is 1 if the occupant has interacted with relatively severe smoke, 0 otherwise, t_∞ represents the addition of an indeterminate period of time, x is the basic period of behavioural change (10 seconds) and r is a random element between 0 and 1.0.

Along with the dynamic drive facility, it is expected that the implementation of a flexible behavioural system will more accurately reflect the manner and extent of occupant reactions, as well as making the difference between the two regimes more significant. It is also a significant step towards the development of an information-processing capability, representing the evacuation as an adaptive rather than a deterministic process.

Again, the development of this new feature forces the model to rely upon individual factors especially the location and therefore the ability to perceive information. If the occupant is not situated in a position where he can receive specific pieces of information, he will react differently than if he was privy to it (e.g. the existence and location of smoke).

7.2.4 VERIFICATION

Given the slightly arbitrary nature of the behavioural dichotomy currently used in the buildingEXODUS model, the transition between the two regimes is investigated to determine that it occurs at *appropriate* moments and *under realistic conditions* and that no anomalous conditions arise. *That is, given the conditions, to which the occupants are subjected, that they react in a manner consistent with available data.*

It is only possible here to examine that the behavioural development of the occupant occurs at realistic and appropriate places during the simulation (see Table 7-5). The real impact of this behaviour is visible when it enables other behavioural features, which are examined in Chapter 8. Therefore only a limited number of cases are examined:

- Examines the appropriateness and sensitivity of the movement between the behavioural regimes.
- Examines the impact of local influences upon the adoption of behavioural regimes.

TABLE 7-5: DESCRIPTION OF VALIDATION CASES.

Scenario	Geometry	Population	Environment
7.2.41	Irregular, single exit (1.5m). Includes several bottlenecks	85, instant response. Patience levels examined	Small section of geometry involves hazard.
7.2.42	Irregular geometry, 1 exit (1.5m).	300, instant response.	Small section of geometry involves hazard.

CASE 7.2.41

In case 7.2.41 the occupant's behavioural response is examined, given a changing environment including a high-density population and a smoke-filled room.

An irregular geometry has been specifically designed to produce bottlenecks, increasing the population density at certain 'pinch' points (see Figure 7-12). Twenty default occupants begin to evacuate and are then confronted by a high-density crowd of 65 occupants, progressing slowly through a small internal passageway. Once this has been navigated, the occupants have to pass through a smoke filled room before exiting. The experiences of these twenty occupants are considered during the simulation.

The occupants are examined with no patience and with a distribution of patience settings (between 1 and 5 seconds). This is an important factor in the movement between regimes and is therefore examined in isolation.

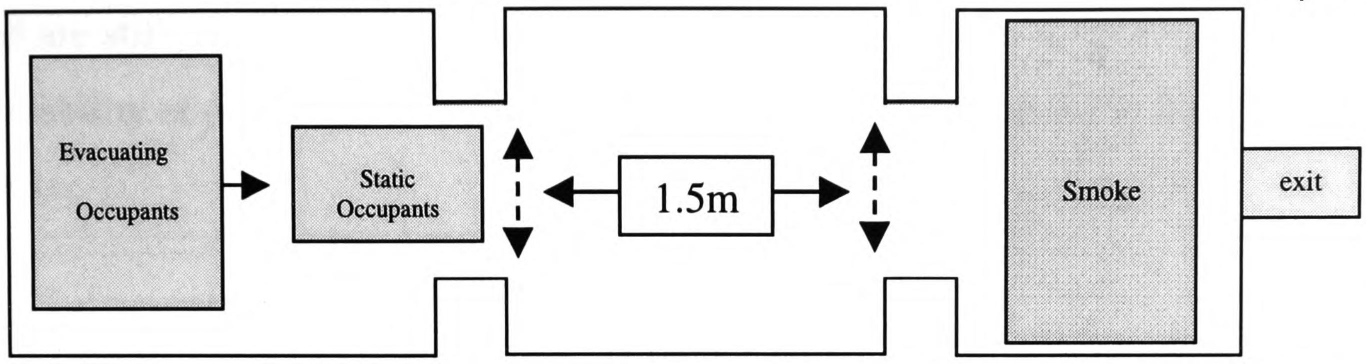


FIGURE 7-12: EXAMINATION OF THE INFLUENCE OF PARTICULAR EXTERNAL CONDITIONS UPON THE BEHAVIOUR REGIME IMPLEMENTED BY THE OCCUPANTS.

Given these conditions, the results produced by the present and proposed models are examined in Scenarios 7.2.411 and 7.2.412 respectively.

RESULTS-CASE 7.2.41

The introduction of the proposed behaviour develops no additional quantitative anomalies within the model. It is apparent that the evacuation time produced does not necessarily benefit from the occupant being able to adapt their motivation or through the subsequent ability of the occupants to adopt less direct paths (see Table 7-6).

TABLE 7-6: EVACUATION TIME GENERATED FROM VALIDATION CASE 7.2.41.

	BEHAVIOURAL MODEL	
PATIENCE LEVEL	PRESENT (SCENARIO 7.2.411)	PROPOSED (SCENARIO 7.2.412)
IMPATIENT	110 sec [108-113]	110 sec [109-110]
DISTRIBUTION	111 sec [109-115]	107 sec [103-109]

The introduction of the proposed behaviour in Scenario 7.2.412 does not significantly (or certainly not globally) alter the resolution of conflicts and therefore does not alter the overall evacuation time in relation to the use of the present model in Scenario 7.2.411, whilst the occupants are impatient. This is due to the levels of occupant motivation, irrespective of their initial position, developing approximately in unison, due to the impact of impatience upon the *DRIVE* calculation. The residual discrepancies in the occupant motivation are reduced as the impatience of the occupants causes them to quickly become motivated.

A slight difference of approximately 3% is visible in the overall evacuation times produced between the two scenarios, once a distribution of patience levels is introduced. This is due to the variation in the levels of occupant motivation *increasing*, according to the different occupant experiences during Scenario 7.2.412. However the differences produced are still relatively small. The minor change in the results is entirely due to the increased ability of occupants to divert their egress path and fluctuations in the resolution of conflicts.

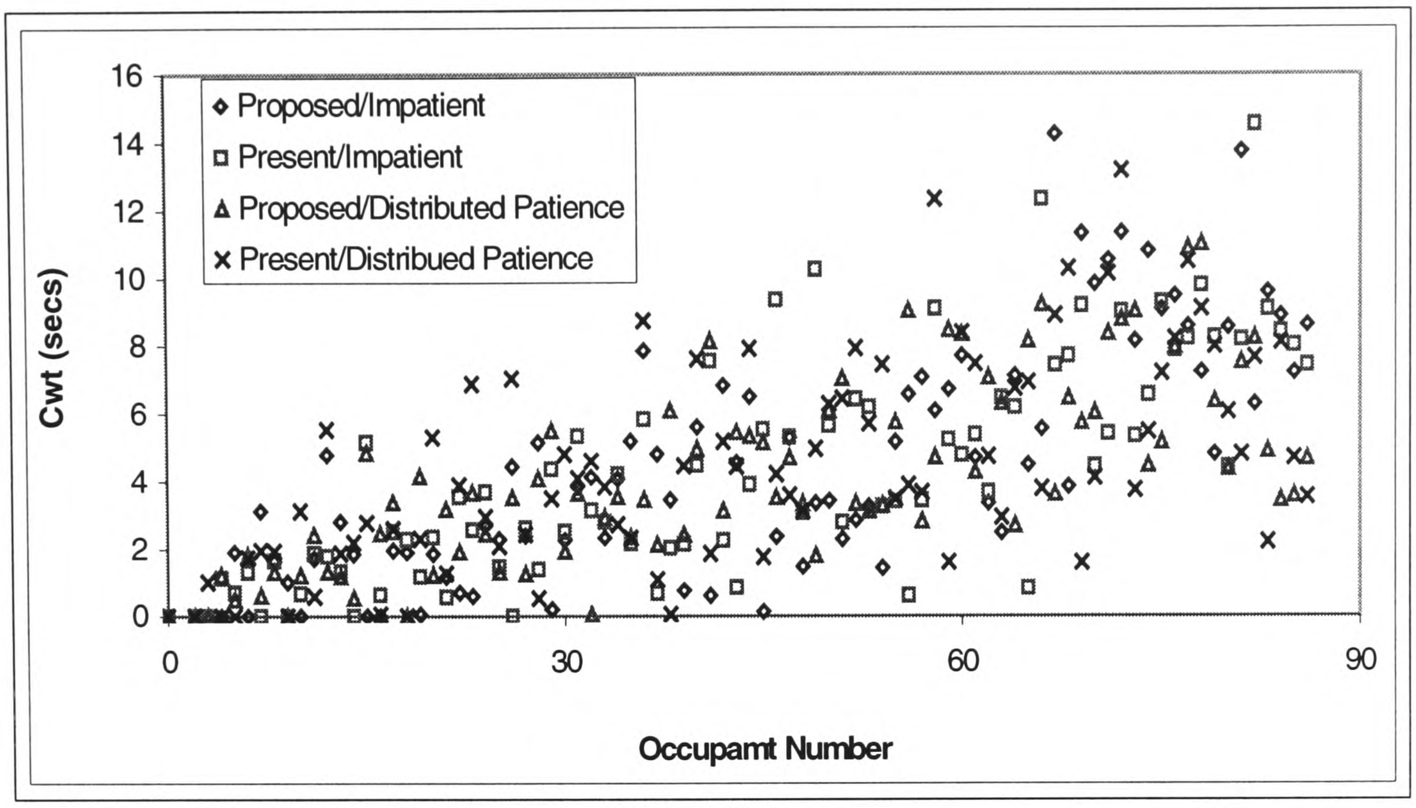


FIGURE 7-13: DISTRIBUTION OF CUMULATIVE WAIT TIMES

In effect, the introduction of the dynamic drive facility by itself does not generate significant overall differences in the resolution of conflicts. The individual experience may include subtle differences according to the occupant experience. This is further borne out through examining the occupants *CUMULATIVE WAIT TIME (CWT)* in Table 7-7, where although the averages generated in the different conditions are very similar, the distribution of the averages, reflected by the standard deviation, demonstrates a more consistent difference. The scenarios involving impatient occupants demonstrate a greater distribution of wait times (see Figure 7-13 and Table 7-7). This reflects the potential advantages or disadvantages that can be gained through the movement to the *EXTREME* behavioural regime and the subsequent route adaptation. Although local differences are evident in the resolution of conflicts, this effect is compensated for in other areas, reducing its effect on the overall average times produced. During the scenarios involving a distribution of *PATIENCE* settings, the occupants are far less likely to become *EXTREME, are consequently unable to adopt a more circuitous route,* and therefore maintain their interaction with those occupants in close proximity.

TABLE 7-7:RESULTS PRODUCED DURING SCENARIO 7.2.41

	BEHAVIOURAL MODEL			
	PRESENT (SCENARIO 7.2.411)		PROPOSED (SCENARIO 7.2.412)	
PATIENCE LEVEL	AVG CWT (SECS)	S.D. (σ)(SECS)	AVG CWT (SECS)	S.D. {σ}(SECS)
IMPATIENT	4.3 [4.1-4.5]	3.6 [3.5-3.8]	4.2 [4.0-4.4]	3.5 [3.4-3.7]
DISTRIBUTION	4.5 [4.4-4.5]	2.8 [2.5-2.9]	4.5 [4.2-4.6]	2.7 [2.4-3.0]

The lack of anomalies and the similarities of the evacuation behaviour in Scenarios 7.2.411 and 7.2.412 can be observed from the cumulative arrival curves in Figure 7-14, where no unusual events or exaggerated differences can be seen from the cases examined. Indeed, all of the cases examined show a large degree of similarity.

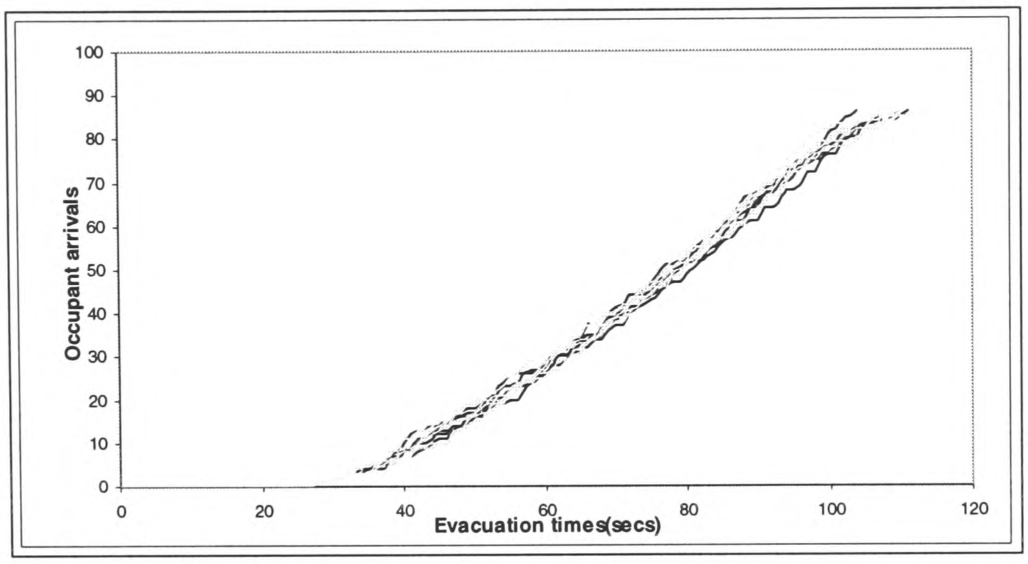


FIGURE 7-14: EVACUATION CURVES FOR THE 7.2.41 CASE. BLACK SIGNIFIES THE SCENARIO 7.2.412, WHILE GREY SIGNIFIES 7.2.411.

In contrast to the quantitative similarities, qualitatively the occupants tended to be in different psychological states depending upon their experiences and their location. Although at this preliminary stage of development these qualitative differences are largely internal, they will, in concert with a number of the proposed features described in Chapter 8, prove vital in the occupant's decision-making process.

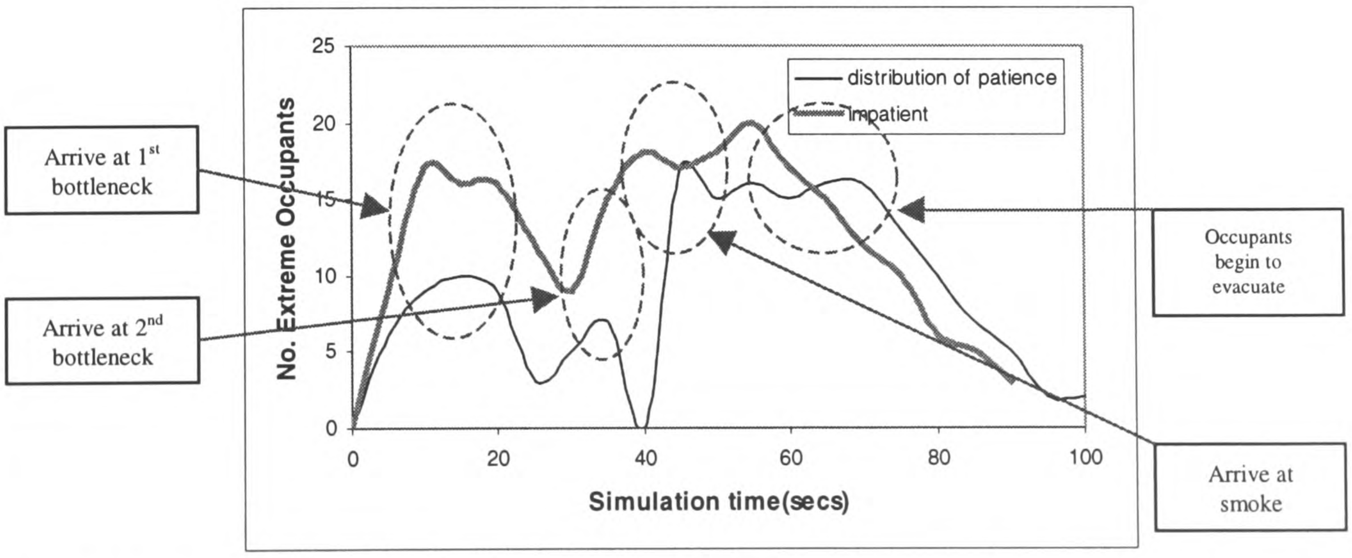


FIGURE 7-15: COMPARISON OF THE NUMBERS OF EXTREME OCCUPANTS FOUND IN THE PROPOSED MODEL.

In Figure 7-15 obvious differences are apparent between the numbers of occupants who have become *EXTREME* in Scenario 7.2.412, in relation to the level of occupant patience. This is especially the case during the interaction with high-density populations at the two bottlenecks. The population density has an increased impact upon the occupant's behavioural regime once the occupant becomes impatient. Once impatience has been imposed, the numbers of occupants who become *EXTREME* are consistently higher under the high-density conditions. The curves converge once the smoke is encountered as this is interpreted independently of the patience level and increases the occupant motivation levels sharply.

If we compare these findings to those produced in Scenario 7.2.411 where the present model is implemented, some significant differences are apparent (see Figure 7-16). Firstly the number of occupants becoming and remaining *EXTREME* is reduced. This is due to the mechanisms that are used to cause this behavioural development and that this transformation only lasts for limited periods of time (as little as 1/12th of a second). Once the occupant has reduced the distance to this target under the present model, the behavioural regime returns to *NORMAL*.

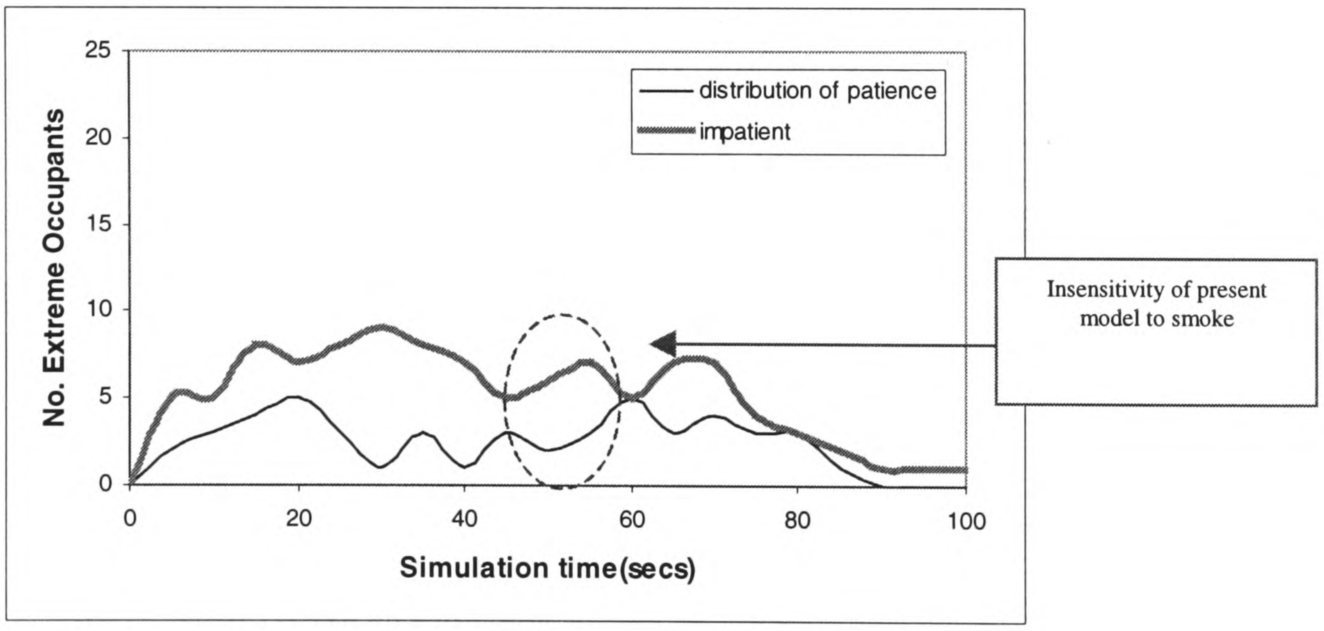


FIGURE 7-16: NUMBER OF EXTREME OCCUPANTS UNDER THE PRESENT MODEL

More importantly, the behavioural development is completely insensitive to the existence of smoke within the environment. Any slight peak in the curves occurring at approximately the 50 second mark in Figure 7-16, from which point the occupants would be expected to interact with the smoke, are due purely to increased congestion. This congestion is caused by the reduced occupant travel speed as a consequence of the environment, rather than being due to any psychological process. This identifies an inconsistency within the capability of the present model, as it is sensitive to possible occupant congestion and, contrary to evidence [24], is insensitive to the existence of smoke.

A similar trend exists in relation to the patience levels of the occupants, with impatient occupants being more likely to become *EXTREME*. This is entirely due to the importance of occupant *PATIENCE* in both of the models.

CASE 7.2.42

The impact of the proposed behaviour upon the individual experience and the overall evacuation time is examined through the introduction of a more complex geometry (see Figure 7-17).

Three separate populations are defined, each of which has a different experience *en route* to their desired exit. A relatively small population of 50 occupants moves towards the exit. These are placed in the upper section of the geometry (Pop 1), and produced relatively low population densities due to the space available to them, shown in Figure 7-17. A larger population of 200 occupants, and consequently the production of higher population densities, is positioned in the central section of the geometry (Pop 2). Finally, 50 occupants are positioned in the lower section of the geometry (Pop 3). These occupants encounter smoke (with an extinction coefficient of 0.4/m) before exiting. All of the occupant's head towards a single exit of 1.5m, attributed with free-flow conditions.

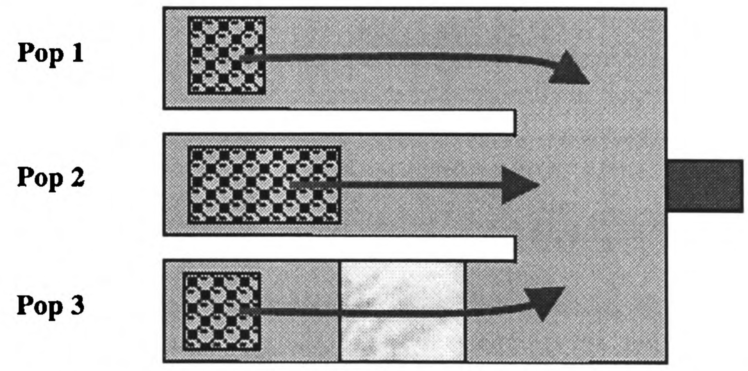


FIGURE 7-17: REPRESENTATION OF GEOMETRY USED IN 7.2.42

These conditions have been designed to examine the importance of the location of the occupants and their awareness of the surrounding conditions upon their motivation and their psychological condition.

The present buildingEXODUS model is examined in Scenario 7.2.421 to provide a control case, while the proposed implementation is examined in 7.2.422.

RESULTS-7.2.42

As the proposed behaviour is not tested in unison with a number of the other proposed behavioural features, the analysis is limited to the evacuation times produced and the impact of the evacuation conditions on the occupant rather than more complicated behavioural issues.

From Table 7-8, there is again only a 4% increase in the overall evacuation time through the introduction of the proposed model. This is because the developments in the occupant drives seen in scenario 7.2.422 are not global, with local effects differing throughout the geometry being dependent upon the experiences of the occupants. Therefore any potential differences caused by the fluctuation of occupant motivation are reduced, as they are not uniform throughout the geometry.

These findings are maintained when the individual experiences of the occupants are examined (see Table 7-8). The *PERSONAL ELAPSED TIME* and *CUMULATIVE WAIT TIMES* produced (as well as the extent and nature of the distributions) are consistent between the models (see Section 3.1, Chapter 3). These results may have been affected by the extensive queuing that occurred towards the end of the simulation, increasing all of the occupant's attribute times.

TABLE 7-8: RESULTS PRODUCED FROM SCENARIO 7.2.42

	BEHAVIOURAL MODEL	
	PRESENT (SCENARIO 7.2.421)	PROPOSED (SCENARIO 7.2.422)
EVACUATION TIME (SECS)	**92.7 [90.6-94.3]**	**96.3 [93.3-99.6]**
AVG. CWT	**5.1 [5.0-5.3]**	**5.2 [5.0-5.4]**
STAN. DEV. CWT	**3.4 [3.3-3.6]**	**3.4 [3.1-3.6]**
AVG. PET	**52.5 [50.8-53.2]**	**52.8 [50.2-53.8]**

A marked difference is evident in the number of *EXTREME* occupants found during Scenario 7.2.421 and 7.2.422. From Figure 7-18 it is apparent that there are large differences in the numbers of occupants becoming *EXTREME* according to the model implemented.

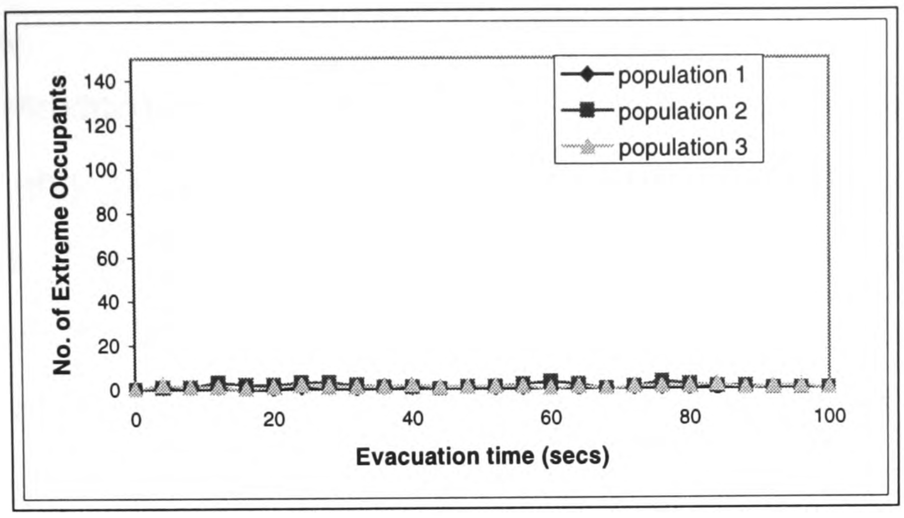
During the implementation of the present model (scenario 7.2.421), the three sections of the geometry produced *similar* results throughout the simulations (see Figure 7-18).

Population 2 exhibits a slightly higher degree of behavioural change, due to the increased population density being more likely to satisfy the conditions of behavioural transformation. The results are again completely insensitive to the existence of smoke other than the additional congestion that may subsequently arise. In this respect the results produced in Population 1 and Population 3 are very similar, being largely centred on a low-density population.

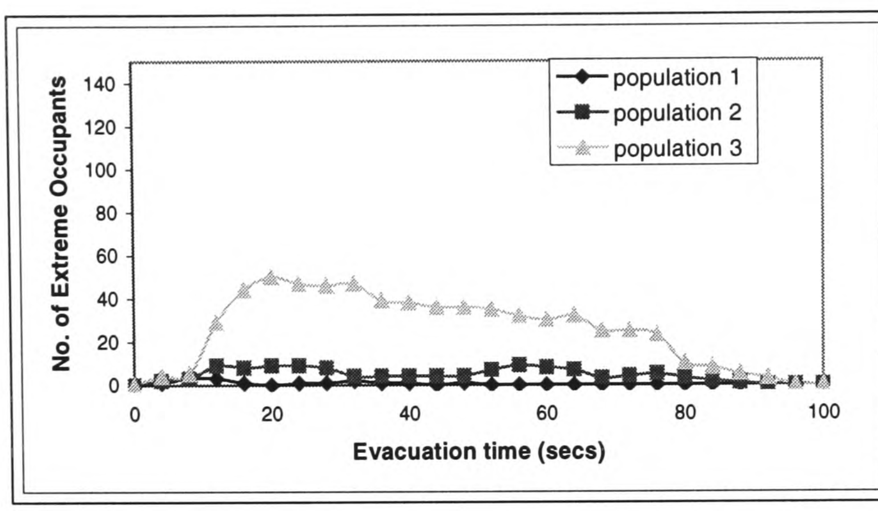
When the proposed model is implemented, significant differences appear between the numbers of occupants becoming *EXTREME* in the three occupant populations. The occupants relying upon occupant density to increase their motivation (and therefore to alter their behavioural regime) have consistently lower rates of behavioural change. In the high-density population conditions experienced by population 2, a slight increase in the number of transformations is evident, while the low-density population (population 1) maintains a very low rate of behavioural development.

The rate of behavioural change evident within population 3 is consistently higher than in the other two areas. This is because the interaction of smoke is dominant, signifying the occurrence of an emergency, and therefore automatically motivating the occupant population. As we would expect, once the occupants have interacted with a smoke-filled environment, they become more motivated to evacuate. Once this interaction takes place, the occupant remains motivated for the rest of the evacuation. The fall in the number of occupants in Population 1 who are highly motivated reflects the increase in the number of occupants who have evacuated.

These findings are specific to this case and may therefore alter significantly given other conditions. However, a fact is fundamental to the introduction of the new behaviour; *that occupants, through interacting with their surroundings, perceive different levels of information and this perception will impact upon their psychological state* (represented by their *DRIVE* and the behavioural regime used).



(a)



(b)

FIGURE 7-18: REFLECTION OF THE AVERAGE NUMBER OF EXTREME OCCUPANTS DURING SCENARIO 7.2.421 (A) AND SCENARIO 7.2.422 (B)

7.2.5 FUTURE WORK

The separation of occupant behaviour into two distinct regimes is an arbitrary one, relating to previous versions of the buildingEXODUS model. In future developments, behavioural transition should be continuous and should not preclude individual actions from being performed. It should only alter the probability of *performing* actions given the surrounding conditions. This development proposed is a significant step in this process and is analogous to those described in the work of Narendra et al.[208,209].

The introduction of the proposed behaviour questions the necessity of the behavioural regime altogether. Even at this early stage, it is rendered as a descriptive tool and is sustained solely to maintain compatibility with previous versions of the software. In future developments, the occupant's psychological condition will be entirely dependent upon the local conditions and experience of the occupant rather than the desire of the user. Generally, the model should be sensitive to the changing motivation of the occupants. This will be dependent upon the occupant's experiences and surroundings. Ideally, this should be implemented without the requirement of model dependent compromises.

7.2.6 Conclusion

As expected the introduction of the proposed development, given the limited nature of the examination, only produces subtle (although still noticeable) differences in the quantitative results. This is due to the limited impact of this behaviour, in isolation. It is important that given the dependence of a number of the proposed behaviours upon the occupant's behavioural regime and subsequently upon the occupant's motivation (see Chapter 8), that the model is sensitive to the experiences and attributes of the occupant, which are analysed and distilled into an appropriate format.

The system has been shown to be sensitive to the experiences of the occupant, increasing their dependence upon their perception and their location enabling them access to information. Although more accurately representing the dynamic nature of occupant perception and their interpretation of the surroundings, it is expected that the most important impact of the dynamic behavioural regime, is its provision for new behavioural features. In conjunction with the dynamic drive facility, it allows the new features outlined in this dissertation to be introduction in a scenario specific fashion, according to the information perceived by the individual, rather than necessarily being a consideration for the user. As well as this, it also provides a means by which these behaviours are performed at realistic points in time during the evacuation.

7.3 Localised representation of occupant familiarity

7.3.1 Expected Occupant Behaviour

Occupant familiarity has long been seen as of fundamental importance to the progress of an evacuation. Instead of occupant's heading towards the nearest exit – of which they may have no prior knowledge - as would be assumed by the majority of present building regulations, they instead move towards other more distant exits with which they have had previous experience and with which they feel more confident [1,4]. As noted by Turner and Killian, in an emergency, the familiarity of an occupant may limit the number of options available to him [210]. Therefore

"When people, attempting to escape from a burning building pile up at a single exit, their behaviour appears highly irrational to someone who learns after the panic that other exits were available. To the actor in the situation who does not recognise the existence of these alternatives, attempting to fight his way to the exit available may seem a very logical choice as opposed to burning to death" [210]

Pauls [99] identified the importance of examining regular social and physical movement and behaviour, to predict the actions of occupants in a difficult and possibly unique situation. This correlation was seen during the King's Cross fire, where passengers, when attempting to evacuate, adopted routes which were closely related to those usually used [1,97], as well as in a number of other cases [58].

Sime and Kimura identified the significance of occupant familiarity with exit choice [96]. In contrast to the assumptions of the majority of building regulations, occupants are not inclined to base their choice of exit solely upon proximity, but instead invoke the influence of familiarity in their choice. Sime and Kimura, through analysis of the available literature concluded that it

> *"indicates that objective travel distance is not necessarily the most important determinant of the direction of movement." [96]*

In addition, occupants cannot move towards exit with which they have no knowledge or experience. This knowledge level may fluctuate during an evacuation [211]. Hidden or isolated exits may be ignored causing inefficient exit usage, contradicting the assumptions of the building regulations. This can only be overcome during an evacuation through communication of the exit's existence in some way (occupant, signage, etc.) [1] An occupant may therefore become aware of an exit during an evacuation, although this awareness may not necessarily guarantee usage. This will be dependent upon the level of confidence that the exit affords the occupant. In Rubes' examination of crowd flow, he found that exit choice was not simply dependent upon awareness but was linked to visibility, allowing the occupant to establish confidence of the exits viability [212].

One of the behavioural features differentiating simulation models from optimisation models (see Section 3.2, Chapter 3) is their ability to reflect the occupant's knowledge of and familiarity with the enclosure. Obviously, the sophistication of the methods used varies, as does the perspective on which they are based. Traditionally, the occupant familiarity has tended to be globally imposed upon the occupant population, who have an identical vision of the enclosure. Recently, models have attempted to reflect some alternatives in occupant knowledge [8]. *None of these models to date represent the occupant's awareness of the enclosure at an individual level.* Indeed recent research suggests that the occupant's awareness of the geometry is far more complex than initially thought, being based around the connectivity of adjoining spaces, rather than a complete map of the enclosure [170,201].

7.3.2 PRESENT BUILDINGEXODUS IMPLEMENTATION

A global/default method is used that defines the attractiveness of each of the exits within an enclosure according to a potential map system. The occupant is assumed to be **fully aware** of the existence of the exits involved, but can be made to be more/less attracted to the exit using a biasing system. This method fulfils the requirements of the building regulations, in that occupants can (if required) be assumed to move to the nearest exit. The manipulation of the biasing attached to individual exits extends/diminishes the catchment area within which that exit appears attractive. Once in this area, an occupant will move towards the exit, unless the user has specifically instructed the occupant to move to another exit through the identification of a *target door*. This identification specifies the exact destination for the occupant and does not provide for alternative routes. This specification functions under the NORMAL behavioural regime. If the EXTREME behavioural regime is selected (at the start of the simulation), once an occupant attains the "EXTREME condition" the occupant will ignore the user specified target exit and select the nearest available exit.

At present, the EXTREME behavioural regime is applied globally. Therefore the ability of occupants to become extreme is dependent upon the user and applies to all of the occupants involved in the simulation. However, the movement to extreme behaviour is also dependent upon the occupant's PATIENCE attribute. The user therefore determines the ability of occupants to become extreme rather than forcing them to do so.

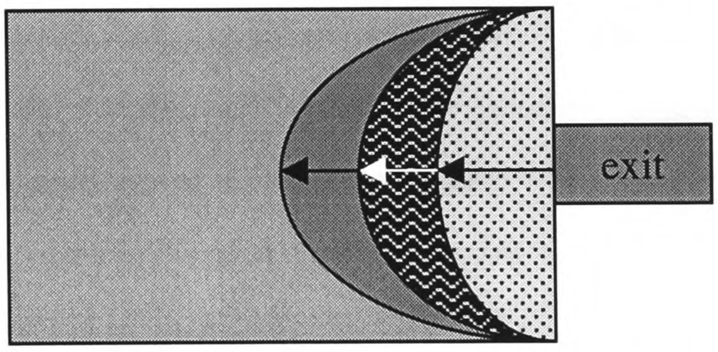


FIGURE 7-19: CATCHMENT AREA INCREASES AS EXIT IS MADE MORE DESIRABLE IN PRESENT VERSION OF BUILDINGEXODUS.

Through the use of *exit biasing* it is possible to make a biased exit globally more or less attractive and thus biasing is a representation of global familiarity i.e. all occupants will be affected equally (see Figure 7-19). Through the use of *target exits*, it is possible to represent the familiarity of a particular occupant with a single exit. However, the occupant does not have the ability to examine the viability of other potential routes to exit. Thus, with the exception of specifying target exits, it is not possible to provide a comprehensive and *individual* representation of an occupant's familiarity with the structure.

7.3.3 PROPOSED BEHAVIOURAL ENHANCEMENTS

It is considered vital not only to represent the occupant's *initial* target, but also to represent the *extent* of the individual occupant's familiarity with the structure. This is less important under non-emergency conditions or conditions of low population density, where the occupant may evacuate unhindered to the target of their choice. However, during situations involving redirection (such as queuing or confrontation with environmental barriers, see Section 8.4, Chapter 8), the existence of alternative routes and the occupant's awareness of these routes becomes significant.

To represent occupant familiarity the proposed implementation credits each occupant with an individual understanding of the exits available, which are stored in a localised list of exits, termed a *DOOR VECTOR*. These exits are drawn from the complete list of exits within the enclosure, defined prior to the simulation.

This produces a shift from a *global system* of occupant familiarity to one based on individual and localised considerations. In reality, this local knowledge will be based on a number of factors including the experiences of the occupant, the role of the occupants, the daily use of the enclosure and several other factors. These factors would then go to describe the occupant's awareness of the enclosure. However, these factors are not presently included within the buildingEXODUS model. As an interim position the occupant is attributed with a *familiarity index*. This can range from 1 to 20 and represents the occupant's awareness of the enclosure. *This index can be seen as a composite of the factors influencing occupant familiarity.*

At present, the attractiveness of an exit within the buildingEXODUS model is attributed by assigning an integer to the exit that then globally skews the potential map. In the proposed model, a similar index is used. However, in this case, although the provision of a static integer is a compromise due to its global nature, it is interpreted *individually* through comparison against the individual's familiarity index. Therefore, *individual occupants will interpret exit conditions differently.*

Means are required for the user to allocate each occupant with the desired list of exits. The proposed method provided is automated. Although the user has a significant degree of control over the occupant's awareness, the *exact* extent of the occupant's awareness cannot be guaranteed. Ideally the ability to specify exit awareness individually should be available, as it would be particularly useful if detailed experimental data was available to the engineer. However, this automated version of exit allocation was felt sufficient to demonstrate the *concept* of individual occupant familiarity and its impact upon the buildingEXODUS model. The necessity for a manual version is noted, but is left for future work.

The probability of the occupant being familiar with a particular exit is therefore dependent on a number of factors. These include the *exit type* (whether the exit is a non-reversible emergency exit or an exit in constant use), the *attractiveness of the exit*, identified by a user-defined index (representing the frequency of its use, as well as a number of other factors) and *occupant attributes* (the familiarity index attributed to the occupant). It is conceded that the ability to define the attractiveness of the exit as an external feature is a compromise within the model. Ideally, this feature should be derived completely from the experience of the occupant (e.g. the exit used by the occupant to gain entrance to the enclosure). Instead, the external representation is seen as being the culmination of signage, the everyday use of the enclosure, architectural assistance, etc. Again, although this is acknowledged as a compromise position, it is felt sufficient to demonstrate the concept of the individual representation of familiarity.

Within the proposed implementation two exit types are represented: EMERGENCY and CONSTANT USE exits. If the exit is defined as an EMERGENCY exit, calculations will be made to determine whether the occupant is initially *aware* of it. Obviously, this may also to be used to represent exits that are used particularly infrequently. Otherwise, if the exit is in CONSTANT USE the occupant is assumed to have knowledge of the exit. All that can then be manipulated by the engineer is then the *attractiveness* of the exit.

The occupant's index of familiarity is assigned prior to the simulation. This is purely an implementational consideration and as such represents a number of factors that could eventually be derived directly from the occupant's internal traits. The likelihood of the occupant being aware of an emergency exit is therefore determined according to

$$\frac{A_j}{A_{\max}} \le \left(\frac{F_i}{F_{\max}} \right)^R \pm \varepsilon \qquad (64)$$

where A_j and A_{max} represent the attractiveness of exit j and the maximum exit attractiveness of an exit respectively, F_i and F_{max} represent the familiarity of the occupant and the maximum achievable familiarity of an occupant, R represents the role of occupant i, and ε is a random number between 0 and 0.5. F_{max} is arbitrarily set to 20 and A_{max} is set at 20, to enable a bounded scales to be determined. This method provides the possibility of the occupant familiarity altering *between* simulation runs. It should be noted that as the user-defined value, A_j, increases, so the exit becomes less likely to be familiar to the occupant.

As the occupant's familiarity index increases, so the likelihood of the occupant being aware of an emergency exit increases. This function has been formulated to allow occupants to have the opportunity of being aware of all but the most underused emergency exits.

Exceptions to this rule are those occupants deemed to be staff (see Section 8.3, Chapter 8). Under these conditions, the occupants are assumed to be completely familiar with the enclosure. This is represented by the R variable in the function above. This is automatically set to 0 for members of staff and to 1 for the rest of the occupant population. Therefore, through simply flagging individual occupants as members of staff, their door vector will then be identical to the complete list of exits, crediting them with a complete awareness of the egress routes available.

Once formed, the exit list (or *door vector*) is ordered according to the occupant's preference. This is based on the occupant distance from the exit (d_i), the exit type (T_i) and the user-defined exit attractiveness (A_i). T_i is a numerical representation of the exit type, such that exits that are in constant use are assigned a value of 5.0 whereas emergency exits are assigned a value of 1.0. These values reflect the propensity of occupants to gravitate towards the familiar (through an exits more frequent use). The original target door approach adopted in the present implementation (see Section 3.1, Chapter 3) may therefore be considered as a door vector containing only a single candidate door.

The exits are ranked according to a preference quota (Q_i), derived from the factors outlined above. The exit that appears most attractive is adopted according to

$$Q_i = (\frac{T^R}{F_i} + \frac{F_i}{d_i + A_i^R}) \pm \varepsilon \qquad (65)$$

with the exit associated with the highest quotient being adopted. The effect of the exit type provides a significant bias towards the exits that are regularly used over emergency exits. Therefore the exit type dominates the exit attractiveness. If exits are of the same type, then the attractiveness of individual exits is still vital in determining their adoption. This form of biasing of an exit is still important, as given the availability of several exits, the attractiveness of the exit may still be the determining factor between them. However, biasing does not form a catchment area as before, but is instead a *consideration* in exit familiarity. As before, an increase in the exit attractiveness, A_i, reduces the perceived quality of an exit. In line with the previous inequality, the role of the occupant infringes upon the equation, so that a member of staff, due to the increased levels of familiarity and subsequent confidence, is assumed to be oblivious to exit types and to the general usage of an exit, represented by A_i. If an occupant is a member of staff, R equals 0 otherwise it is set to 1. This therefore removes the impact of the exit type and the user-defined attractiveness of the exit. The quotient generated is purely for internal comparison in the decision of the occupant to select an exit and has no intrinsic value in itself.

To clarify this equation, a brief example is provided. Consider two occupants. Occupant A is a regular user of an enclosure and is attributed by the user with a familiarity of 20 (F^A=20). Occupant B uses the enclosure far less frequently and is attributed with a familiarity index of only 5 (F^B=5). Both Occupant A and Occupant B are located 10m (d_{emerg}=10) from their nearest emergency exit and 30m (d_{reg}=30) from their nearest exit that is in regular use. The emergency exit is seen as less attractive than the exit in regular use. Therefore the emergency exit is attributed with an attractiveness of 10 (A_{emerg}=10), whereas the exit in regular use has an attractiveness of 5 (A_{reg}=10, representing the increased frequency of use of the non-emergency exit). The random factor is ignored to simplify the calculation.

If we examine the calculation as to the preference quota Q of these exits (assuming the occupants are aware of both exits although neither are members of staff), Occupant A attributes a value of $\frac{23}{28}$ to the regular exit, given that

$$Q_i = (\frac{T^R}{F_i} + \frac{F_i}{d_i + A_i^R})$$, (from equation (65)) then

$$\frac{5}{20} + (\frac{20}{30+5}) = \frac{23}{28}$$

and a value of $\frac{63}{60}$ to the emergency exit, calculated according to

$$\frac{1}{20} + (\frac{20}{10+10}) = \frac{63}{60}$$

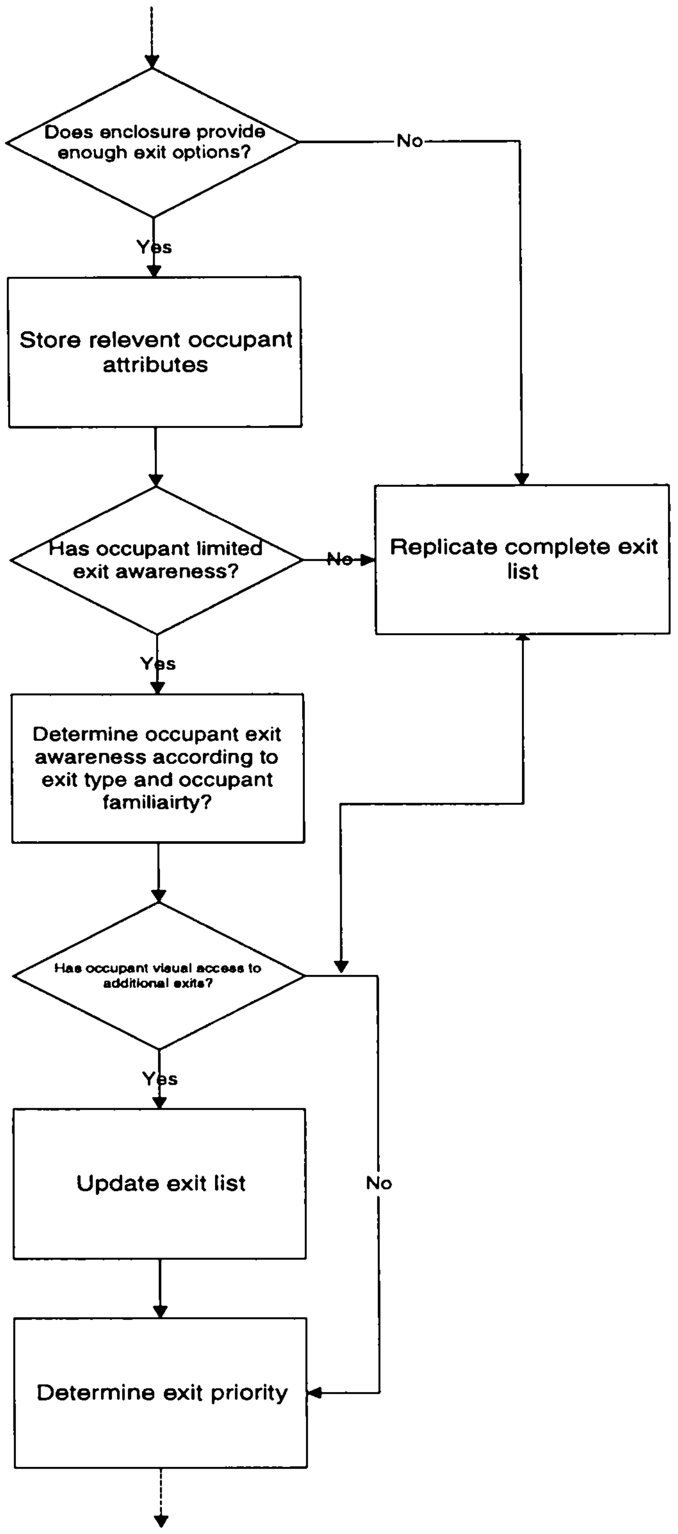


FIGURE 7-20: FLOW CHART OF PROPOSED REPRESENTATION OF OCCUPANT FAMILIARITY.

Therefore, Occupant A, a regular user of the enclosure, will adopt the emergency exit, as he is more familiar with the enclosure, allowing him to take advantage of the proximity of the exit.

Occupant B attributes a preference quota of $\frac{8}{7}$ to the regular exit calculated according to

$$\frac{5}{5}+(\frac{5}{30+5})=\frac{8}{7}$$

and a value of $\frac{9}{20}$ to the emergency exit from

$$\frac{1}{5}+(\frac{5}{10+10})=\frac{9}{20}$$

Therefore, Occupant B will not find the emergency exit attractive and will initially move towards the exit that is used more regularly. This demonstrates the impact that the occupant attributes can have upon their interpretation of the layout of the geometry.

Given these calculations, the occupant is attributed with individual exit awareness on a probabilistic basis, which is significantly influenced by the identity of the occupant. *The occupant awareness of particular exits may therefore alter between different simulations.*

It should be remembered that the knowledge of an exit does not simply describe an occupant's final destination, but implicitly defines the occupant's understanding of the routes that may be available to him within the structure. Occupant egress, in terms of both the short-term navigation and the long-term target adoption, will be dependent upon the occupant's exit awareness.

This calculation is made prior to the starting of the simulation. Once formed the ordering of the door vector is maintained, unless an outside influence affects the occupant. This includes the provision of new information from other occupants, staff or from the environment. Under these circumstances, an exit may become more attractive according to instruction, or a new exit may enter the vector that had previously not been familiar to the occupant. The influence of communication upon the proposed behaviour cannot be overestimated. However, due to the complexity of this behaviour, it is dealt with in some detail in Section 8.4, Chapter 8.

The door vector is therefore intended to be dynamic reflecting the changing levels of occupant awareness during the evacuation. As noted, a number of external factors directly affect the extent of the occupant's exit list. According to their path, the occupant may also become aware of previously unknown exits through line-of-sight calculations (see Section 5.4, Chapter 5). The willingness of an occupant to adopt a new exit according to line-of-sight is now addressed.

Given that the occupant is *visually aware* of an exit (i.e. they can receive information from it), it may then be added to their door vector. This will depend on the information afforded to the occupant by their location, the position of other occupants and the environmental conditions (see Section 5.4, Chapter 5). The occupant therefore receives new information that can provide additional awareness of the enclosure. This is achieved through sporadically examining the occupant's present position and their ability to receive new information on his surroundings, according to the occupant's present motivation and their ability to perceive the existence of a new exit. Utilising this feature, the exit list may expand according to new information, allowing for new exits to become available.

The occupant may be encouraged to adopt a previously unfamiliar exit, especially if it is perceived as being used by a limited number of other occupants. This is based on the assumption that an exit being used is perceived as being a more viable means of egress than one that is not being used as the occupant is more confident that the exit is operable [52,53,200]. Initially, the occupant is examined to determine whether he becomes aware of the new exit (according to the factors highlighted in Section 5.4, Chapter 5). The newly acquired exit is then examined to determine whether it will be adopted as a new target. Firstly, it has to present an advantage over the present exit, according to travel distance, such that

$$\|R - S\|_2 > \|R - T\|_2 \quad (66)$$

where $R=[x_{present}, y_{present}]$, $S=[x_{exit}, y_{exit}]$ and $T=[x_{exit'}, y_{exit'}]$. Once this has been established the motivation of the occupant is examined (D_i), as a reflection of the perceived seriousness of the situation in conjunction with the perceived reliability of the exit in the form of the number of occupants already using the exit (p_i), such that

$$Q_i' = \frac{D_i}{D_{max}} + \frac{\max((P - p_i), 0)}{5P} \quad (67)$$

where P is a maximum threshold above which the exit is deemed to be unattractive due to excessive congestion. The denominator is calculated to *contain* the influence of the existence of a crowd around the target exit. The attractiveness of the newly formed exit (Q_i') is then compared against a random number to determine whether it is adopted as the new target exit.

$$\frac{Q_i'}{Q_{\max}} > r \tag{68}$$

If this is satisfied, then the occupant will adopt the previously unfamiliar exit as their new target.

A number of checks have to be implemented to prevent the occupant having no target exit; effectively having no familiarity with the enclosure. Firstly, if there are only a small number of exits within a structure (less than 3), then it is assumed that the occupant is aware of *all* of the exits. Ideally, a search facility might be developed to cater for an occupant who initially has no exits available to him.

Secondly, if *all* of the exits are emergency exits (in reality, an unlikely situation), then due to mechanisms used to calculate the extent of the door vector, an occupant may be attributed with no exit awareness. Under these circumstances, the occupant will automatically be attributed with the nearest exit. There is therefore no possibility of an occupant being without an exit.

If the proposed implementation is compared with the various methods presently available an obvious increase in the sophistication is apparent. In the present system, if the potential map system is used, the occupant is assumed to have a complete awareness of the enclosure. The global exit attractiveness can then be manipulated by the user through biasing the exits, allowing some influence to be exerted over the exit choice. If the target exit system is used, the occupant has a restricted understanding of the enclosure, although under this method, exit biasing has no impact. The proposed method combines the capability of manipulating occupant awareness (although locally) with the capacity to influence their exit preferences, both of which exist in a limited form in the present model, although not simultaneously.

The movement from a globally defined familiarity map to one that is individually defined is vital to the advance of behavioural sophistication in the buildingEXODUS model. Obviously, this implementation is a starting point given the compromises outlined. The possible advances gained from its introduction are outlined later, but the storage of knowledge as an individual attribute rather than a global one allows a far greater degree of flexibility in the occupant behaviour in itself. It also more accurately represents the different levels of information that might exist within the occupant population, instead of assuming that knowledge is a global commodity.

The introduction of the door vector not only allows the improved representation of occupant familiarity, but also provides the occupant with information that might be later communicated.

7.3.4 Verification

Three separate cases are examined to determine the impact of the proposed behaviour upon the buildingEXODUS model. These are:

- 7.3.41 Designed to examine the impact of exit adoption given occupant traits
- 7.3.42 Designed to examine the impact of the proposed behaviour given a complex geometry and a distribution of occupant awareness due to natural occupant variation
- 7.3.43 The impact of the occupant's ability to become aware of exits during an evacuation

The results are compared against the present model to demonstrate any subsequent differences in the results produced, where appropriate.

Table 7-9: Description of the validation cases used to examine the use of the proposed model

Scenario	Geometry	Population	Exit
7.3.41	10m x 10m	100, instant response Familiarity index =5,10,15, 20	4 exits (1m), one main 3 fire exits (equally biased)
7.3.42	Complex geometry	150 default occupants, instant response	Biased to represent main exit (2.5m) and three fire exits (1.5m)
7.3.43	Irregular geometry	1 occupant, drive=5,10,15,20, possible crowd of 12	2 exits (1m), 1 of which is unfamiliar

Case 7.3.41

To demonstrate the importance of the occupant identity upon the adoption of exits into their door vector and the flexibility of the system, a simple geometry is produced with four exits (see Figure 7-21). Three of these exits are EMERGENCY exits, restricting occupant awareness, whilst the other is an exit in CONSTANT USE (the main exit), allowing universal familiarity. These exits each have a width of 1m and are placed at the four-corners of the geometry. As the occupants are positioned centrally, once unbiased all of the exits have the same number of occupants initially attracted to them (25 occupants).

The present model is implemented in 7.3.411-3.413. In Scenario 7.3.411, no biasing is applied to the exits. In Scenario 7.3.412, the biasing is altered so that exits 1,2 and 3 are simulated as being emergency exits (or at least significantly less attractive). This is achieved by attributing exits 1,2 and 3 with a bias of 2 and exit 4 with a bias of 0. This 'emergency' (in this Scenario represented as being the less attractive exits) exit biasing is increased in Scenario 7.3.413 to 5, increasing the relative attractiveness of the main exit. All of these simulations use the default population, generated using the Population Panel System (see Section 3.1, Chapter 3).

In the remaining scenarios, the proposed model is used. In Scenario 7.3.414, no biasing is applied and the default occupant population is used. This is to allow comparison with the control case in 7.3.411. In Scenario 7.3.415, three of the exits are defined as EMERGENCY exits and are biased to simulate the occupants' possible lack of familiarity with the emergency exits. Due to the sensitivity of the proposed model to this feature and the diminutive size of the geometry, the emergency exits are attributed with an attractiveness of +1 in comparison to the exit in regular use.

To examine the impact of occupant attributes, four separate occupant populations are examined. The difference between the population is the familiarity index attributed to them. This is uniformly attributed across the population and is incremented in steps of 5 between 5 and 20 units.

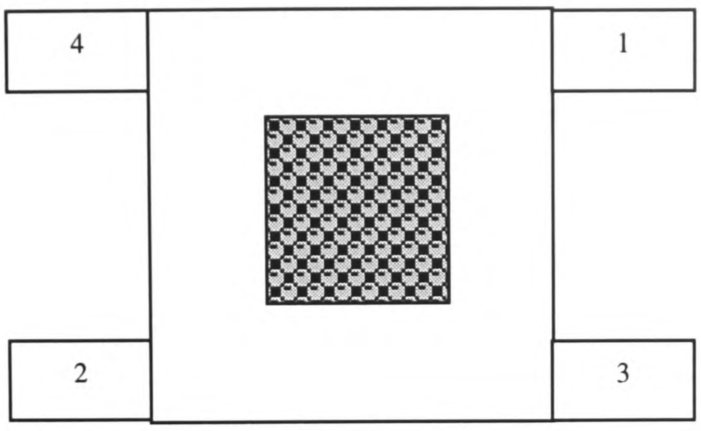


FIGURE 7-21: REPRESENTATION OF 7.3.41 WHERE THE IMPACT OF ALTERING THE ATTRACTIVENESS OF THE EXITS AND THE POPULATION ATTRIBUTES UPON EXIT USAGE IS EXAMINED.

RESULTS-CASE 7.3.41

Under the present model only the occupant's position and the biasing attached to an exit is considered. Therefore if the biasing of an exit is altered, the adoption rate of particular exits changes *deterministically*, according to the population's position within the geometry (see Figure 7-22). *No occupant attributes impact upon the familiarity of the occupant.*

TABLE 7-10: EXIT USAGE UNDER THE PRESENT IMPLEMENTATION.

Scenario	Exit 4 (Main exit)	Exit 1 (Emergency exit)	Exit 2 (Emergency exit)	Exit 3 (Emergency exit)
7.3.411	25	25	25	25
7.3.412	50	14	22	14
7.3.413	95	0	0	5

If Table 7-10 is examined, a consistent and simplistic adoption of the exits is portrayed. No distributions are included, as none were generated. As the attractiveness of these exits is altered, so the occupant adoption alters *deterministically*. The simplicity of this effect is demonstrated in Figure 7-22 where the occupant's relationship to the selected exit is clearly shown as being *location* dependent.

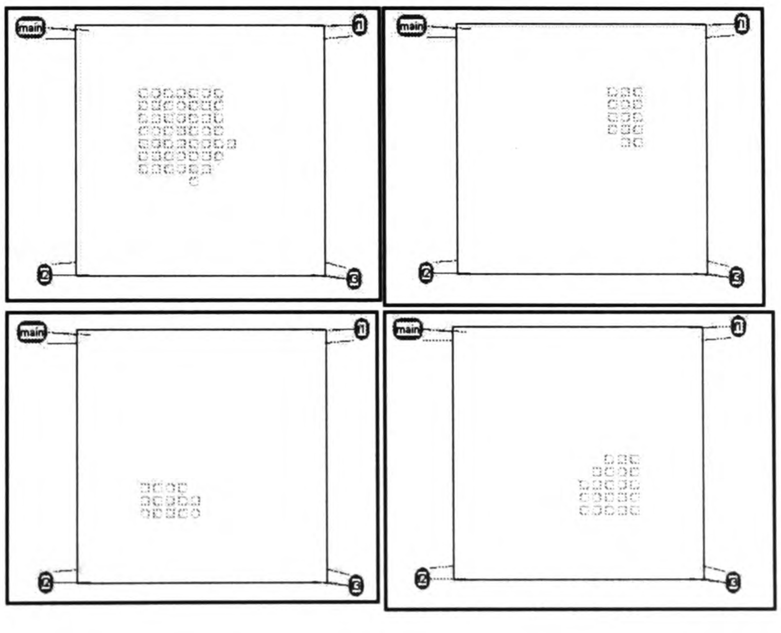


FIGURE 7-22: EXIT USAGE ACCORDING TO THE OCCUPANT STARTING LOCATION, IN SCENARIO 7.3.412. THE DIAGRAMS ARE ORDERED ACCORDING TO EXIT POSITION.

From Figure 7-22 the catchment area system is clearly reflected in the starting location of the occupants using each of the exits. The pattern of the biasing system is evident, as the main, unbiased exit (positioned top left in Figure 7-22) is more popular than the other exits. The exit use also revolves around proximity to the exit location. Therefore, given that an occupant is aware of a specific exit and that the occupant falls within the area of attraction, that exit will *automatically* be used.

The effect that familiarity can have upon the evacuation times produced is demonstrated in Table 7-11. In the optimal evacuation settings of scenario 7.3.411, assuming complete familiarity and equal distribution between the exits, the evacuation times average 14.4 seconds. This is entirely due to the even usage of the available exits (see Table 7-10). In Scenario 7.3.412, where a moderate bias is applied, exit usage is skewed, increasing the average evacuation times to 22.1 seconds. This trend is extended as the exit biasing increases in 7.3.413. This is entirely due to the increased congestion around the main exit due to the its extended catchment area. The distribution of the evacuation times is due to the resolution of conflict amongst the population congestion immediately around the exits and not to any change in the adoption of exits within each of the scenarios.

TABLE 7-11: EVACUATION TIMES PRODUCED IN SCENARIOS 7.3.411-413.

Scenario	Evacuation Times (secs)
7.3.411	14.4 [13.8-14.7
7.3.412	22.1 [21.1-22.9]
7.3.413	39.3 [37.5-40.8]

When the proposed model is used in scenario 7.3.414 to simulate the optimal information conditions (complete awareness and familiarity), the results produced are similar to those of scenario 7.3.411 (see Table 7-12 and Table 7-13). The major difference is the production of a distribution of exit usage. This is entirely due to the variation that is introduced into the equation that calculates the attractiveness of each exit. These findings are important, as the proposed model should be able to replicate the original functionality of the present model. In scenario 7.3.415 the sensitivity of the proposed model to the familiarity index is examined.

TABLE 7-12:EVACUATION TIMES PRODUCED IN SCENARIO 7.3.414

Scenario	Evac. Times (secs)
7.3.414	14.8 [13.1-15.2]

TABLE 7-13: EXIT USAGE DURING SCENARIO 7.3.14

Scenario	Exit 4 (Main exit)	Exit 1	Exit 2	Exit 3
7.3.414	25.7 [23-26]	24.8 [24-25]	25.1 [24-26]	25.5 [25-26]

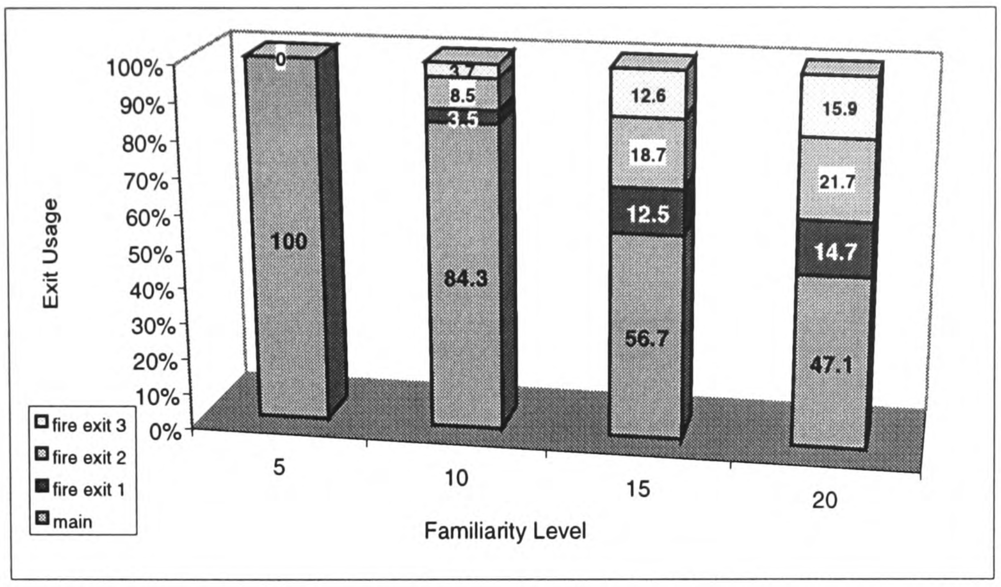
During the implementation of the proposed behaviour in Scenario 7.3.415, the occupant's familiarity index is examined as a variable that influences exit awareness. *As the index is increased so the occupant familiarity with the enclosure rises, with more exits becoming available.* It also impacts upon the manner in which the occupant is attracted to the exits available. The difference in the evacuation times produced, due to the changes in occupant familiarity, can be seen from Figure 7-23, where the occupants become more evenly distributed between the exits.

TABLE 7-14: EVACUATION TIMES GENERATED BY THE PROPOSED MODEL.

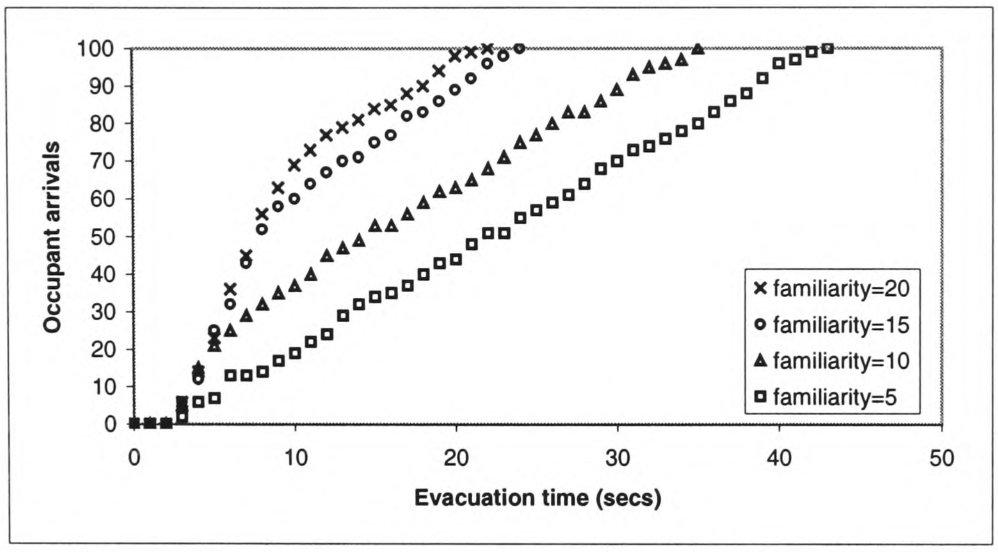
	Familiarity Index			
Scenario	**5**	**10**	**15**	**20**
7.3.415	42.7 [40.8-43.1]	33.9 [31.3-35.6]	24.3 [21.6-25.6]	20.1 [18.9-22.8]

An obvious trend is visible; *as the occupant familiarity is increased so the exit adoption changes which impacts upon the overall evacuation times.* This is apparent from Figure 7-23. When the occupant has a relatively low familiarity (of 5 or 10), the arrival curves produced are largely dependent upon the exit conditions around the main exit (exit 4), generating a smooth and relatively shallow curve. This is particularly the case when the occupant population has a familiarity of 5, as under these conditions the *main* exit is always adopted. Once the adoption of the EMERGENCY exits increases due to an elevated occupant familiarity, the occupants become more evenly distributed between the exits, allowing a more complex pattern to emerge. This is reflected in a curve that is obviously non-linear.

The addition of new exits to the occupant's door vector will have a progressively muted impact, once the occupant is aware of their nearest exit. These additional exits would be significant, if it was coupled with the adaptive behaviour outlined in Chapter 8. Therefore although the introduction of the door vector has an obvious influence over exit adoption, this influence will increase in concert with other forms of behaviour.



(a)



(b)

FIGURE 7-23: DESCRIPTION OF THE AVERAGE EXIT USAGE (A) AND THE ARRIVAL CURVE (B) FOR CASE 7.3.415.

It should be remembered that the exit usage results presented in Figure 7-23 are averages. Distributions were formed due to the stochastic nature of the proposed behaviour. This is more apparent from examining Table 7-15 where clear variation is visible in the exit usage, within the categories provided. Only at a very low familiarity level do that occupants show no variation in their behaviour. This is due to a low rate of exit awareness coupled with the relative unattractiveness of emergency exits to unfamiliar occupants.

TABLE 7-15: EXIT USAGE DURING SCENARIO 7.3.415

Familiarity Index	Main exit	Exit 1	Exit 2	Exit 3
5	100	0	0	0
10	84.3 [82-86]	3.5 [2-6]	8.5 [6-11]	3.7 [2-5]
15	56.7 [54-58]	12.5 [11-15]	18.7 [16-20]	12.6 [10-15]
20	47.1 [43-50]	14.7 [13-18]	21.7 [17-23]	15.9 [14-17]

Obviously, in different geometries and with different exit biasing the results will alter. It might not always be the case that occupants who have larger door vectors will automatically evacuate more quickly.

This case presents an example of the more complicated catchment areas that can be achieved within relatively simple geometries. This is demonstrated in Figure 7-24, which displays the complex use of the exits available under the proposed model. Although the main exit is the most popular, due to its global familiarity and its regular use, its usage is not simply based around occupant proximity. As the occupant awareness of other exits is not guaranteed, the patterns of adoption do not form simplistic patterns according to location (see Figure 7-24).

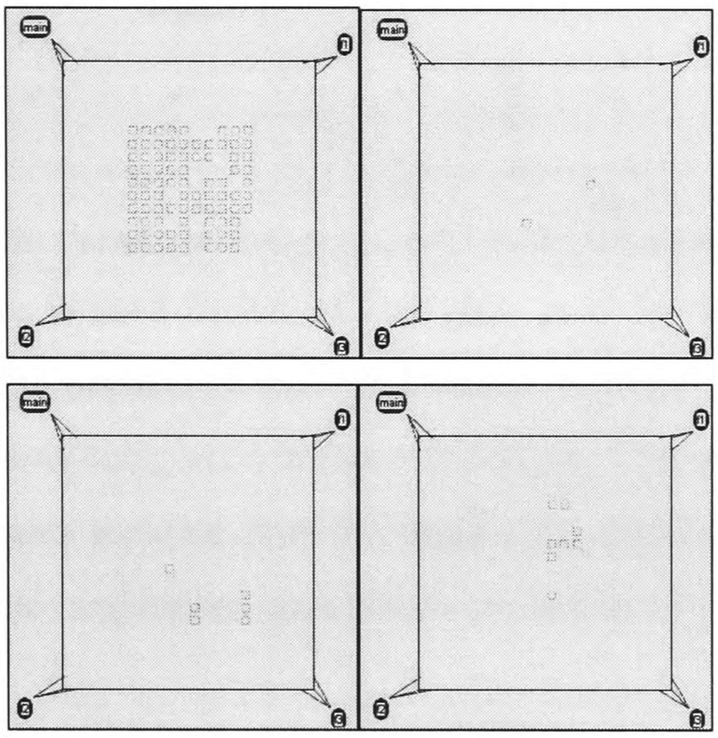


FIGURE 7-24: AN EXAMPLE OF THE EXIT USAGE DURING 7.3.415, AT A FAMILIARITY LEVEL OF 10. THE DIAGRAMS ARE ORDERED ACCORDING TO EXIT POSITION.

The use of the familiarity index as a representation of occupant familiarity in this case is arbitrary. Other indices may be introduced to represent occupant familiarity. More importantly, a method has been established which allows the user to differentiate between the familiarity of individual occupants with their surroundings without imposing target exits to them.

CASE 7.3.42

Scenario 7.3.42 demonstrates the impact of the proposed behaviour upon a complex geometry and a distributed population. The geometry used allows a more realistic analysis and representation of occupant movement (see Figure 7-25).

A population of 150 occupants is distributed throughout the geometry. The occupants have an instant response and are generated using the Population Panel feature (see Chapter 3) providing a distribution of occupant characteristics. No analysis of the response times is made at present, as this has no direct influence over the adoption of particular exits. This might not have been the case if other proposed behavioural features had been included.

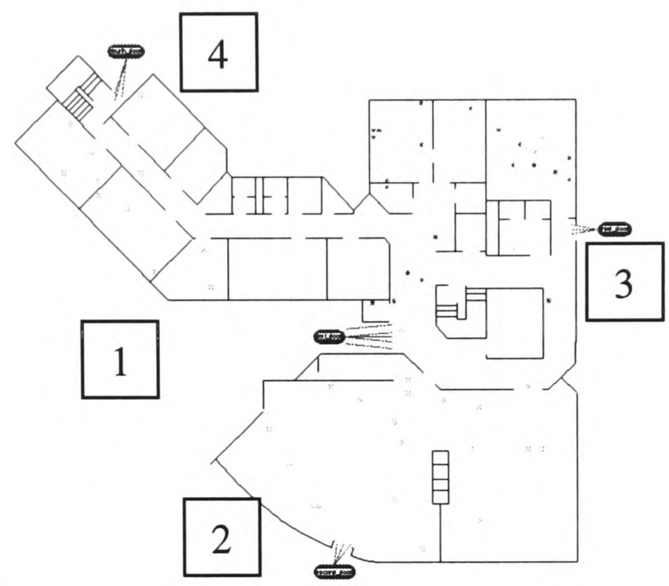


FIGURE 7-25: GEOMETRY USED IN CASE 7.3.42 WITH EXIT NUMBERING

The simulations were conducted in sets of five runs, prior to the randomisation of the occupant population. The population was randomised on three occasions, with each of the new occupant locations being used in five simulations. This allowed the examination of relocating the occupants separate from the impact of variation generated through the algorithm. These separate randomised populations are labelled P_1-P_3.

In Scenario 7.3.421 the present model is examined, while the proposed model is examined in Scenario 7.3.422. In all of the scenarios examined, exit 1 is deemed to be the main exit. It is therefore biased, in both models, 10 units less than the other exits, allowing it to be *significantly* more attractive to the occupant population. The manifestation of this attractiveness is examined in the scenarios. A degree of sensitivity analysis was conducted to ensure that the level of biasing produced similar levels of attractiveness in both models. In Scenario 7.3.422 exits 2,3 and 4 are defined as emergency exits, so that occupant familiarity is not guaranteed.

RESULTS-CASE 7.3.42

In Scenario 7.3.421, where the present model is examined, variations in the exit usage are only apparent *between* the randomisation procedures rather than *within* the populations. This is entirely due to the deterministic nature of exit adoption use in the present buildingEXODUS model, being dependent upon the starting position of the occupant (see Table 7-16).

TABLE 7-16: RESULTS GENERATED IN SCENARIO 7.3.421

	P_1	P_2	P_3	Avg
Use of Exit 1	132	130	127	134
Use of Exit 2	48	46	50	46
Use of Exit 3	20	24	20	25
Use of Exit 4	50	50	53	47
Avg. CWT	**3.4**	**3.5**	**3.4**	**3.3**
Avg. Evac. Times (sec)	34.2 [33.6-35.6]	32.3 [31.6-34.5]	36.5 [34.5-37.5]	35.7 [33.1-38.3]

This determinism is evident from Figure 7-26 where the *exit usage is demonstrated as being completely dependent upon the occupant's initial location.* It would be unlikely that in real-life that the occupant population would conform to such distinct exit usage.

Even once the occupant population has been randomised, the exit usage is still relatively stable. This is entirely due to the biasing attributed to the exits.

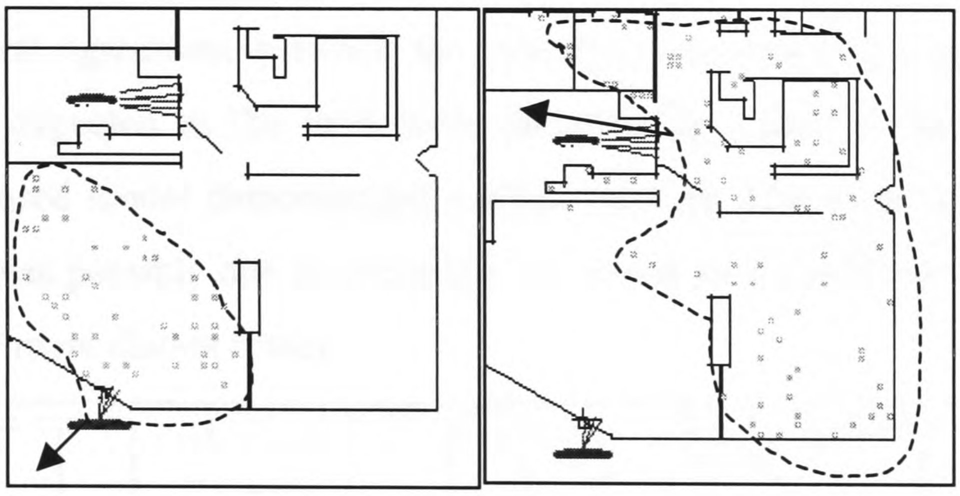


FIGURE 7-26: EXAMINATION OF THE OCCUPANT EXIT USAGE FOR THE PRESENT MODEL. INITIAL OCCUPANT LOCATION IS DENOTED BY THE SMALL SQUARES

If we now examine Scenario 7.3.422, differences become immediately apparent. From Table 7-17 two distinct forms of variability can be determined. The first is due to the stochastic nature of the exit adoption produced within the algorithm. This can be seen from the variability of the exit usage *within* the populations in Table 7-17. The results also vary *between* populations as the distribution of the occupant throughout the geometry is altered through randomisation.

Therefore significant variation in the exit adoption is not simply due to the randomisation of occupant position, but is also due to the stochastic calculations that are used to calculate occupant familiarity.

TABLE 7-17: RESULTS GENERATED BY THE PROPOSED MODEL IN SCENARIO 7.3.422

	Population Index			
	P_1	P_2	P_3	Avg
Use of Exit 1	136 [132-139]	141 [140-144]	150 [145-152]	142 [132-152]
Use of Exit 2	52 [51-54]	50 [49-51]	37 [35-38]	46 [35-54]
Use of Exit 3	21 [18-23]	18 [17-20]	32 [25-32]	24 [17-32]
Use of Exit 4	41.3 [39-43]	41 [40-42]	35 [35]	39 [35-43]
Avg. CWT	1.6 [1.5-1.7]	1.5 [1.5-1.6]	1.6 [1.5-1.6]	1.5 [1.5-1.7]
Avg. Overall Evac. (secs)	36 [33-39]	36 [35-37]	37 [35-40]	36 [33-40]

The probabilistic and complex nature of exit adoption can best be seen from Figure 7-27. Here the overlapping nature of the exit populations is clearly visible. The figure on the left indicates the usage of exit 4 (the bottom-left of the diagram), whereas the right-hand figure represents the usage of exit 1, the main exit (upper-left of diagram). *The overlapping exit usage is demonstrated as not being entirely dependent upon the starting position of the occupant, although this is still an important factor.*

There is a general agreement between the overall evacuation times produced by the models. This is expected as the exits were intentionally biased to encourage similar usage. The proposed model demonstrated a slight increase in average evacuation times produced. This was possibly due to occupants not being aware of their nearest exit and adopting slightly more distant routes.

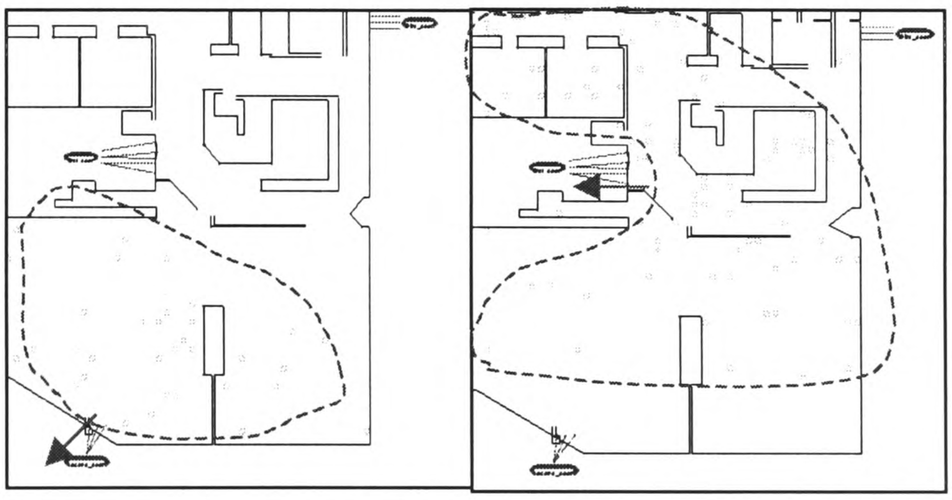


FIGURE 7-27: THE INITIAL OCCUPANT LOCATION OF THOSE USING A SPECIFIC EXIT FOR THE PROPOSED MODEL, DENOTED BY THE SMALL SQUARES.

Other differences are also observable from the results, especially in the individual experience of the occupants. Under the present model, the occupants experienced extended cumulative wait time (see Table 7-16). This was due to the occupants coming from more compact areas of the enclosure, causing the occupants to arrive at closer time intervals. This was *alleviated* in the proposed model due to the more dispersed nature of the occupant location prior to exit adoption (see Table 7-18). This effect is scenario specific and therefore would not always be the case, however it does demonstrate that the effect of a simplistic representation of exit adoption is not limited to the use of exits, but extends to the evacuation experience of individual occupants.

CASE 7.3.43

The final validation case is used to examine the occupant's ability to adapt their knowledge of the enclosure according to their perception of new exits. The purpose of this validation case is to demonstrate the ability of occupants to add to their door vector through the perception of new exit information. This is achieved through the occupant being made aware of unfamiliar exits through *visual contact* (see Section 5.4, Chapter 5).

An area of approximately 25m^2 is defined as affording the occupant visual access to the unfamiliar exit, exit 2. This is highlighted in Figure 7-28. Once the occupant crosses this area there is the possibility of adopting the new exit, according to the motivation and the occupant population around the new exit.

As we are interested in the perception process rather than the communication process, the case has been simplified. Only a single evacuee is placed within the central section of the geometry, therefore precluding any other influences other than the possible visual influence. The geometry is specifically designed so that the occupant would eventually be able to see the unfamiliar exit *en route* to their present target. The geometry is described in Figure 7-28. The occupant initially heads toward exit 1 and is unfamiliar with the other exit, exit 2.

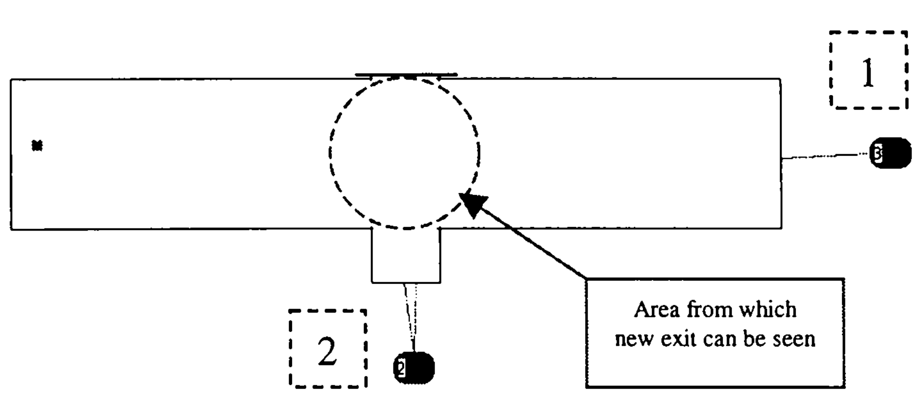


FIGURE 7-28: GRAPHIC OF THE 7.3.43 GEOMETRY. THE OCCUPANT IS AWARE OF EXIT 1AND THEREFORE INITIALLY HEADS OFF TOWARDS IT. AS THE OCCUPANT PASSES EXIT 2 HE HAS THE POSSIBILITY OF ADOPTING IT AS HIS NEW TARGET.

In Scenario 7.3.431, the likelihood of the occupant adopting new information is compared against changing the occupant's motivation. This will be achieved by varying the motivational index between 5 and 20 in increments of 5.

In Scenario 7.3.432, the adoption of the exit 2 according to its current level of use is examined. This is achieved through positioning 12 occupants around the unfamiliar exit. This then allows the determination of the possible increase in the occupant confidence in the usefulness of the previously unknown exit, due to the use by other members of the population (see Figure 7-29).

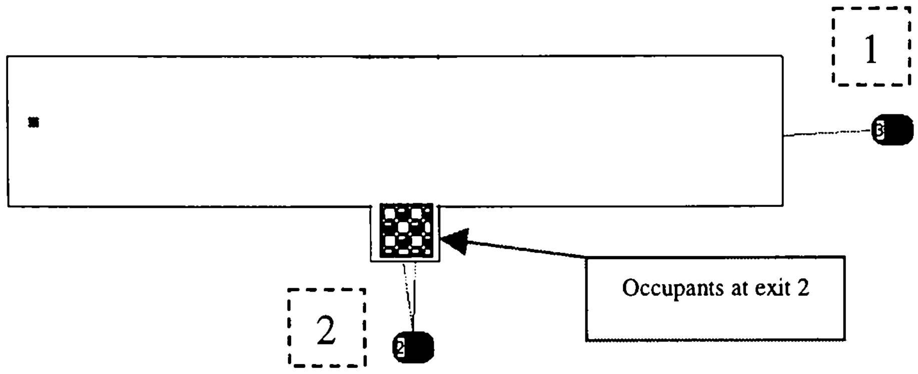


FIGURE 7-29: LOCATION OF QUEUING OCCUPANTS AROUND EXIT 2.

No comparison is made against the present model, as it is unable to take these factors into consideration.

In this example, the safety check concerning the total lack of familiarity caused by reduced exits numbers is disabled to allow this case to be examined more clearly.

RESULTS-CASE 7.3.43

The likelihood of occupants adopting new exit information is examined against the occupant's initial motivation level in 7.3.431. From Figure 7-30 an obvious trend is visible with the occupant becoming increasingly likely to adopt the unfamiliar exit as their motivation increases. *This is based on the assumption that the occupant's desire to evacuate as quickly as possible increases according to the severity of the conditions, an indication of which is provided by the occupant's motivation.* This desire is potentially facilitated by the adoption of the closer, unfamiliar exit. Through adopting the new exit, the occupant has reduced the distance that he has to travel. This calculation will have been made prior to the occupant adopting the exit. Therefore instead of the occupant continuing toward exit 1, he redirects to exit 2.

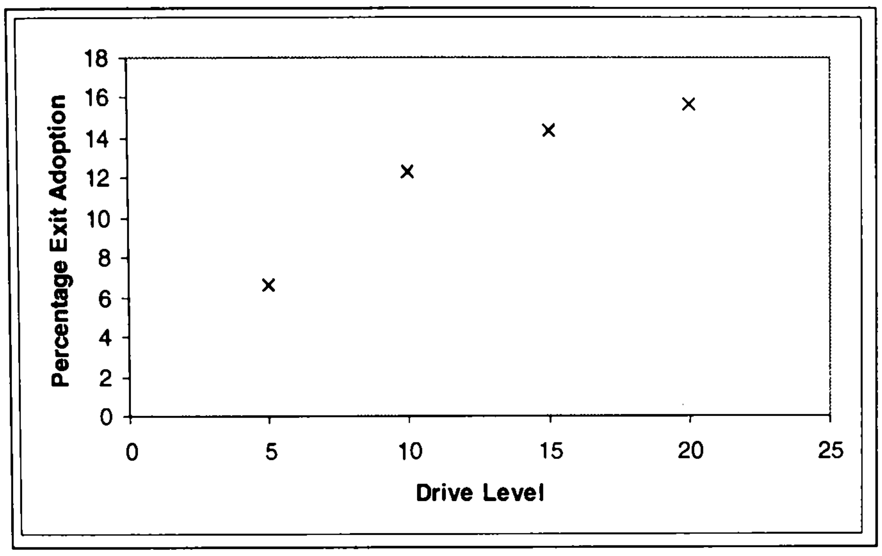


FIGURE 7-30: THE RELATIONSHIP BETWEEN THE OCCUPANT'S MOTIVATION AND THEIR ABILITY TO RECEIVE NEW INFORMATION IN 7.3.431

Therefore as the occupant is deemed to be more motivated to evacuate, so the occupant is more likely to accept new information and, in this case, reduced the evacuation time.

A secondary aspect of this behaviour concerns the adoption of the unfamiliar exit according to its use. In Scenario 7.3.432, 12 occupants are positioned around exit 2, of which they were initially aware and towards which they move. From Figure 7-31 the presence of these occupants *encourages* the single evacuating occupant to change route. This occupant is initially unaware of exit 2, but adopts it as the confidence level is increased in the safety and availability of this exit.

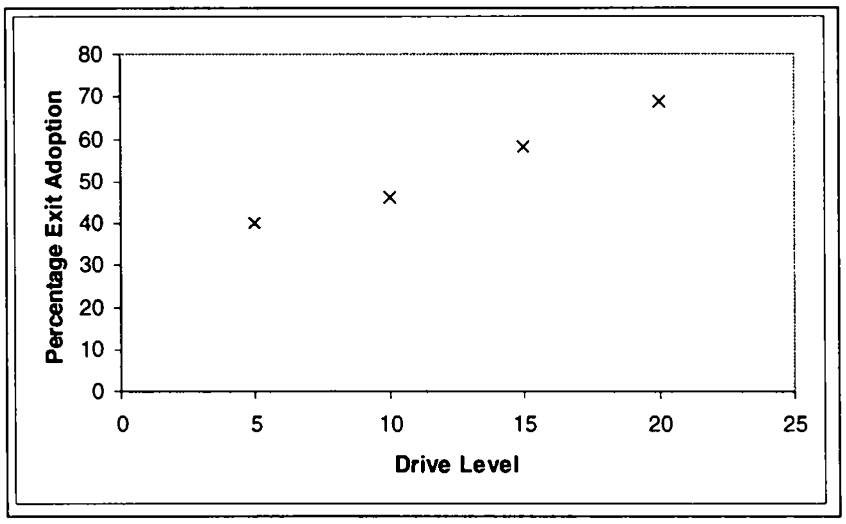


FIGURE 7-31: IMPACT OF OCCUPANTS USING THE SECONDARY EXIT UPON THE ADOPTION RATE IN 7.3.432

In this instance, the occupant is redirecting to an exit that is assumed to be functional and secure, due to its use by other occupants. The occupant is indirectly guaranteeing safe evacuation, by moving towards an exit that is assumed to lead to safety as it is in use. Although the surrounding crowd may slightly increase the occupant's evacuation time, the perceived security of the exit is seen as compensating for this factor.

As the verification conditions are somewhat contrived, the evacuation times generated are only of use in comparison. From Table 7-18 there are two main differences in the results. Firstly, there is an obvious difference in the extent of the times due to the crowding around the exit. Secondly, the slight trends that are evident in both cases are conflicting.

TABLE 7-18: EVACUATION TIMES GENERATED FROM VALIDATION CASE 7.3.43.

	Drive Level			
Scenario	5	10	15	20
7.3.431	15.0 [11.6-15.3]	14.9 [11.7-15.3]	14.8 [11.5-15.3]	14.7 [11.6-15.3]
7.3.432	20.0 [19.1-22.1]	20.1 [18.6-21.4]	20.1 [18.9-20.6]	20.4 [18.3-22.1]

In 7.3.431, where only one occupant is involved, redirection *reduces* the evacuation times, as the exit presents a closer escape route. On average if the occupants maintains course and evacuates through exit 1, he takes 15.3 seconds. If he decides to redirect towards exit 2, he takes 11.6 seconds to evacuate. *Therefore, as the proportion of occupants redirecting increases, so the overall evacuation times decrease.*

In 7.3.432, the level of occupant redirection has increased threefold due to the increased level of occupant confidence (see Figure 7-31). If the occupant maintains course towards exit 1 the average overall evacuation time is 18.9 seconds. If the occupant redirects towards exit 2 where the other occupants are situated, the average overall time increases to 21.6 seconds. An increase in the overall evacuation time is evident, due to excessive population crowding around the exit (see Table 7-18). Therefore the increase in occupant redirection due to the presence of occupants already using an exit, does not *necessarily* provide an advantage to the occupants involved. This will be determined according to scenario specific conditions.

This result suggests the inclusion of behaviour that addresses occupant congestion, based on a more sophisticated mechanism. This is addressed in Sections 8.1 and 8.2 in Chapter 8.

7.3.5 FUTURE WORK

It might be useful for the user to be able to assign the entrance door to particular occupants [96]. This might be represented implicitly through the biasing system proposed. However, if the model had the capability of taking the entrance door into consideration it would make the process simpler for the user.

The user should be able to determine the exact nature of the occupant's familiarity. This would involve a relatively simple programming task, rather than a modelling development, allowing the occupant to select the exact exits with which the occupant is familiar from a list of available exits

A proposal for a more sophisticated representation of occupant familiarity includes a representation of *internal exits*. This would certainly require an extensive restructuring of the present model. This would enable occupants to adapt their path according to the crowding at internal exits in the same manner as external exits (see Sections 8.1 and 8.2 in Chapter 8). It would also allow communication and line-of-sight calculations to treat internal exits as they treat external exits (see Section 5.4, Chapter 5). Most importantly, it would allow the occupant's to adopt egress routes based around their familiarity with the enclosure and their usual paths, rather than according to a generalised potential map.

This development points to the adoption of a two-tier nodal system; one that describes localised, small-scale navigation, while the other represents sections of the route that require goal-oriented movement. This would more accurately reflect the decisions made by occupants in response to their movement. Given that the occupant has either sufficient awareness or time to calculate an egress route, the occupant may be able to make their decisions on long-term goals reflecting their eventual departure from the enclosure. In contrast, if the conditions are severe or the occupant's awareness of the structure is limited, the direction of the occupant's movement may be based around short-term goals, such as leaving a room, rather than clearing the building.

7.3.6 Conclusion

The introduction of localised knowledge has been demonstrated as being more flexible than the present methods used in the buildingEXODUS model, in its representation of the occupant's awareness of the structure. The vast weight of evidence suggests that not only do occupants have different levels of exit awareness, but also this awareness will significantly impact upon the evacuation process.

In the proposed behaviour, the process of including an individual representation of occupant familiarity has been initiated. Not only is this process localised, but may develop dynamically according to the experiences of the occupant, during the evacuation (in the form of their motivation). The method used to indicate individual familiarity is contrived. It requires further development so that it is either based upon realistic factors, such as upon daily use, or so that it is open to user control. However, the *concept* of individual awareness has been demonstrated as having an important effect over the evacuation, which therefore justifies further and more detailed analysis.

The results from the verification cases demonstrate an increase in the flexibility and functionality of the representation. This shows a less rigid adherence to a globally defined navigation system as well as enabling the occupant to adapt to the provision of new information and fluctuating circumstances.

7.4 The Impact of the Evacuation upon the Occupant: Concluding Remarks

The developments outlined in this chapter represent significant advances in the development of a behavioural model (see Table 7-19). This is due to the dynamic and individualised interpretation of the surrounding conditions, as well as the ability for these perceptions to affect the decision-making process. The more sophisticated representation of the impact of the environment demonstrates the capacity of the simulated individual to be affected by the environment, but then attempt to adjust through a recognised coping mechanism (namely maintaining close proximity to the enclosure). The perception of external events are now internalised by the occupant, more accurately reflecting their experiences and allowing decisions not to be made at random but instead to rely on the passage of the occupant. Most importantly of all, the knowledge of the occupants everyday life is represented through his individualised awareness of the enclosure. This experience may be added to throughout the evacuation, representing the evacuee's constant search for knowledge to enable him safe passage.

Table 7-19: Summary of the behavioural developments in this chapter

Section	Development	Description
7.1	Occupant Movement Through Smoke	Enables more detailed representation of occupant movement through smoke-filled environment
7.2	Dynamic Behavioural Representation	Enables more appropriate representation of the dynamic nature of the occupant's motivation during the simulation
7.3	Localised Representation Of Occupant Familiarity	Enables exit selection according to the occupant's understanding of the enclosure

CHAPTER 8 THE ADAPTATION OF THE OCCUPANT TO THE EVACUATION

"Those who cannot remember the past are condemned to repeat it"[213]

The final behavioural developments either introduce a level of information dependency or accredit the occupant population with the ability of interrogating the surroundings and *adapting* their behaviour accordingly. This may involve the occupant analysing the information in a sophisticated manner or crediting the occupant with the ability to estimate future possible alternatives. As noted by Feinberg and Johnson, the occupants do not act without referring to the information available to them. Instead Feinberg and Johnson

> *"Suggest...that evacuees make rough calculations of the time available for exit and adjust their specific responses accordingly...The most important cues in the decision to exit are warnings from the staff and direct evidence of the severity of the fire, but the behaviour of others can also be a cue to the threat. Evacuation begins when the evidence - physical, social or both - leads to a collective definition of the situation as sufficiently threatening" [187]*

These representations include:

- **8.1. ADAPTIVE REASONING IN RESPONSE TO CROWD FORMATIONS**
- **8.2. LONG TERM ROUTE ADAPTATION**
- **8.3. COMMUNICATION AS AN ADAPTIVE RESPONSE** [199]
- **8.4. THE ADAPTIVE OCCUPANT RESPONSE TO APPROACHING A SMOKE-FILLED ENVIRONMENT**

This section requires some reference to the earlier new proposals, to fully test and demonstrate the impact of the features.

8.1. ADAPTIVE REASONING IN RESPONSE TO CROWD FORMATIONS

For a more detailed analysis of this behaviour please refer to the paper suggested [26].

8.1.1 EXPECTED OCCUPANT BEHAVIOUR

The manner in which occupants queue is of fundamental importance to the success of an evacuation. Their ability to ascertain the likelihood of extensive delays and possibly alter their exit route accordingly is essential to the navigation process.

The nature of the queue will depend on the physical restrictions imposed upon the population as well as the severity of the environmental conditions [1,66,106].

Occupants determine their choice of exit through examining a number of factors. Initially, the occupant must be *aware of the existence of an exit.* Obviously, inherent in this knowledge is the geometric layout of the enclosure surrounding that exit. Therefore the familiarity will extend to the surrounding terrain and geometry of the exit. Occupant familiarity has long been seen as of fundamental importance to the progress of an evacuation. Instead of occupant's heading towards the nearest exit – of which they may have no prior knowledge - as would be assumed by the majority of present building regulations, they are more likely to move towards other more distant exits with which they have had previous experience [1,4]. Pauls [99] identified the importance of examining regular social and physical movement and behaviour to predict the actions of occupants in a difficult and possibly unique situation. This correlation was also seen during the King's Cross fire, where passengers, when attempting to evacuate, adopted routes which were closely related to those usually used [1,4,97].

The impact of familiarity upon the behaviour of the occupant is not limited to exit usage (see Section 7.3, Chapter 7). Horiuchi recorded the increased levels of confidence which familiarity bred in occupants, allowing them to perform actions not directly linked with speedy evacuation [1,98]. Familiarity with the enclosure may generate a level of confidence that allows the occupant to attempt activities such as fire-fighting, delaying their response or attempting to follow alternative, less direct routes. Although in the short term these routes may not be considered optimal, they will have been adopted through calculation on the occupant's part to guarantee safe egress and to minimise the imminent risk and the evacuation time.

Of utmost importance are the perceived queuing conditions evident at the desired exit [106]. Variables within this consideration will include the perceived extent of the queuing population, the environmental conditions, as well as the manner in which the crowd is moving. The movement of the queue will in itself be dependent upon the geometry (terrain, size of exit, etc.) as well as the make-up of the crowd.

It is unlikely that occupants make decisions concerning redirection in isolation, but instead weigh up the data available to arrive at a final decision. Of utmost importance are the perceived queuing conditions evident at the desired exit [106]. Variables within this consideration will include the *perceived extent of the queuing population*, the *environmental conditions*, as well as *the manner in which the crowd is moving*. The movement of the queue will in itself be dependent upon the geometry (terrain, size of exit, etc.) as well as the make-up of the crowd. As a survivor of the Beverly Hills Supper Club incident recalls

"My dad told us that since the exit was so crowded to turn around and climb over the railing and go out the entrance doors"[52]

In this incident, before the occupant commits to another course of action, he is considering information concerning the exit configuration and the crowd conditions around each of the exits.

Except for the occupant's initial familiarity with the enclosure, all of the factors outlined require the occupant to be in visual contact to make the relevant determinations. Therefore, the decision to redirect egress movement is not solely based on factors determined prior to the evacuation but is likely to be influenced by dynamic factors such as population size and environmental considerations.

The visibility of the exit determines the level of information that the occupant may use in any calculation of the tenability of any future use [200]. For a thorough appraisal to take place, the occupant has to be in visual contact with the exit, to examine the surrounding population, environmental conditions, etc. If the exit is not within visual range, the occupant has to rely solely on their recollection of exit details from memory, such as position and distance, or possibly from information communicated to them from the surrounding population or from a procedural influence such as an intelligent alarm systems [1].

Finally, through examining these factors and their own experience, the occupant must come to a decision on a course of action. This might involve a crude determination of which route would enable the most 'efficient' and safest path of egress. As highlighted previously, this calculation can only be made in respect to the information available to the occupant and any previous experience that he might have. This represents the occupant as being capable of information processing as described in recent psychology literature [214].

8.1.2 Present buildingEXODUS implementation.

Within the current version of buildingEXODUS (and most other evacuation models) [8], the implementation of the occupant's ability to determine their choice of exit, 'redirective' behaviour and the factors highlighted above is somewhat limited. The occupant's familiarity with the enclosure can, at present, be represented using the potential map and target doors facility [24].

A global/default method can be used which defines the attractiveness of each of the exits within an enclosure according to a potential map system. The occupant is assumed to be ***fully aware*** of the existence of the exits involved, but can be made to be more/less attracted to the exit using a biasing system. This method allows occupants to (if required) move to the nearest exit or to a more distant but familiar exit. The manipulation of the biasing attached to individual exits extends/diminishes the catchment area within which that exit appears attractive. Once in this area, an occupant will move towards the exit, unless the user has specifically instructed the occupant to move to another exit through the identification of a *"target door"*. This identification specifies the exact destination for the occupant and does not provide for alternative routes.

Through the use of *"exit biasing"* it is possible to make a biased exit globally more or less attractive and thus biasing is a representation of global familiarity i.e. all occupants will be affected equally. Through the use of *"target exits"*, it is possible to represent the familiarity of a particular occupant with a single exit. However, the occupant does not have the ability to examine the viability of other potential routes to exit. Thus, with the exception of specifying target exits, it is not possible to provide a comprehensive and *individual* representation of an occupant's familiarity with the structure.

8.1.3PROPOSED BEHAVIOURAL DEVELOPMENTS

The likelihood of the occupant moving between exits is dependent upon a number of conditions that are examined prior to the occupant's decision (including the distance from the exit, the distance and availability to alternative exits, the behavioural regime being used by the occupant). Most importantly, the occupant's interaction with smoke is seen as an important consideration. Given that this interaction has occurred and that the occupant is now queuing in a relatively clean environment, the propensity to remain queuing is seen to increase relative to the likelihood of moving back into an enclosure within which smoke was experienced [52,58]. Occupant motivation is also a key factor in the occupant's decision, although this is also affected by the interaction with smoke.

The other conditions, previously described (proximity of doors and patience (see Section 7.3, Chapter 7) are also represented, with one major difference. The occupant's awareness of the enclosure is incorporated into the calculation of whether the occupant should redirect. This more accurately reflects the changing levels of knowledge within the population, than the present implementation.

Precautions had to be taken to prevent occupants continuously flipping between nearby available exits. To prevent this occurrence, occupants were only permitted to alter their target if they had not done so before. The development of this aspect of the proposed behaviour is left for further work.

It is considered vital not only to represent the initial occupant target, but also to represent the individual occupant's familiarity with the structure. This is less important under non-emergency conditions or conditions of low population density, where the occupant may evacuate unhindered to the target of their choice. However, during situations involving redirection (such as queuing or confrontation with environmental barriers), the existence of alternative routes and the occupant's awareness of these routes becomes significant.

The proposed adaptive queuing behaviour is therefore reliant upon the introduction of the door vector (see Section 7.3, Chapter 7) and the exit line-of-sight feature (see Section 5.4, Chapter 5).

Initially, the occupant situation is examined to determine whether he desires (i.e. estimated exit time is reduced) and whether it is possible for them to alter their target. This involves the examination of a number of factors including

- the extent of time the occupant has spent waiting,
- the distance between the occupant and the exit
- the occupants patience level,
- whether the occupant is completely surrounded by other occupants,
- the estimated time of arrival at the alternative exit,
- the estimated time of arrival at the current exit, etc. This decision making process is stochastic in nature.
- the distance travelled to the present exit

As an example of how these factors influence occupant's decisions, consider the following case. An evacuating occupant has waited in an exit queue for a period of time greater than his patience level. He is therefore now *willing* to consider redirection. The occupant is situated on the periphery of the crowd and is therefore *able* to contemplate redirection. Examining the exits available to him, he determines that he can arrive at another exit more quickly. The occupant therefore, moves off towards his new target.

This decision making process contains a stochastic element and will therefore alter between repeated simulation runs. A number of other factors need to be considered. These are left to future research. These include considering the degree of commitment of an occupant to the exit and the possibility of occupant's ignoring underused exits.

Once the decision to redirect has been made, the occupant's door vector is interrogated. Initially, those exits that are visible are examined. The visible exit that is seen as most viable is then stored. This viability is dependent upon the time the occupant estimates it will take him to arrive at that exit, given its distance and the crowding around the exit. The non-visible exits are then interrogated. In this case the viability is determined according to distance and familiarity only, as crowding information is not available. The introduction of the line-of-sight therefore determines the manner in which exits are treated. If a visible exit is stored it will be adopted as a new target otherwise the most viable non-visible exit will be adopted. This is based on the assumption that an occupant would prefer to reduce their queuing time through movement towards visibly preferable exits rather than taking the more risky option of moving towards unseen exits. If neither exists, the occupant will remain queuing.

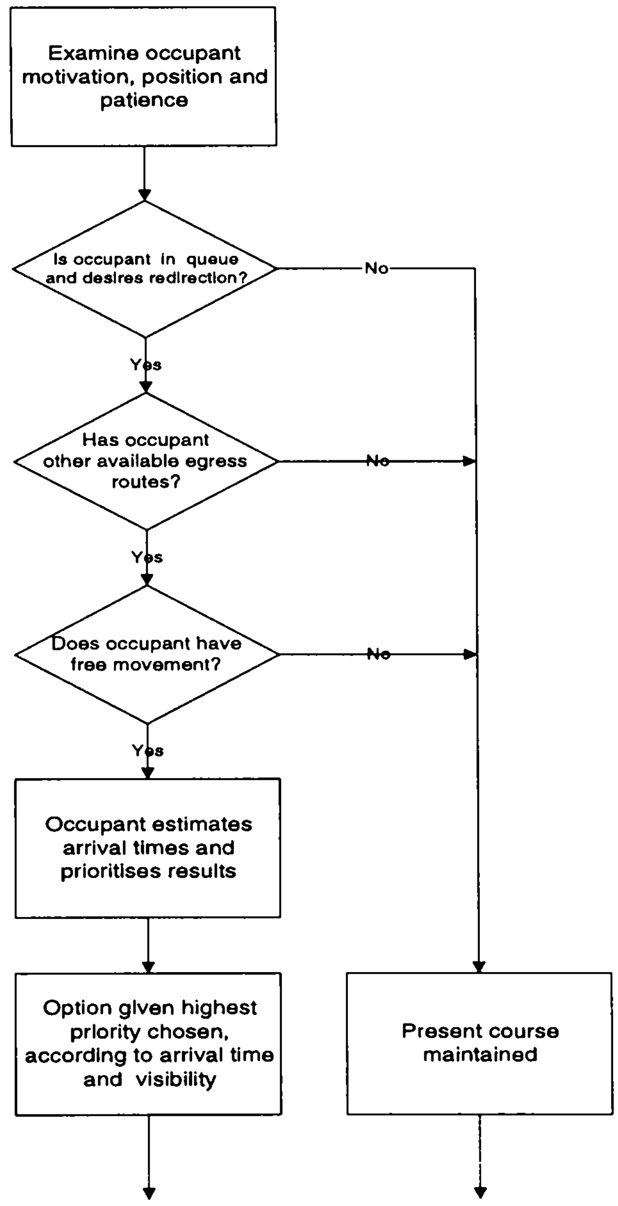


FIGURE 8-1: FLOWCHART REPRESENTING PROPOSED BEHAVIOUR

The determination as to whether the occupant redirects is calculated according to the following equations. Initially the situation is examined as to whether the occupant is ***able*** to redirect; that is he is outside of a pre-defined area within which he is assumed to remain queuing and that the occupant is not completely surrounded by other members of the population. This is determined according to

$$\max(\|P-Q\|_2-\Delta,0).\max((\rho_{\max}-\frac{\sum_{j=1}^{n}\sum per}{n}),0)>0 \quad (69)$$

where ρ_{max} is the maximum population density, P and Q are the co-ordinates of the occupant's present location and the exit location respectively and Δ is a constant default exit catchment area (arbitrarily set to 2.5m). If the occupant is within a threshold distance from the exit or is completely surrounded then he is not able to redirect. The occupant is then examined to determine whether he ***desires*** to redirect according to

$$(w_i-p_i)\geq 0 \quad (70)$$

where w_i is the time the occupant has spent waiting, p_i is the occupant's patience (indicating that the occupant is impatient),

$$\frac{D_i}{D_{\max}}\geq r \quad (71)$$

D_i is the occupant's drive, D_{max} is the maximum possible drive setting and r is a random number (indicating that the occupant is sufficiently motivated) and

$$1-\frac{d_i}{\max(\|P-Q\|_2+d_i,\mathrm{K})}>r \quad (72)$$

that determines whether the occupant is not sufficiently committed to the present exit, to be able to redirect [4,61]. Here, P and Q are the co-ordinates of the occupant's present location and the exit location respectively, d_i is the distance travelled so far and K is a threshold designed to prevent small travel distances distorting the calculation.

Finally the attractiveness of individual exits are examined, to determine which of them will be adopted, given that the occupant wishes to redirect. If the exit is visible, the time for the occupant to reach it, t_v, is calculated according to

$$t_v=\frac{\|P-Q\|_2}{v_i}+\frac{c_v}{f_v.w_v}+\varepsilon \quad (73)$$

where v_i is the occupant's maximum velocity, c_v is the size of the crowd formation around the exit, f_v is the estimated flow rate through the exit, w_v is the exit width and ε is a random number (0-0.1) introducing noise into the equation. The occupant's present target is assumed to be interrogated in this manner.

Otherwise, if the exit is not visible, the calculated time to arrival, t_n, is purely determined according to the distance required to reach it,

$$t_n = \frac{\|P - Q\|_2}{v_i} + \varepsilon \tag{74}$$

The arrival times of the exits are then compared, with priority given to the visible exits. If a visible exit reduces the time required to exit, such that

$$t_v < t_{pres} \tag{75}$$

it will be adopted. Otherwise the non-visible exit with the shortest travel distance will be adopted if it presents an advantage satisfying

$$t_n < t_{pres} \tag{76}$$

There is of course no guarantee that recommitting to another exit will produce a better outcome for the individual (i.e. decrease personal evacuation time). Taking this course of action may result in a sub-optimal outcome for the individual concerned. Furthermore, by allowing the occupant to move to an unseen exit, the chances of the occupant delaying their evacuation are greatly increased. This is due to the fact that the unseen exit may in-fact not be viable due to the extent of crowding around the exit. As the exit is unseen, the occupant is deprived of this information and essentially takes a chance.

Once adopted, the new exit will be adhered to irrespective of the new queuing considerations with which the occupant is faced. If the new exit is visible, it is assumed that the conditions are favourable so as to have encouraged redirection. Otherwise, the occupant, once redirected, is assumed to have committed himself to the new target. This is to prevent the occupant rebounding continually between target exits. From a computer-modelling viewpoint, it would be a relatively easy task to modify this condition and allow the occupant to be redirected a number of times. However, at present there is insufficient observational data upon which to base a sound rational for this type of behaviour. The increased sophistication of this and a number of other features are left for future work.

8.1.4 Verification

The prototype behavioural features are demonstrated through a series of scenarios based on the geometries depicted in Figure 8-2 and Figure 8-6. The geometries are relatively complex and enable the demonstration of the differences introduced through the line-of-sight calculation as well as the possibility of the occupants being unaware of certain exits (see Table 8-1).

TABLE 8-1: SUMMARY OF SCENARIOS INVESTIGATED

Scenario	Population	Geometry
8.1.41	234 occupants responding instantly	4 exits, differing levels of visual access. Simplistic design to demonstrate impact of redirection
8.1.42	400 occupants, responding instantly	4 exits, differing levels of visual access. More realistic geometry.

The introduction of an adaptive decision-making capability, where the occupant is able to redirect according to a crude predictive capacity in response to the information available, is incrementally compared against the present buildingEXODUS capabilities. The results will be provided in terms of an average figure and the distribution of results generated. Those averages without distribution figures indicate static/negligible variation in the results.

CASE 8.1.41

For the scenarios involving geometry 1 (scenarios 8.1.411-8.1.414), it is assumed that the evacuation has been underway for some time and has resulted in crowding around two of the four available exits (see Figure 8-2). The crowd located around exit 3 is identified as Pop 3 and consists of 108 people, while the crowd located around exit 4 is identified as Pop 4 and consists of 126 people. The size of these crowds varies in order to demonstrate the importance of the tenability calculations made by the occupants that are then used in their decisions to re-commit to another exit. The size of the populations around exits 1 and 2 (identified as Pop 1 and Pop 2 respectively) are zero initially.

The size of the exits is 1.5m for exits 1 and 2 and 1.0m for exits 3 and 4. In each of the scenarios, the apparent visibility of each of the exits is changed (see Figure 8-2) in order to demonstrate the impact of exit visibility. The first scenario is a base case that utilises the existing software features while the remaining three scenarios involve the prototype behavioural features.

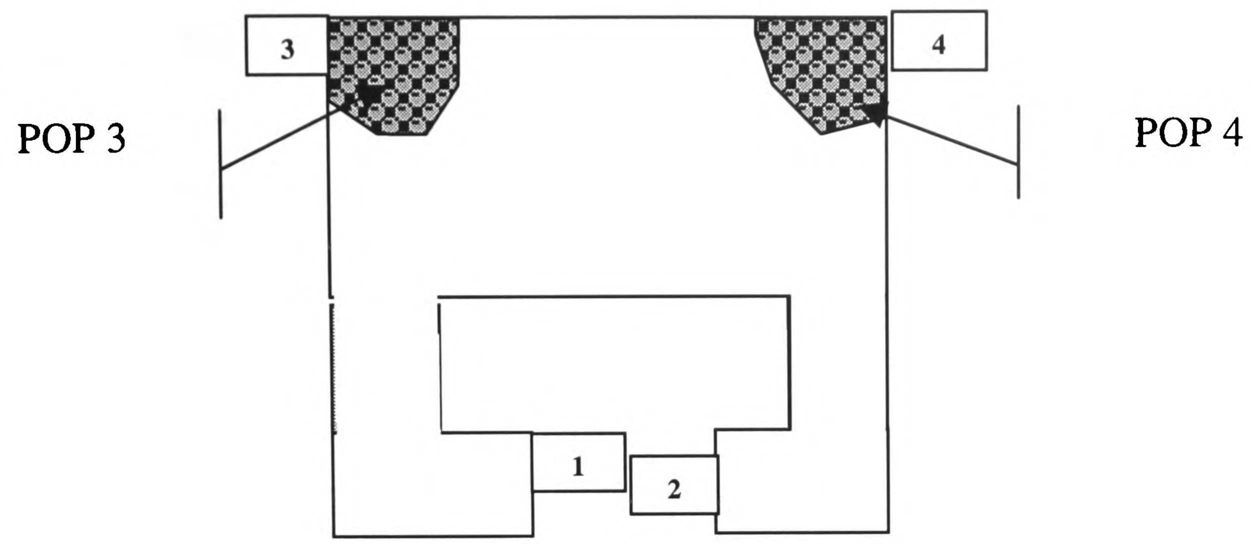


FIGURE 8-2: REPRESENTATION OF GEOMETRY 1 USED IN SCENARIOS 8.1.411-4, SHOWING LOCATION OF THE FOUR EXITS AND THE POSITION OF THE CROWDS AROUND EXIT 3 (POP 4) AND EXIT 4 (POP 3).

As the effect of occupant exit familiarity is examined in these scenarios, it is necessary to state the nature of the occupant awareness of individual exits. On average, 4% of the occupants are only aware of door 1, 5% of the occupants are only aware of door 2 and 32% of the occupants are aware of both doors 1 and 2. The remaining occupants are unaware of both exits 1 and 2. Each scenario was repeated five times to establish a level of consistency within the results.

TABLE 8-2: DESCRIPTION OF SCENARIOS EXAMINED

Scenario	Queuing Behaviour	Geometry	Exit status	Bias
8.1.411	Present	4 exit, irregular	N/A	0
8.1.412	Proposed	4 exit, irregular	All Visible fully aware	0
8.1.413	Proposed	4 exit, irregular	2-Visible, 2-non-visible, fully aware	0
8.1.414	Proposed	4 exit, irregular	2-visible, 2-non-visible variable awareness	Non-visible exits have reduced attractiveness

Four scenarios are investigated, the first scenario, 8.1.411 is the base case that utilises the existing software features while the remaining three scenarios test the new features (see Table 8-2). Scenario 8.1.412 affords the occupant complete access to all of the information available, irrespective of any other considerations. This is not intended to represent a realistic scenario, but is included to allow comparison with Scenarios 8.1.413 and 8.1.414 where the occupant access is varied according to familiarity and visibility.

In Table 8-2, 'fully aware' indicates that all the occupants have a complete knowledge of the location of all the exits within the enclosure (i.e. their door vectors contain the complete listing of available exits). 'All visible' indicates that all of the exits are within line-of-sight (hence occupants have full knowledge of exit status). 'Non-visible' indicates that these exits are not within line-of-sight of the other exits. 'Variable awareness' indicates that not all of the occupants will be aware of the location of the non-visible exits (i.e. these do not appear in their door vector). 'Variable visibility' indicates a more complex visual relationship depending on the occupant's position. The "bias" is an indication of the exit bias. An exit bias of 0 indicates that occupants will move towards their nearest exit.

RESULTS-CASE 8.1.41

Examining the results for Scenarios 8.1.411-4 (see Table 8-3) we note that the introduction of the new behavioural features significantly impacts upon the evacuation results. However, these results are complicated due to the introduction of familiarity as a significant factor.

Scenario 8.1.41 represents the behaviour exhibited in the current buildingEXODUS implementation. It produces the longest evacuation time (58 seconds), the longest average evacuation time (25.8 seconds) and the longest average CWT (2.7 seconds). In this case there is no migration between exits, and therefore the occupants spend the entire simulation waiting for access to their initial target. This is reflected in the extensive evacuation times generated and the time spent waiting by each occupant (see Table 8-3 and Figure 8-3).

TABLE 8-3: EVACUATION TIMES FOR SCENARIOS 8.1.41-4

Scenario	Avg cwt (secs)	Evac times(secs)	Avg pet(secs)
8.1.411	2.7 [2.5-3.3]	58 [56-64]	25.8 [23-27]
8.1.412	1.7 [1.5-2.2]	37.7 [35.3-43]	17.7 [16-20.8]
8.1.413	1.7 [1.5-2.3]	38.5 [37.5-43]	19.0 [18.6-22]
8.1.414	1.9 [1.7-2.4]	46.9 [45.6-48.8]	21.2 [20.1-22.7]

As expected, Scenario 8.1.412, where the population is fully aware of all of the exits and are able to determine the extent of the queue at each exit, produces the most effective evacuation (see Figure 8-3 and Table 8-3). This case may be considered somewhat unrealistic as all the occupants are fully aware of all the exits, even the ones that are not actually in line-of-sight. It produces the smallest average PET and overall evacuation times and causes the occupants to wait for the least amount of time. It also more evenly distributes the occupants between the exits, reducing possible queuing time (see Table 8-4).

Indeed, the behaviour introduced into Scenario 8.1.412 reduces the evacuation times generated in Scenario 8.1.411 by 54% (see Table 8-3). In general, occupants chose to migrate towards the initially underused exits. As the simulation progressed and congestion appeared at all of the exits, less migration to these exits was evident. However, the migration that was evident was more evenly distributed between the exits, as these became equivalently populated.

TABLE 8-4: EXIT USAGE (NUMBER OF OCCUPANTS) FOR SCENARIOS 8.1.41-4

Scenario	Exit 1	Exit 2	Exit 3	Exit 4
8.1.411	0	0	108	126
8.1.412	49 [45-52]	63 [58-65]	58 [56-63]	64 [60-70]
8.1.413	54 [46-57]	42 [40-48]	80 [79-95]	58 [54-67]
8.1.414	26 [24-31]	34 [26-35]	94 [89-97]	80 [79-93]

Scenario 8.1.413, where visibility was introduced as a factor, demonstrates the subtlety of the occupants' adaptation to their surroundings. In this case, while occupants are aware of all the exits they do not have line-of-sight with exits 1 and 2 and so cannot ascertain the full potential advantage of diverting to these exits. Due to the initial inequalities in the population distributions, large numbers of occupants migrated towards the unseen exits.

Due to the queuing at the visible exits, unseen exits become more attractive. This migration was based upon the distance which had to be covered as no other information was available to the occupants (see phase 1 migration in Figure 8-4). After this initial wave of migration, the populations around exit 3 and exit 4 had diminished dramatically.

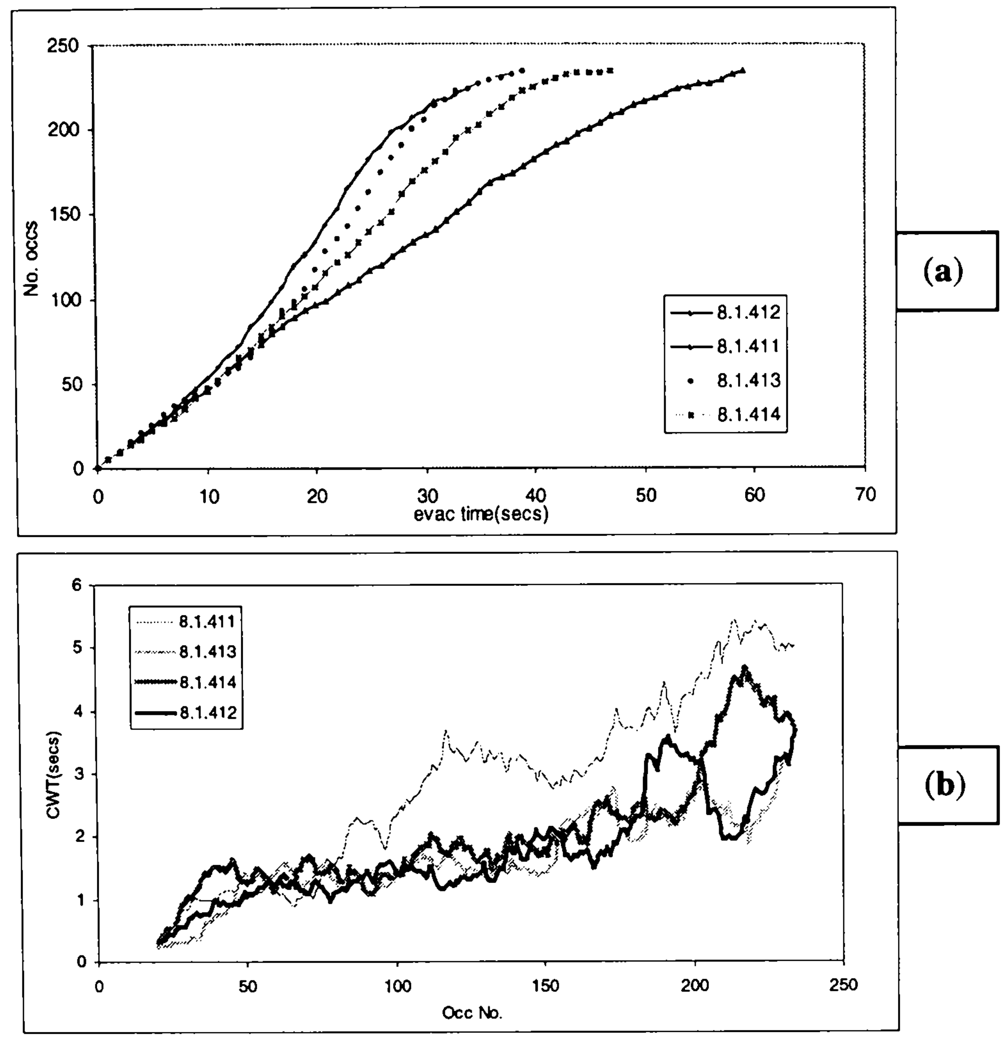


FIGURE 8-3: CUMULATIVE EVACUATION TIMES (FIGURE 3A) AND CUMULATIVE WAIT TIMES (FIGURE 3B) FOR SCENARIOS 8.1.411-4.

Due to the slight inequalities in the initial populations around these exits, exit 3 eventually became a viable exit for redirection for some of the occupants queuing at exit 4 (see phase 2 migration in Figure 8-4). Therefore, as priority is given to visible exits, occupants began to migrate between exit 4 and exit 3. It should be noted that these occupants were not able to interrogate the two unseen exits, therefore the build up of occupants around these exits went unnoticed and was not a factor in the movement to the visible exit.

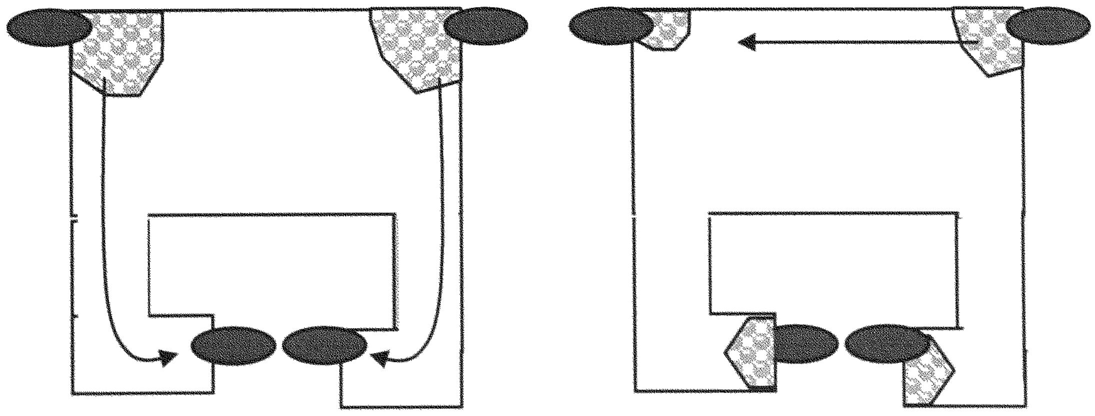


FIGURE 8-4: SCHEMATIC OF THE TWO PHASES OF MOVEMENT DURING SCENARIO 8.1.413. PHASE 1 SHOWN ON LEFT, PHASE 2 IS SHOWN ON THE RIGHT.

This behaviour is responsible for the eventual discrepancy between the two exit (exit 3 and exit 4) populations (see Table 8-4). The overall evacuation times produced are on average only 2% slower than those of Scenario 8.1.412.

During scenario 8.1.414 a lesser degree of redirection amongst the occupants is noted compared with scenario 3 because of the distribution of awareness levels of the unseen exits (see Table 8-4). Recall that in this scenario not all of the occupants around exits 3 and 4 are aware of the unseen exits.

In scenario 8.1.414, the redirection included the movement between the large populations around exits 3 and 4 observed in previous scenarios, but was most notable for the decrease in occupant movement to the less crowded unseen exits. This is due to the imposition of the more realistic assumption that not all of the occupants are fully aware of all the available exits. In addition, a contra-flow or cross-over movement was produced by a minority of the migrating occupants who were aware of a more distant unseen exit as opposed to the closer of the unseen exits (see Figure 8-5). This demonstrates the significant qualitative differences that can be generated through a subtle change in the implementation of this behaviour.

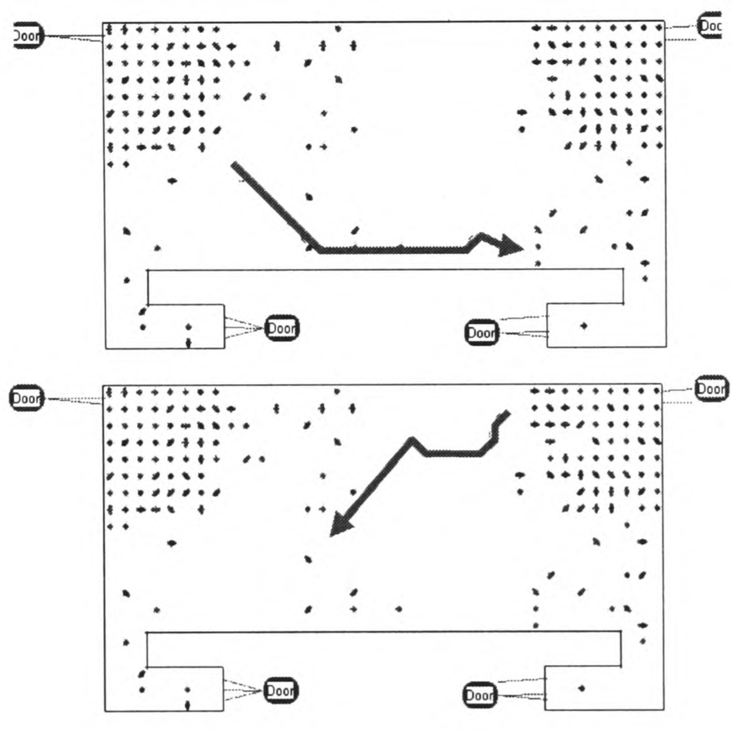


FIGURE 8-5: EXODUS SCREENGRABS OF OCCUPANT PATHS FROM SCENARIO 8.1.414 OCCUPANTS CAN BE SEEN HEADING TO THE FURTHEST UNSEEN DOOR. THIS IS DUE TO THE INCOMPLETE OCCUPANT KNOWLEDGE OF THE ENCLOSURE.

A systematic comparison of CWT between the scenarios is complicated through the introduction of the awareness factor, and is therefore more difficult to interpret (see Table 8-3). Recall that the CWT is a measure of the amount of time an occupant spends stationary within congestion regions. Thus it can be used as a measure of the evacuation efficiency. Clearly, small CWT values are desirable as they suggest only short periods of time are wasted during an evacuation in non-moving queues.

The introduction of the prototype behaviour has clearly made a difference to the overall evacuation efficiency - as measured by CWT and overall evacuation times (see Figure 8-3 and Table 8-3). It is clear that the introduction of the prototype behaviour has reduced the CWT for all of the occupants (see Figure 8-3), thus reducing the congestion at the exits resulting is a more efficient evacuation. Indeed, scenario 2 has resulted in a 37% decrease in average CWT (compared with scenario 1) while the more realistic scenario 8.1.414 has produced a 30% reduction in average CWT.

From examining the average evacuation time for each occupant the individual experience of occupants differs between the scenarios, according to our expectations, with significant differences in the time spent in the enclosure, along with the differences in the occupant waiting times already identified.

Finally, it is important to note that considerable variation was achieved through repetition of the simulations (see Table 8-4). Due to the inherent stochastic nature of both the buildingEXODUS model and the prototype behavioural rules, if a simulation is repeated, occupants may not decide to repeat each and every one of their actions. Thus the outcome will vary with each repeated simulation.

CASE 8.1.42

In scenarios 8.1.421 and 8.1.422, geometry 2 is used. Here, 400 occupants are distributed throughout a more complex geometry. Scenario 8.1.421 provides the base case, implementing the present behavioural features, while scenario 8.1.422 demonstrates the prototype behavioural features. In this example, the simulation is run from the start of the evacuation. The occupants are distributed throughout the building in what can be considered a typical "starting distribution". In these scenarios, all occupants are assumed to have complete familiarity with the structure and hence have complete knowledge of the location of all exits.

The only factor preventing the information being received concerning the exit conditions is their visibility from the occupant's vantage-point (see Table 8-5). It is assumed that information can be transmitted between Exit 2 and Exit 4, Exit 4 and Exit 1 and Exit 1 and Exit 3. Therefore an occupant queuing at Exit 1 can estimate the extent of the crowding at Exit 3 and Exit 4.

TABLE 8-5: DESCRIPTION OF SCENARIOS INVESTIGATED

Scenario	Queuing Behaviour	Geometry	Exit status	Bias
8.1.421	Present	4 exits, irregular, complex	N/A	0
8.1.422	Proposed	4 exits, irregular, complex	Fully aware Variable visibility	0

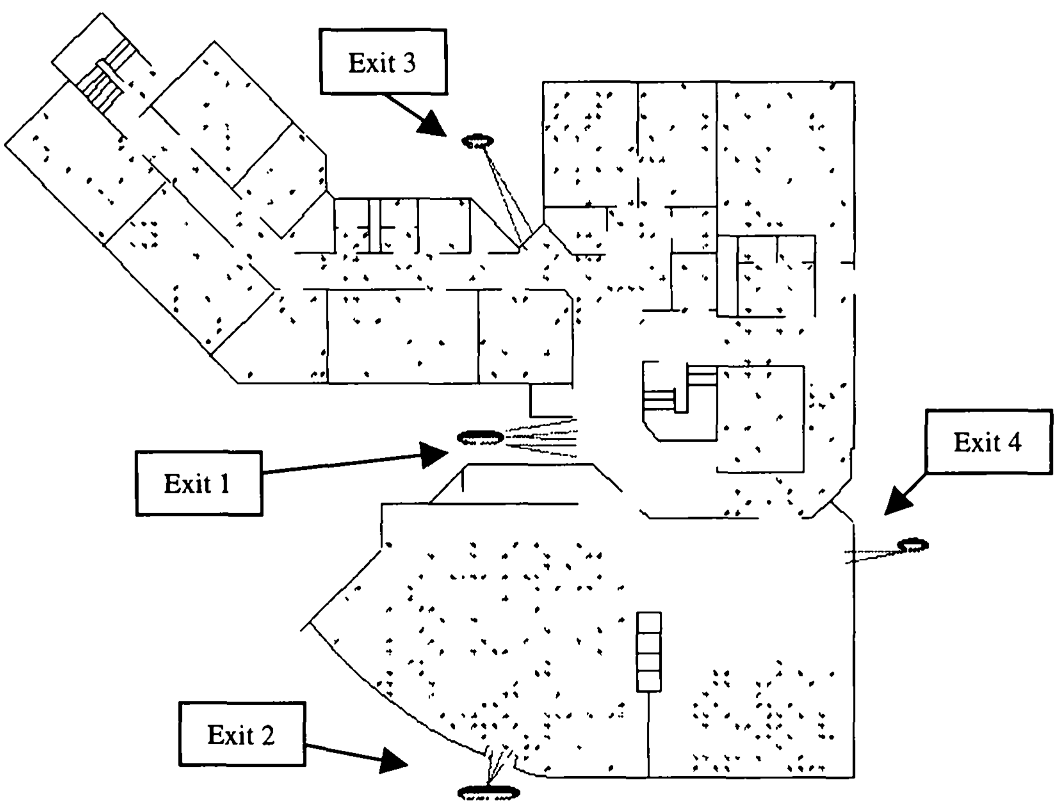


FIGURE 8-6: REPRESENTATION OF GEOMETRY 2 USED IN SCENARIOS 8.1.421-2 SHOWING LOCATION OF THE FOUR EXITS AND THE STARTING LOCATION OF THE OCCUPANTS.

RESULTS- SCENARIO 8.1.42

In these scenarios the prototype behaviour is demonstrated in a more complex geometry and a more realistic scenario. Scenario 8.1.421 represents the behaviour exhibited in the current buildingEXODUS implementation. Scenario 8.1.422 demonstrates the impact of the introduction of the prototype behaviour. In these scenarios occupants are assumed to have complete familiarity with the structure. Scenario 8.1.421 has thus been configured to allow occupants to move to their nearest exit solely under the influence of the potential map. All of the exits have equal potential.

The qualitative differences in the behaviour are demonstrated through examining Figure 8-8. This figure depicts the situation 30 seconds into the simulation for both scenarios 8.1.421 and 8.1.422. As a result of the initial starting locations of the occupants, large crowds congregate around most of the available exits. The crowding is a function of the initial proximity to the exits. As a result, the main exit (exit 1) is underused, while the peripheral exits experience significant crowding.

In scenario 8.1.422 crowding still develops around the same exits as in scenario 8.1.421. This is to be expected, as the starting positions of the occupants are identical in both cases. However, occupants can be observed redirecting to visibly underused exits. Failing this, occupants risk redirecting to other exits where information cannot be perceived, given that they are making little progress at their present congested exit. A large number of occupants move towards Exit 1 from the other overused exits (this movement is indicated by the solid arrows in Figure 8-8). The majority of these occupants will have been able to see the conditions at exit 1 (i.e. those at exits 4 and 3). However, the occupants redirecting from Exit 2 to Exit 1 have done so without being aware of the beneficial conditions at Exit 1. A smaller number of occupants move from Exit 2 to Exit 4 (this movement is indicated by the broken arrow in Figure 8-8). This relatively small movement of people can be explained by the interaction of Exits 1, 2 and 4. Initially, occupants at Exit 4 are attracted to the greatly under utilised Exit 1 (Exit 1 is visible from Exit 4). While Exit 4 is congested, it does not present an attractive option to the occupants at Exit 2 (Exit 4 is visible from Exit 2), thus making Exit 1 the only viable alternative. At this stage very little if any migration occurs to Exit 4 from Exit 2. However, as occupants migrate from Exit 4 towards Exit 1, the congestion at Exit 4 decreases, thereby making this exit more attractive to occupants at Exit 2. A small migration then ensues between Exit 2 and Exit 4.

From Table 8-6 and Table 8-7 the quantitative differences caused by the adaptive behaviour of the occupants are evident. There is a 19.8% reduction in the overall evacuation times of scenario 8.1.422 in comparison with scenario 8.1.421. This reflects the ability of the occupants to redirect according to the information available, rather than remaining committed to their initial exit selection irrespective of the conditions. The differences in the individual occupant experience can be determined through interrogating the average CWT and average PET, where there are reductions of 27% and 20% respectively. This is entirely due to the occupant's ability to redirect given that there is significant congestion (see Table 8-6).

TABLE 8-6: EVACUATION TIMES FOR SCENARIOS 8.1.421-2

SCENARIO	AVG CWT (SECS)	EVAC TIMES(SECS)	AVG PET(SECS)
8.1.421	3.3 [3.1-3.5]	67.7 [64.1-71.9]	28.0 [26.5-30.2]
8.1.422	2.4 [2.3-2.5]	54.3 [52.4-56.3]	22.3 [21.6-22.6]

From Table 8-7 it is clear that a more efficient exit usage has resulted through the introduction of the prototype behaviour. Not only are the exits used more evenly under the prototype behaviour, but the adaptive process alters significantly between individual runs. This can be seen from examining scenario 8.1.422 in Table 8-7, where significant distributions are evident in the exit usage. It is apparent through examining scenario 8.1.421, that the exit usage is both deterministic and non-adaptive under the present behavioural model.

TABLE 8-7: EXIT USAGE (NUMBER OF OCCUPANTS) FOR SCENARIOS 8.1.421-2

SCENARIO	EXIT 1	EXIT 2	EXIT 3	EXIT 4
8.1.421	16	92	179	113
8.1.422	144 [139-151]	83 [80-85]	96 [92-99]	77 [73-83]

Again significant differences are evident in the overall arrival of occupants at the available exits. From Figure 8-7, both scenarios 8.1.421 and 8.1.422 produce almost identical outcomes during the first 20 seconds of the simulation. However, as occupant redirection begins to take effect, we find that the evacuation in scenario 6 becomes more efficient as occupants make use of under utilised exit capacity.

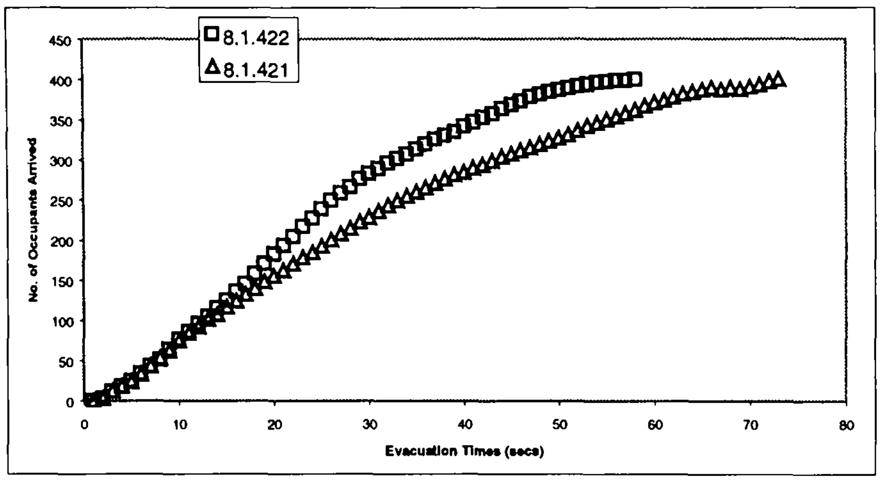


FIGURE 8-7: THE AVERAGE CUMULATIVE ARRIVALS FROM SCENARIO 8.1.42.

These results also reflect how the relatively small distances covered during the redirection process did not compromise the advantages gained through its performance. This is due to the nature of the geometry and the small distances between the exits. This will certainly not always be the case.

The introduction of an adaptive capability into the occupant decision-making process has significantly affected the outcome of all the simulations presented in this paper. It is important to note that this effect is not uniform across the evacuating population, nor is it limited to either qualitative or quantitative factors, but is instead localised and specific to the individual experience. Furthermore, in the simulations presented in this paper, the introduction of this behaviour has lead to an improvement in the overall efficiency of the evacuations and in the personal outcome for each individual. This should not be considered to be a guaranteed outcome resulting from the introduction of this behaviour. The influence is scenario specific. For instance, in more densely populated environments, occupants redirecting to unseen exits may be faced with similar or worsening queuing conditions, reducing the overall optimality of their performance.

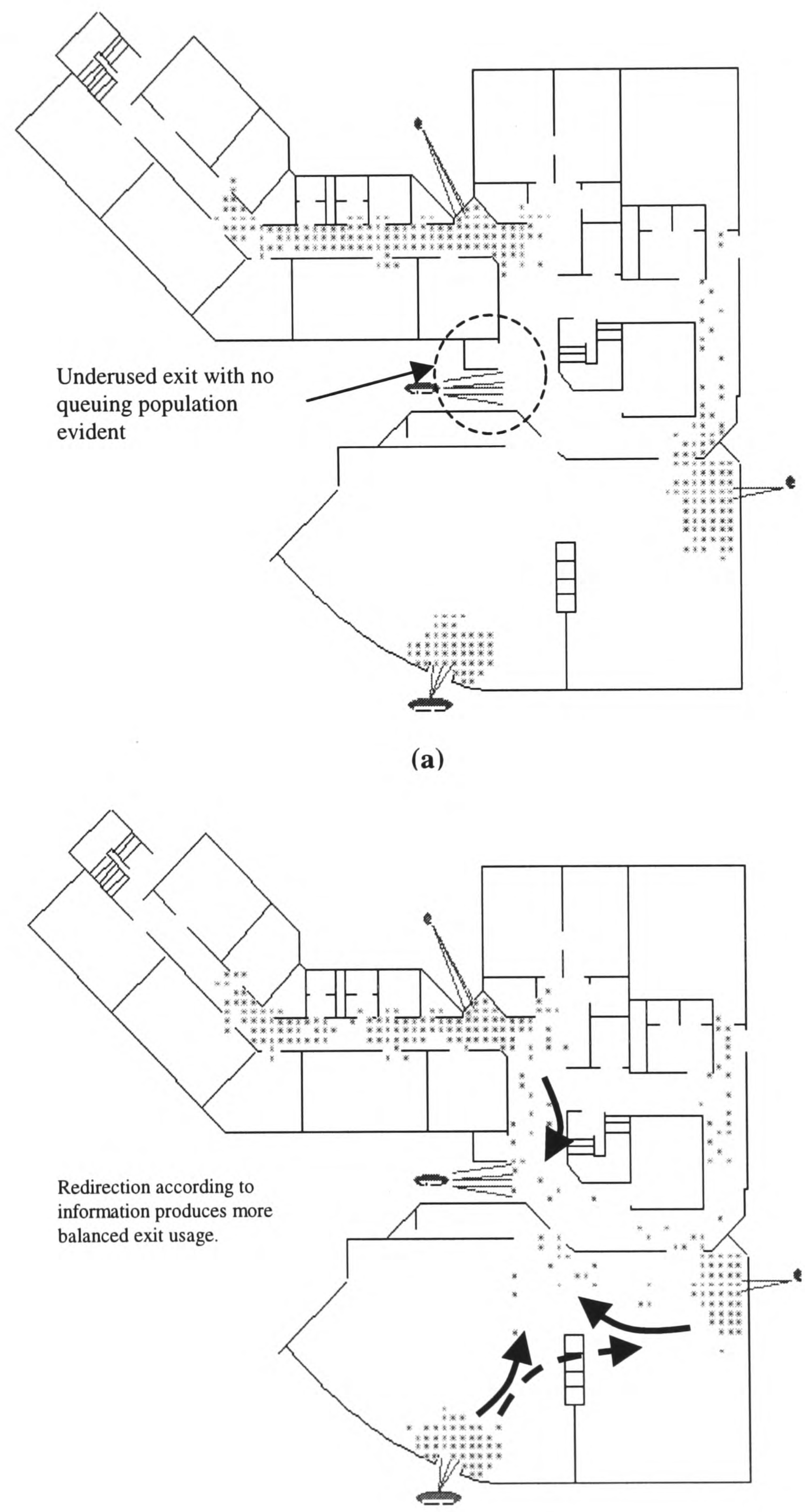


FIGURE 8-8: SITUATION 30 SECONDS INTO SCENARIO 8.1.421 (FIGURE A) AND SCENARIO 8.1.422 (FIGURE B). SOLID ARROWS INDICATE EXTENSIVE CROWD MOVEMENT WHILE BROKEN ARROWS INDICATE LESSER REDIRECTION.

Finally, through the introduction of the prototype behaviour, occupants are able to adapt their behaviour according to the information available to them. If circumstances are changing beyond their scope of awareness, then their decisions may prove to be unsuitable, leading to a potentially worse situation. The level of individual awareness incorporated within the model may be extended through the introduction of the concept of communication. In planned further developments it is proposed to introduce the capability for occupants to communicate either with other occupants, staff members or through information provided by intelligent alarm systems.

8.1.5 FUTURE WORK

This behaviour could be extended to include a more advanced representation of the occupant's ability to redirect several times. This may be calculated according to internal attributes, previous locations and linked possibly to a memory of the conditions at those locations. More evidence would have to be found for this more sophisticated type of behaviour to be implemented, although it would be a simple matter to allow the occupant a greater degree of freedom.

Although extensive sensitivity analysis was conducted concerning the influence of the occupant's personal attributes upon the evacuation process, significant evidence is required so as to calibrate the behaviour further (be it experimental or based on actual events). At present, only anecdotal behaviour is available, although this exists in significant amounts [1,52,53,58,106].

8.1.6 CONCLUSION

This section has demonstrated the potential advantages associated with the introduction of an adaptive behavioural capability within evacuation models. This was demonstrated through enabling occupants to make decisions concerning the selection of the most viable available exit during an evacuation. These decisions were based on considerations such as prior experience, structural familiarity, line-of-sight, and the extent of the crowding around the available exits. The implementation was shown to provide a more complex and arguably more realistic representation of this behaviour than that provided by the existing model. The implementation demonstrated the significance to both the evacuation as a whole and the occupant as individuals of the inclusion of such behaviour.

If the occupant is able to utilise his ability to determine a more effective route through the analysis of exit crowding, then the optimality of the evacuation is increased. However, the capability of the occupant to switch between available exits does not guarantee the reduction of individual and total evacuation times.

The introduction of this behaviour increases the functionality of the buildingEXODUS model and improves the quantitative accuracy of the model through the qualitative development of occupant behaviour.

8.2. Long term route adaptation

8.2.1Expected Occupant Behaviour

As identified in the previous section when examining queuing behaviour, the reaction of the occupant to large-scale crowd congestion is vital to their progress during the evacuation [1,66]. As identified by Feinberg,

> *"Research suggests that the choice of an exit is a function of proximity, familiarity, and the length of the queue moving toward a particular exit" [187]*

However, analogous to the behaviour of occupants engulfed in smoke, and those approaching smoke, the occupant's behaviour in relation to a static occupant population may be seen in two distinct phases.

Once an occupant is surrounded or is on the periphery of a high-density crowd, his options are to remain queuing or to redirect. However, this does not represent the occupant *approaching* a high-density population crowding around an exit, which can be observed from some distance. This would afford him several different options:

1. The occupant could continue on toward the crowding, maintaining his present direction and eventually joining the crowd formation [1,4,52,58,211]
2. The occupant could redirect, changing his target exit due to the occupant crowding and avoid the crowd altogether [1,4,52,58,211].

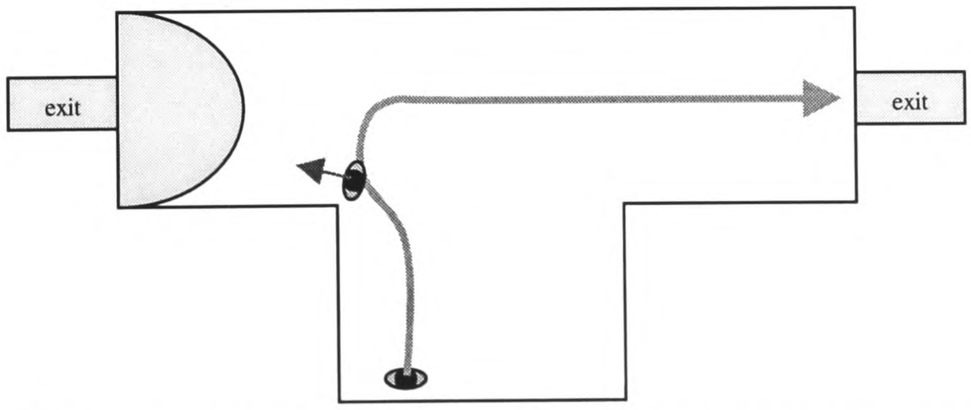


Figure 8-9: Occupant redirects to available exit once desired exit is seen to be obstructed by high-density occupant population.

The occupant analyses the situation according to the conditions and evidence available. The occupant does not therefore approach a crowd formation irrespective of the availability of other options, but instead does so in *relation* to the options available and his perception of the conditions.

The desire to redirect will be dependent upon a number of factors, similar to those highlighted in the previous section. These include

- the ability of the occupant to perceive the conditions at his desired target
- the occupant's awareness of alternative egress routes
- the ability of the occupant to estimate his evacuation time given the surrounding conditions and his capabilities
- the experiences of the occupant thus far.

Much of the evidence cited in support of the queuing behaviour is also relevant here [1,4,52,58,211]. Indeed, the two forms of behaviour are, similar except for the *exact position* of the occupant. In the previous section the occupant is faced with the possibility of leaving a queue whereas here the occupant may refuse to join a queue. In both cases, it is the occupant's commitment to queue that is in question. The difference is in the occupant location relative to the crowd formation.

8.2.2 PRESENT BUILDINGEXODUS BEHAVIOUR

At present the existence of other occupants is seen only in terms of the difficulty they may present in the occupation of floor-space. This treatment is strictly localised, as no long-term route examination other than the existence of the potential map or a specified exit target.

There is also no mechanism present for the occupant to make predictive or anticipatory calculations of his environment, irrespective of the information available. Therefore, no analysis can take place concerning the possible impediment provided to future egress movement.

8.2.3 PROPOSED BEHAVIOURAL MODIFICATION

As with the representation of the adaptive queuing behaviour described earlier in this chapter, the occupant must make his decisions in relation to the knowledge available to him. In this context, the knowledge available to the occupant is:

- The occupant's motivation (see Section 7.2, Chapter 7)

- The occupant's patience (see Section 3.1, Chapter 3)
- The occupant's distance to the exits with which he is familiar and the estimated time it might take to cover this distance (see Section 5.4, Chapter 5 and Section 7.3, Chapter 7)
- The visibility of these exits (see Section 5.4, Chapter 5)
- The crowding around the visible exits (see Section 5.5, Chapter 5)
- The estimated time that these exits will clear (see Section 5.5,Chapter 5).
- The environmental conditions at the prospective exits (see Section 7.1, Chapter 7)

Each of these components will affect the occupant's decision to redirect his egress route, albeit at different stages and to differing degrees. The proposed behaviour is therefore reliant upon a number of new features outlined previously including the door vector, the advanced line-of-sight feature and the ability to analyse occupant crowding (see Chapter 5 and 6).

As the occupant approaches an exit, the occupant's vantage-point will determine the information available concerning alternative routes (see Chapter 5). Irrespective of this availability, the occupant has to be in a conducive frame of mind to redirect at this early phase. *The occupant will only consider redirection, i.e. analyse the situation and proceed through the decision-making process, if in visual contact with the present target exit* (see Figure 8-11). Therefore the occupant has to be convinced that his present target is significantly congested, before redirection can be considered. As in previous redirective behaviours, the occupant is limited to a single redirection to prevent anomalies occurring.

The decision process occurs while the occupant is moving towards the desired exit. This therefore prevents the simultaneous triggering of this behaviour and that described in the previous section relating to the occupant analysis of congestion once they are already queuing.

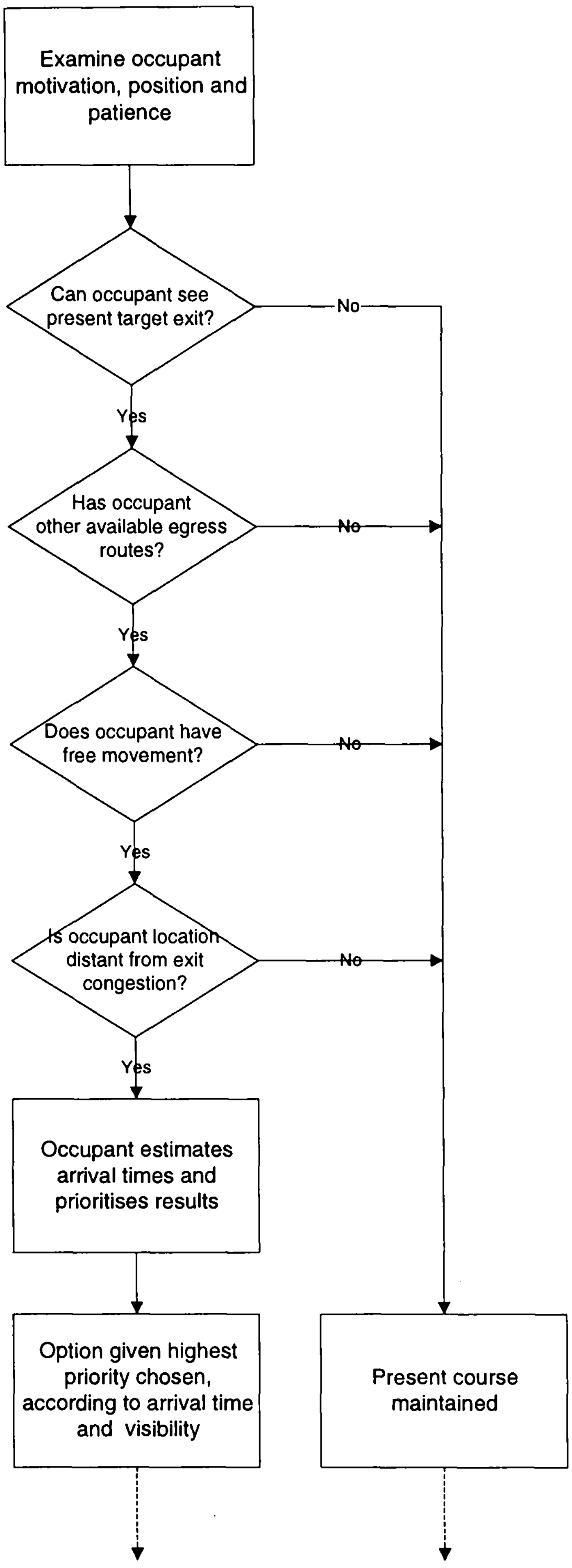


FIGURE 8-10: FLOWCHART REPRESENTING PROPOSED BEHAVIOUR

In this instance, the free movement of the occupant is simulated by the occupant still remaining patient. The occupant would have to be involved in some form of delay to cause impatience, through the increase of his cumulative wait time (CWT), implicitly representing in interruption in his movement.

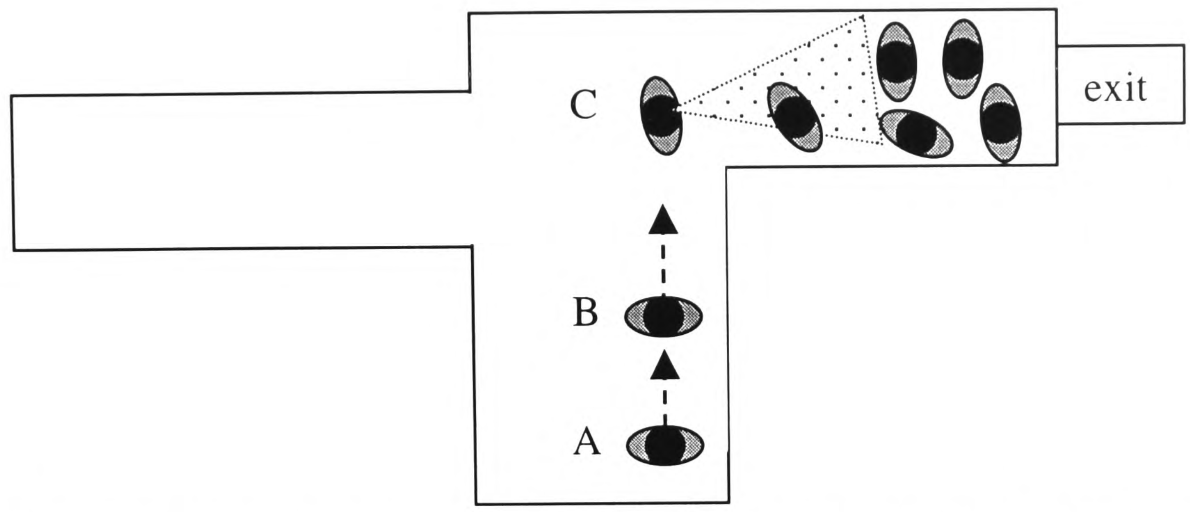


FIGURE 8-11: THE OCCUPANT STARTS AT POINT A AND MOVES TOWARDS THE TARGET EXIT. AT POINT B NO INFORMATION IS AVAILABLE AS THE OCCUPANT IS NOT ABLE TO SEE THE TARGET EXIT, THEREFORE NO ANALYSES ARE MADE. ONCE POINT C HAS BEEN REACHED, THE OCCUPANT RECEIVES INFORMATION AND PROCEEDS TO ANALYSE THE SITUATION.

To prevent anomalous behaviour, the occupant must also be positioned greater than a pre-defined distance from the exit. These factors are formulated as

$$\max(w_i - p_i, 0) \leq 0 \tag{77}$$

where w_i is the time the occupant has spent waiting, p_i is the occupant's patience. The satisfaction of this function indicates that the occupant is still patient. The position of the occupant in relation to the target is described by

$$d_i - \Delta_t > 0 \tag{78}$$

where d_i is the distance of the occupant from his present target and Δ_t is a constant default exit distance threshold. This distance threshold is based around the occupant's initial drive and the attractiveness of the exit, as well as containing some random noise such that

$$\Delta_t = (\mathrm{H} + A_j.\frac{D_{\max} - D_i}{D_{\max}}) + \varepsilon \tag{79}$$

where H is the default distance threshold (arbitrarily set to 5m), D_i and D_{max} are the drive setting of occupant i and the maximum drive setting, A_j is the attractiveness of exit j and ε is a random number between 0.0 and 1.0. The attractiveness of the exit, A_j, is scaled to minimise the potential variation of Δ_t, producing a range of values between 5m and 7m.

This form of representation also allows this behavioural development to be used in tandem with the queuing behaviour, as the causal conditions do not occur simultaneously.

The occupant's commitment to a specific exit is taken into account when determining the likelihood of the occupant redirecting. The distance that the occupant has travelled in reaching his present target has a negative impact upon the probability of redirection. This is based on the assumption that an occupant who has committed a substantial amount of resources to his present target, (time spent travelling and distance covered) will be more reluctant to redirect than a less committed occupant. This is calculated in an identical manner to the process described in the previous section, using the formulation

$$1-\frac{d_i}{\max(\|P-Q\|_2+d_i,\mathrm{K})}>r \qquad (80)$$

where, P and Q are the co-ordinates of the occupant's present location and the exit location respectively, d_i is the distance travelled so far and K is a threshold designed to prevent small travel distances distorting the calculation. Therefore as the distance travelled by the occupant increases, the likelihood of the occupant redirecting away from his present target reduces, due to the resources committed.

Given that the occupant wishes to redirect, the occupant initially examines the visible exits to determine whether an improvement exists in comparison to his present route. This is achieved in an identical manner as that used in the queuing behaviour and uses the line-of-sight calculations described in Chapter 5. This calculation can therefore be affected by the existence of smoke and high-density populations that will prevent information being received by the occupant.

If this appraisal does not provide a viable alternative then non-visible exits are examined, without the advantage of the occupant being aware of the exit conditions. The occupant is still able to adopt an exit, given that he is only aware of the distance that must be covered to reach it. Under these circumstances the occupant's motivation affects the likelihood of the occupant adopting the riskier option. These decisions are calculated in an identical fashion to the calculation evident in equations presented earlier in this chapter.

8.2.4 VERIFICATION

Two cases are examined to demonstrate the proposed behaviour (see Table 8-8). The cases examined are

- 8.2.41 This examines the impact of occupant attributes on redirective behaviour

– 8.2.42 This is designed to examine the ability of occupants to redirect in a complex geometry in response to the existence of exit congestion

TABLE 8-8: DESCRIPTION OF THE VERIFICATION CASES.

Scenario	Population	Geometry
8.2.41	45 occupants at exit, 36 approaching. Second exit is vacant.	T shape 152m^2. 2 exits, width 1m each
8.2.42	Populations of 100,70 and 49 at exit 1,2 and 3. Approaching populations Of 40, 30 and 30.	Irregular,318 m^2. 3 exits of 1.5m width

VERIFICATION CASE 8.2.41

Scenario 8.2.41 examines a simple, two-exit geometry. One of these exits initially has a crowd present, whilst the other is immediately available for use. The motivation of the population is altered (ranging between 5,10,15 and 20 amongst the occupant population) to examine the impact upon the probability of redirection. All of the occupants respond instantly.

Forty-five occupants are situated at exit 1, with 30 other occupants approaching. Initially, no occupants are situated at or approaching exit 2. These conditions suggest that occupants *should* consider redirection to prevent undue congestion.

All of the occupants are aware of both exits; that is both exits appear in the occupant's door vector (see Section 7.3, Chapter 7). Initially, all of the occupants move towards exit 1. Due to the nature of the geometry, both exits are visible once the approaching occupants turn toward exit 1 (see Figure 8-12). It is only at this stage that the occupants begin to analyse the situation.

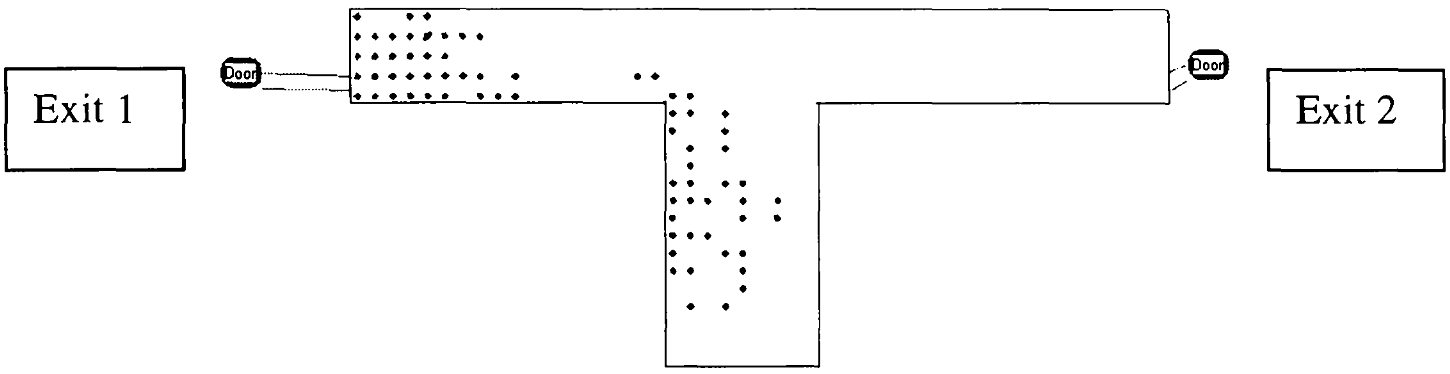


FIGURE 8-12: SIMPLISTIC GEOMETRY USED TO EXAMINE THE INFLUENCE OF THE DRIVE UPON THE LONG DISTANCE ANALYSIS OF EXITS

RESULTS VERIFICATION CASE 8.2.41

The purpose of this scenario is to demonstrate the impact of the occupant's motivation upon their likelihood of redirecting and the impact of this redirection upon the overall evacuation times.

From Figure 8-13 the occupants can be seen to adapt their path of egress, given the availability of a more *viable* option. The adaptation is dependent upon the level of congestion around exit one and the motivation of the occupants involved. Both of these trends are evident in Figure 8-13. *The algorithm therefore successfully reproduces the assumption that occupants who are highly motivated will be more likely to redirect, given that the circumstances are conducive for them to do so.*

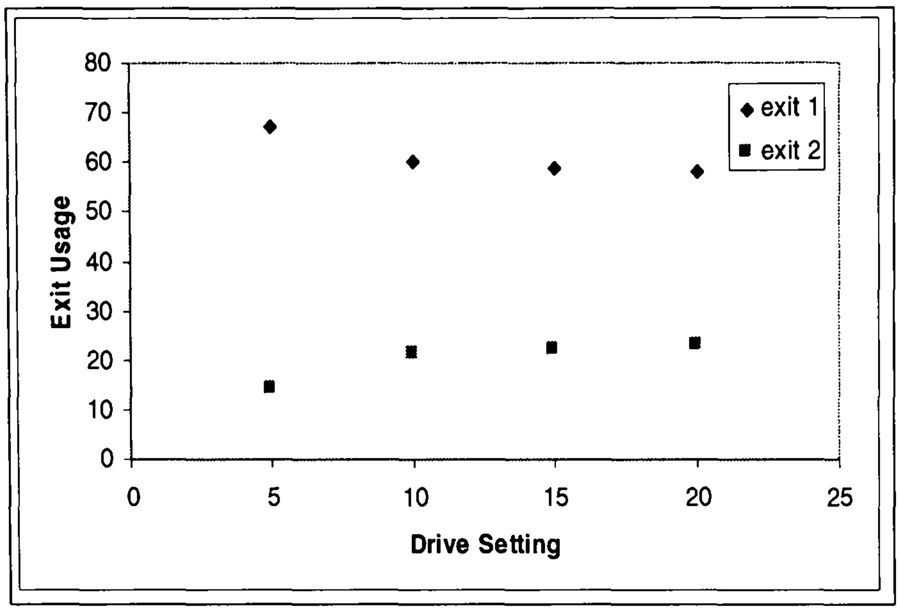


FIGURE 8-13: COMPARISON BETWEEN EXIT USE AND THE DRIVE SETTING OF THE MOBILE POPULATION [EXIT 2 IS THE ALTERNATIVE EXIT]

However, it should not be taken for granted that this redirection will automatically guarantee the minimisation of the overall evacuation time. In Table 8-9 the evacuation times demonstrate a steady, although small, reduction, until the motivation level of the population has risen to 20. This is because the crowding around exit 1 is alleviated as occupants increasingly avoid this route.

TABLE 8-9: RESULTS PRODUCED FROM SCENARIO 8.2.41

Drive	Evacuation times (secs)	CWT(secs)
5	30.2 [28.4-32.1]	2.0 [1.8-1.9]
10	29.3 [28.4-30.9]	1.8 [1.8-1.9]
15	28.4 [27.3-30.1]	1.8 [1.7-1.9]
20	29.5 [27.8-35.1]	1.7 [1.6-1.8]

However, once the motivation level has reached 20, the number of occupants redirecting increases to over 20 (see Figure 8-13). These occupants therefore have to travel across the geometry (a distance of approximately 20m) to arrive at their secondary exit. This will take at least 13 seconds, given the limitations on the occupant travel speed provided by buildingEXODUS [24]. Their new exit may also be subject to congestion, further delaying their progress.

Examining the occupant's CWT (see Table 8-9), we can see that the occupant's experienced progressively smaller wait times as their motivation levels increased. This reflects the reduced amount of queuing once the level of redirection has increased to sufficient levels, replaced by either movement between the exits or an early exit.

For comparison, the results produced by the present model are represented in Table 8-10. The evacuation times produced are consistently greater than those seen previously, as level of queuing was vastly increased as no redirection occurred. The CWT of the individual occupants has also seen to increase for the same reason. No differences can be determined through varying the occupant's motivation, as no decisions are made on this basis.

TABLE 8-10: RESULTS PRODUCED FROM THE PRESENT MODEL.

Drive	Evacuation times (secs)	CWT(secs)
5	37.9 [35.1-41.1]	3.1 [3.0-3.3]
10	40.4 [41.4-42.4]	3.6 [3.2-3.8]
15	39.9 [37.8-41.4]	3.7 [3.3-3.9]
20	40.1 [39.3-44.4]	3.2 [3.1-3.6]

VERIFICATION CASE 8.2.42

A geometry with three exits is produced (see Figure 8-14), providing the evacuating occupants with a number of alternative routes. Initially these exits are congested, as well as having three distant populations who are approaching them. This is to demonstrate the occupant's capability to adapt to the information available.

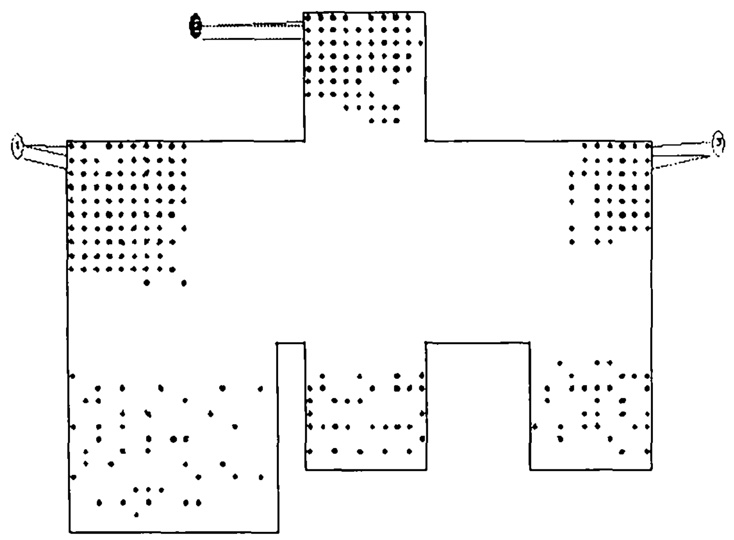


FIGURE 8-14: DIAGRAM OF THE GEOMETRY USED. EXIT 1 (FAR LEFT), EXIT 2 (CENTRAL), EXIT 3 (FAR RIGHT)

The three exits have identical dimensions of 1.5m and are attributed with free-flow conditions. Each of the exits initially has different levels of crowding around them. These populations consist of 100 (at exit 1), 70 (at exit 2) and 49 (at exit 3) occupants. These numbers, although arbitrary in their extent, generate differences in the tenability calculations of each of the exits. The approaching populations also have slight differences in them, consisting of 40 (approaching exit 1), 30 (approaching exit 2) and 30 (approaching exit 3) occupants. This is again an attempt to introduce differences into the considerations of the occupant decision-making process. The oncoming occupants have limited *visual access* to the conditions around the three exits, although the occupants are familiar with all of the exits available. The level of crowding around the three exits includes subtle differences to introduce discrepancies in the arrival calculations of the occupants.

TABLE 8-11: SCENARIOS EXAMINED IN 8.2.2

Scenario	Visual Awareness	Familiarity	Behaviour
8.2.421	Complete	Complete	Long Distance
8.2.422	Complete	Complete	Long Distance/ Queuing
8.2.423	Not Applicable	N/A	Present
8.2.424	Visual	Complete	Long Distance
8.2.425	Visual	Complete	Long Distance/ Queuing

The behavioural model and visual awareness of the occupant population is altered to examine the impact of these factors upon the eventual outcome. In Scenario 8.2.421-2 the occupant is assumed to be completely aware of the exit conditions; that is the occupant's are aware of the existence of the exits and the congestion at each of the exits. In 8.2.421 the population is capable of redirecting whilst approaching the crowd formations, whilst in 8.2.422 the occupants can redirect either approaching or once involved in a static crowd formation. In 8.2.423 the present buildingEXODUS model is examined. Scenarios 8.2.424-5 mirror 8.2.421-2 except that occupant awareness of the exit conditions is now based on their *visual perception* of the conditions, whilst maintaining a complete familiarity with the structure.

RESULTS-VERIFICATION CASE 8.2.42

In Scenario 8.2.42, a number of variables have been examined to determine the sensitivity of the proposed behaviour to variations in the population and to the behavioural conditions. The ability of the occupant to apply both the queuing behaviour and the proposed behaviour simultaneously is also examined for anomalies.

The first point of note, is that the use of the present model in Scenario 8.2.423, where occupants queue blindly at their primary exit and approach exits irrespective of their use, *extends* the evacuation times generated (see Table 8-12).

Of the proposed model scenarios the most important variable examined was the *visual awareness* of the available exits. Irrespective of the redirective behaviour implemented, the visual contact of the occupants with the exits provides an important influence over the results. This reflects the importance associated with the occupant access to information in Section 5.4, Chapter 5.

TABLE 8-12: RESULTS FROM VALDAITION CASE 8.2.42.

Scenario	Evacuation times (secs)	OPS	CWT (secs)
8.2.421	35.3 [33.3-37.1]	0.06 [0.03-0.09]	1.7 [1.6-1.8]
8.2.422	35.3 [34.1-36.8]	0.07 [0.03-0.14]	1.7 [1.6-1.8]
8.2.423	43.5 [40.1-46.8]	0.34 [0.26-0.4]	1.9 [1.8-2.0]
8.2.424	38.1 [36.3-40.3]	0.19 [0.18-0.24]	1.6 [1.6-1.7]
8.2.425	36.5 [40.3-37.1]	0.12 [0.1-0.17]	1.7 [1.6-1.8]

From examining the evacuation times of scenarios 8.2.421-2 and 8.2.424-5, the full awareness of the occupants decreases the evacuation times by 5.7 % on average, over the equivalent scenarios implementing partial awareness (scenarios 8.2.424-5).

The quantitative differences between the results produced through the different redirective options are neglible. This is because once both redirective options are enabled (in 8.2.422 and 8.2.425) they effectively counteract each other. Once both forms of redirection are enabled, the crowding around the original exits reduces as the load is more evenly distributed due to large-scale queuing adaptivity. Once the long distance behaviour alone is enabled, the mobile occupants are more likely to redirect as they approach the crowds at the exit, who are more static, maintaining the initial inequalities in the exit congestion. The two scenarios therefore almost produce equivalent results (see Figure 8-15).

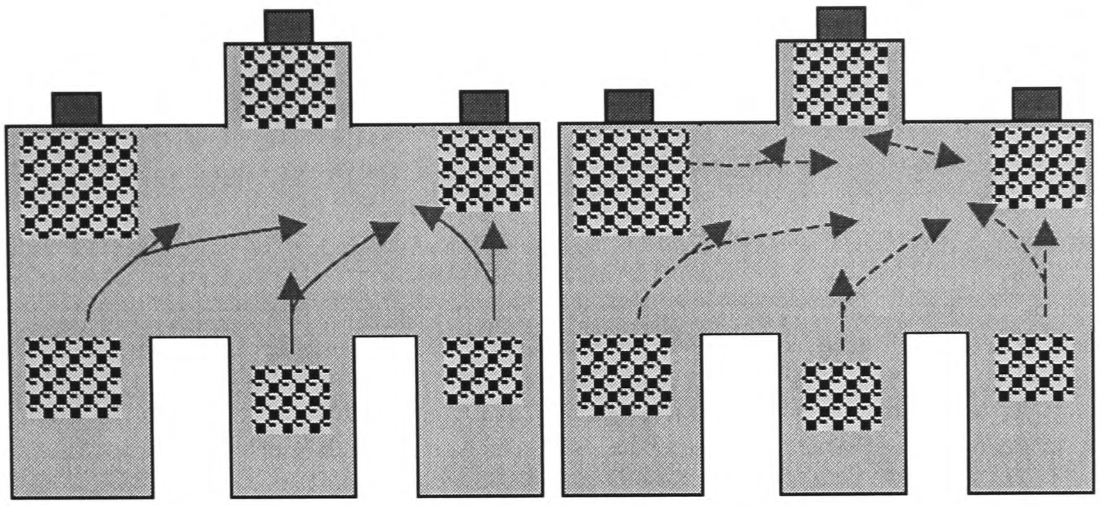


FIGURE 8-15: DESCRIPTION OF THE POSSIBLE SCENARIOS. ON THE LEFT, ONLY THE LONG DISTANCE REDIRECTIVE BEHAVIOUR IS ENABLED, WHILST ON THE RIGHT BOTH LONG TERM AND QUEUING REDIRECTION IS ENABLED.

The results from these simulations can be further interpreted through examining the exit usage. As expected the most even distribution of the occupants amongst the exit occurs when the occupants are *fully aware* of the exit conditions and having either one or both of the redirective behaviours. This efficiency is reduced when the occupants are only partially aware of the exit conditions, as the exits may not be visible allowing the occupant to make irrational decisions, such as moving to an even more crowded exit.

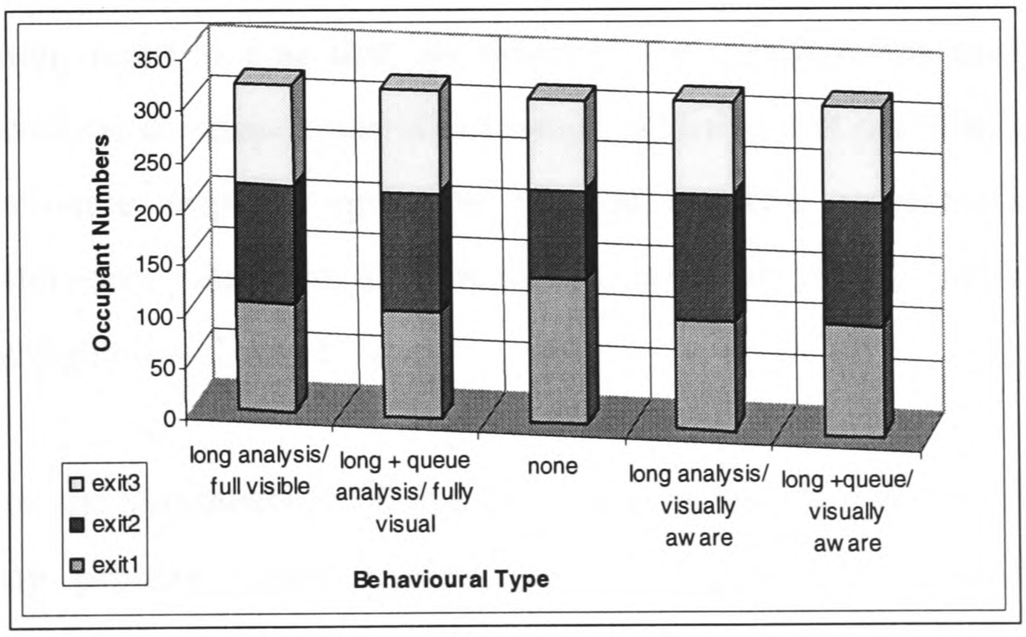


FIGURE 8-16: EXAMINATION OF EXIT USAGE DURING DIFFERENT VARIATIONS OF THE LONG DISTANCE ANALYSIS

By far the least efficient method is the present method where the occupant's decisions are entirely based on proximity rather than the external conditions. This therefore causes a much more uneven distribution of occupants amongst the exits (see Figure 8-16).

Other statistics recorded include the overall efficiency of the exit usage, in the form of the OPS figure and the time spent waiting by each of the occupants (CWT). As expected, the simulations involving no redirective produce the least efficient use of the exits, in this case (see Table 8-12).

Very little difference exists between those simulations crediting the occupants with complete knowledge of the enclosure. When information is dependent upon visibility the implementation of the use of both long-term and queuing adaptation appears slightly more efficient. However, the assumption that occupants have complete knowledge is always more efficient than those simulations assuming knowledge based on visibility.

Examining the occupant's cumulative waiting time, it can be seen that the occupant's individual experience differed between the scenarios. However, here there was little difference between those simulations adopting the proposed behaviour. This may have been due to the high density crowding which eventually resulted, irrespective of the level of occupant awareness. There was an appreciable difference between these and the simulations implementing the present behaviour, which had significantly longer CWT times. This is due the vastly uneven distribution of occupants, forcing some to have extremely long CWT times.

It is an important point to note that the effect of the simultaneous use of two of the proposed behavioural developmetnts is not simply additive, but has both immediate and long-term qualitative impacts upon the evacuation. This is demonstrated in the qualitative differences observed previously, as well as in the subtle quantitative differences highlighted in Table 8-12.

Fundamental to the introduction of this behaviour is the fact that it is not a global decision-making process where optimal decisions were calculated for the entire population. Instead, *the occupants make decisions given the information available and the ability to perform estimations concerning their future behaviour.* This therefore, more accurately reflects the actual methods applied to solving these problems which would be distributed, fallible and entirely dependent upon the occupant's faculties and the information available to them,

8.2.5 FUTURE WORK

An obvious future development is the unification of this behaviour and the queuing behaviour identified earlier in the chapter. The two would generally be combined in any sensible simulation of occupant queuing under the present implementation. The differences are purely technical and could be represented to the user as a unified behaviour at present. However, the algorithm should be actually unified with the occupant able to distinguish their position and act accordingly.

It might also be possible to allow occupants to examine bottlenecks/internal exits for more 'optimal' evacuation routes. This would have to be introduced alongside the introduction of the internal exit or a more sophisticated analytical mechanism that allowed the occupants to investigate their possible future conditions.

8.2.6 CONCLUSION

It is important that the behavioural model that is produced relating to the long distance analysis of crowd congestion is compatible with the other developments proposed in relation to crowd formations. This was specifically addressed in the verification cases, where several of the proposed behavioural features were examined in unison. The effect was not simply an increase in the redirective behaviour, as one would have expected in simplistic or global behaviour. In these cases the occupant behaviour produced had qualitative differences, with the occupants adopting different egress paths. However, the numbers of occupants redirecting or the overall exit usage has far fewer differences, due to the changing conditions produced by the introduction of the behavioural models.

The proposed behaviour is over-restrictive in that an arbitrary limit is placed upon the occupant redirection. This is only to prevent the occupant bouncing between exits. This might be removed in the future. However, it has shown to be a useful and appropriate improvement to the existing behavioural model, which detracts from the physical sophistication of the present model.

8.3. COMMUNICATION AS AN ADAPTIVE RESPONSE [199]

8.3.1 EXPECTED OCCUPANT BEHAVIOUR

"People are known to actively seek information during an emergency" [82]

Prescriptive regulations imposed upon the design of buildings assume that the identity of occupants involved in an evacuation will have a negligible impact upon the subsequent events. This is based on the view that the physical impact of the structure's design will far out way other influences upon the evacuation [203]. This point of view is implicit in the building regulations, in the absence of any discussion concerning the impact of occupant behaviour upon the evacuation [203].

It is certainly the case that the physical restrictions imposed by the structure and the occupant's location within it delimit the behavioural options available. However, as described in Chapter 2, a number of other factors affect the options available to the individual and the choice eventually made.

In recent history, a number of tragic events (including the Beverly Hills Supper Club, the Summerland, the World Trade Centre, the Ottawa office fire and the King's Cross incident [52, 53, 58, 97, 106, 128]) have borne a surprisingly consistent message; ***that the occupant's identity, the identity of the surrounding population and the subsequent relationships between them significantly affected the decisions made and the actions adopted by the occupant population.*** As one participant in the B-everly Hills Supper Club incident recalls,

"one of the people in my party said, 'Let's go on the stage and there's got to be a way backstage.' And he and I discussed it for a moment whether to do that and I said, 'No, we shouldn't because now we're just creating another avenue of confusion for a lot of people. A lot of people might start following us and I don't think we should do that.' He said,' Yeah but there is no other way, you know, look at the people trying to get out here.' ...he said,' Come on let's go this way.' So we got on the stage and [the stage performers] told us there was no way out this way...[we] turned around and started to go toward the way that we came in..."[52]

The party members, who are obviously familiar with each other, *discuss and influence* each other's actions [207]. Not only are these occupants attempting to move their own group to safety, but are concerned with the well being of other occupants. This form of action is continued until the group meets an unfamiliar member of the staff who is perceived to be more knowledgeable in this environment.

In the light of anecdotal evidence of this nature and a large amount of other research evidence [1,52,53,58,95,97,106,128,163], it is apparent that an important variable in determining occupant response is the presence of other occupants and the relationships that exist with the surrounding population.

The maintenance of an occupant's position in the social hierarchy is based on one critical assumption; that the extraordinary conditions in which they are placed have not damaged the existing social norms. This destruction of the social norms was the accepted wisdom for the majority of this century [72-74]. However, the overwhelming weight of evidence relating to evacuee behaviour suggests that social roles and norms are maintained and possibly extended in the majority of cases [1,52,53,58,97,106,128,163]. This process of definition and re-definition was recognised by Feinberg and Johnson in their examination of the Beverly Hills Supper Club incident, when they stated that

"Research based on reports by employees of their own behaviour showed that employees continued to comply with, even extended, the relevant role dimensions."[215]

This is a reflection of the ability to maintain a sense of social awareness even when faced with imminent danger. As noted by Crouch [216], humans do not necessarily become irrational and selfish when faced with imminent danger (such as in an evacuation). Those involved may initially be stunned due to the occurrence of the event and obviously afraid. Given these feelings it would be wholly rational for them to engage in evacuation as quickly as possible. These actions may be mistakenly defined by a third-party observer alternately as 'panic behaviour', 'fleeing', 'herd instinct' or as a 'dog eat dog' situation (this was certainly the case in the newspaper reporting of the Beverly Hills Supper Club incident [52]). This can be noted from the CNN report concerning the Gothenburg incident of 1998, killing over 60 occupants, where it was claimed that,

"It was chaos. Everybody was trying to get out and people trampled on each other on the way to the exit. ... Others kicked out the windows and jumped out."[217]

The sub-optimal performance of evacuation activities by occupants may well be due to lack of experience, lack of training, or the occupant being unfamiliar with the situation as well as difficulties provided by a hazardous environment, rather than being due to the inability of the occupant to reason rationally.

Therefore occupants perform actions which, given the information available to them, are rational and appropriate, and do so "under purposive control" [218].

In short, occupants categorised as panicking might be *ignoring* the pre-existing social norms rather than breaking them [55]. Occupants tend to control their cognitive processes irrespective of their external conditions. A complete breakdown of these processes is rare [1]. Far more likely is their constructive interaction with either prominent unfamiliar occupants or familiar group members.

Just as it is a fallacy to assume that the identity and relationship of occupants have no bearing upon the evacuation, it is equally fallacious to assume that the formation of collectives is guaranteed and once formed that the motivation of such a group dominates that of the individual. For a significant time it was believed that groups (or crowds [72,216,218]) were *segregated* and *suggestible*. This implies that the occupants within the grouping were completely subservient to the wishes of the group and that the behaviour of group members was qualitatively different to non-members. Further, this group would be suggestible to the directions of external supervision. Given that individual members were controlled by the wishes of the group, they were therefore suggestible to external forces.

There is an obvious logical difficulty in the application of this theory to fire safety; if it were the case, then the implementation of signage and alarm systems would be far *more* effective than they are at present. As MacPhail states in examining the response of a purposive crowd to external advice,

"If crowd members were uniquely suggestible, authorities would merely propose that the crowd desist and disperse"[218]

A more dynamic and individually based system seems to be more conducive to the evidence available.

Given that the majority of occupants do not evacuate in isolation, their behaviour is conducted, to some degree, in relation to the surrounding crowd. Indeed, the very presence of other people has been shown to affect the likelihood of performing certain actions [198].

Given that social norms do not dissolve during the evacuation process [55,128,207], to what extent do they impact upon the process. Hewitt and Jones identified that the social conditioning of the occupants had a significant affect upon the behaviour exhibited. Even between complete strangers the level of altruism demonstrated by occupants during an evacuation is surprisingly high [1,163], but amongst related or socially acquainted individuals, behaviour tends to be co-operative, displaying communication and behavioural adaptation [163] even during life-threatening situations. As noted by Johnston when reporting the recollections of a survivor of the Beverly Hills Supper Club disaster at the height of the extreme conditions, that

"Even then...social bonds had not collapsed, for as the wife looked back to see how many people were behind, she observed that some of the men were helping the elderly people on the first level to get over the rail" [52]

Therefore, even under extreme conditions, altruistic actions were occurring between unfamiliar occupants.

However, the appropriateness and effectiveness of altruistic behaviour is not guaranteed, being dependent upon the surrounding conditions and the accuracy and extent of the information provided [163]. Therefore, even in situations where altruistic acts have occurred, the evacuation can be adversely affected in the form of incorrect advice. An example of such behaviour is the delaying of fast moving occupants in response to a slower moving relative. As noted by Proulx,

"These group formations likely delayed the speed of movement of the group because members tended to assume the speed of the slowest person." [*80*]

Instead of a natural dichotomy occurring between the reaction to familiar and unfamiliar occupants, the relationship seems more complex. A significant amount of evidence suggests that a more continuous refinement exists ranging from the strengthening of the social bonding down to the removal of these bonds. This scale is not linear. For instance, the increase in perceived severity of a situation may initially strengthen a social tie, while the further worsening of this perception may cause both physical and mental impediment to the maintenance of these social ties [1,52, 207].

The social bonding system is again not a two-state system, but has a number of different refinements. Some of these position are seemingly impenetrable to external influences such that

"Primary ties such as within the nuclear family breaking down last, if at all, and the requirements of the citizen role—the norm of civilised behaviour, even to strangers—being the first to break down." [49]

However, as the social bonding decreases in strength, the less formal the altruistic behaviour and therefore the less reliable. None of this discussion should be seen as endorsing the view of unrestrained competition often cited. Here, the maintenance of social formations and the offering of assistance rather than the retraction of civility are the main focus.

It should also be remembered that social groupings are not static. As identified by Hewitt and Jones [58], social roles and social norms can emerge from a population. This is especially the case in certain circumstances including:

- the lack of a pre-existing social order from which a social hierarchy may be extracted
- the existence of more than one social order
- the dissatisfaction of the population with the existing social hierarchy due to conflicting ideas or inappropriate actions [52,58].

Therefore, in what may be considered a small amount of time, the adoption of roles due to an occupant's position in the social hierarchy may significantly alter (for instance a complete stranger may assume responsibility for an elderly occupant).

The occupant response to significant others, whether they are members of a social grouping, a respected figure of authority, or an individual who spontaneously joins a social group, is important and might be influenced in a number of ways including

- the type of information that might be passed, which include the existence of exits, the existence of a hazard, etc [58] .
- the seriousness with which that information is treated and the likelihood of utilising that piece of information [58,97].
- the possibility of refraining from or engaging in specific actions due to the identity of the population around you (these actions might include a change in direction, waiting, the maintenance of the present course of action, etc.)[52, 128]

The picture outlined is not compatible with the one generally applied that consists of selfish, socially isolated competitors, struggling for their safety at any costs. Instead, a dynamic, interrelated mesh of social actors exists, coping with a generally unfamiliar and hazardous environment, without discarding the social norms by which they shape their regular existence until catastrophic circumstances arise.

In summary, occupants exist in a social framework. This does not dissolve under the presence of an emergency, but may sustain through horrific conditions. The reaction of occupants towards each other will be affected by the social organisation in which they are immersed, but will also be affected by a more general social awareness. Responsibilities, which might manifest themselves as the provision of assistance are dependent upon the occupant's role within the immediate social grouping (e.g. family, etc.) as well as a wider social position, based on a general respect for other occupants. This is a departure from the competitive, individualistic model originally put forward as describing evacuee behaviour.

8.3.2 PRESENT BUILDINGEXODUS IMPLEMENTATION

At present no recognition of social relationships exists in the buildingEXODUS model and none of the above factors are considered. In this respect buildingEXODUS represents the occupant population as automatons lacking an identity, who treat each other as *mobile obstacles*. The surrounding population has no bearing upon the behavioural choices of an occupant other than a physical one, providing barriers to maintaining their present route.

8.3.3 PROPOSED BEHAVIOURAL MODIFICATION

The proposed behaviour is an attempt at representing social structures and subsequent occupant behaviour that is generated. To simplify this description of the behavioural developments, the proposed behaviour is separated into three sections:

- ***Formation***- describing the initial stages of collective behaviour
- ***Communication***- describing the content of the information passed between occupants and the context in which it is passed
- ***Adaptation***- the occupant's response to the provision of new information

These definitions are not mutually exclusive as a number of factors fall into more than one category. However, they should provide some assistance in comprehending these complex behavioural developments.

FORMATION: *THE EXISTENCE OF A COLLECTIVE*

In the proposed behaviour, two distinct forms of collective behaviour are addressed. These are

- *Imposed Social Hierarchies*-Those occupants that are associated with members of the occupant's social grouping prior to the evacuation; an occupant with whom the individual is familiar and would therefore implicitly recognise that occupants 'role'.
- *Emergent Social Hierarchies*-The interaction between non-familiar occupants, where the social relationship is either negotiated or emerges.

This difference between these two social structures is one simply of pre-existing or emerging social norms. As such, much of the behaviour that may arise under their influence is very similar (Indeed the behavioural systems will co-exist and overlap within populations). The differences that are represented are based on anecdotal recollections of actual evacuees, as well as behavioural features derived from theoretical work [1,4,49,58,80,106, 207]. These differences tend to be based on the *extent* of behaviour change rather than the *content* of the behaviour itself.

The representation of the familiar is dependent upon the formation of social groupings prior to the simulation, representing pre-existing social ties. This is based on the assumption that occupants are aware of each other's identity prior to the occurrence of the evacuation. Given this social identity, the occupant has an implied position within the group's social hierarchy. Therefore occupants are attributed with information that is not *primarily* for use in an evacuation but which impacts upon the incident once it occurs.

Once the occupant population has been appropriately attributed with their social relationships, using the '*gene*' method described in Chapter 5, the population is interrogated to determine those occupants who share a common gene and are therefore socially connected. These then go on to form social groupings (e.g. familial/work mates etc.), which are stored within those individuals who are members of these groupings. Therefore each member of the population who has been identified as being a member of a social group will contain an internal representation of the structure of this social group *prior to the evacuation* (see Figure 8-17).

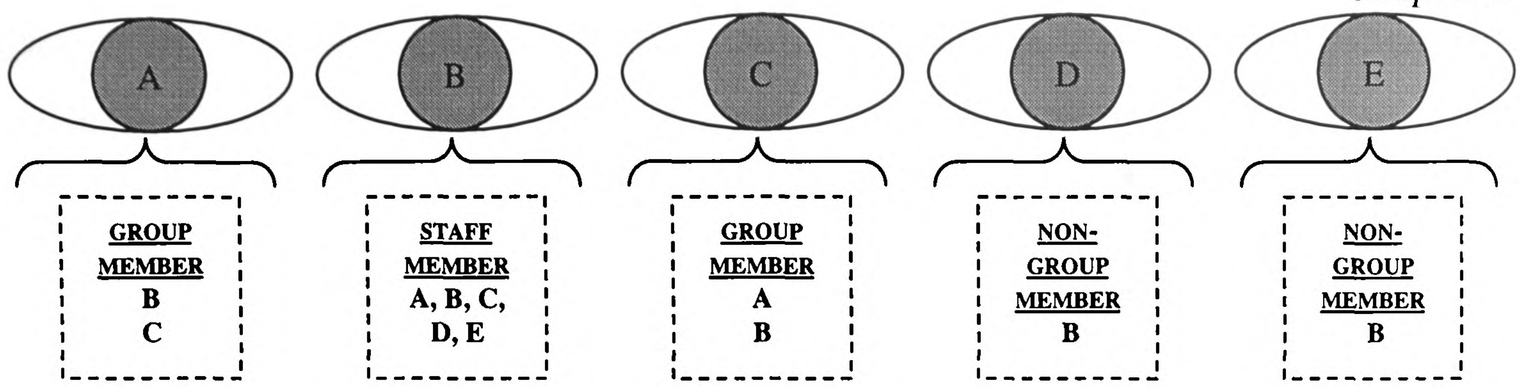


FIGURE 8-17: THOSE OCCUPANTS DEFINED AS BEING FAMILIAR HAVE AN INTERNAL REPRESENTATION OF THIS FAMILIARITY, WHILE OTHER OCCUPANTS MIGHT HAVE NO PREDEFINED MEMORY, OTHER THAN THE MEMBER OF STAFF.

To represent the altruistic behaviour that develops spontaneously, as identified by Juliet and others [1,58,106,163], an occupant may be added to the list of occupant's group members *during the evacuation*. Therefore the list of group members may be extended during the evacuation. If occupants are encountered who are immobile, young/elderly, etc. (therefore they are perceived as being less mobile or junior to the occupant), they *may* be incorporated into the group and treated as an equal member. This process is stochastic and is largely based on anecdotal evidence. However, the existence of the new group member is localised to those group members involved in the provision of assistance. This prevents occupants receiving information without them encountering or being aware of the developments. Once formed these group members may behave in a similar manner as those described earlier.

An important addition to this method is the description of staff members. These are assumed to be 'global' group members. Therefore given that they are defined as staff members, they will be added to all of the individual occupant group lists (see Figure 8-17) and therefore be treated accordingly.

This group list is traversed at each time interval to determine the proximity of each individual and therefore the possibility of communication. This is an attempt to model the general awareness and interest of group members of the location of other members of the group. Initially, only those relations who fall within a *zone of influence* surrounding the object occupant will be affected.

The *zone of influence* represents the area within which occupants may communicate. It represents the ability to influence others in a number of different forms including visually and aurally. The impact of these factors as being influential over the ability to communicate has been influenced by the work of Klein [199], Bales [219], etc. (see

Chapter 5). This work identifies that the level of influence exerted by an occupant is dependent upon their identity and the perception of this identity by the surrounding occupants. In reality, communication may arrive in a number of forms, including the reception of visual, aural, olfactory cues. These influences will have different strengths of perception and may be perceived in different areas of perception. For instance, visual cues may be limited to a cone, positioned in front of the occupant although stretching for some distance. This should be compared with aural cues, that may arrive from any direction, although may have a more limited range. Given the limited representation of these cues within the buildingEXODUS model, a number of compromises were necessary.

The *zone of influence* is described by a circle surrounding the occupant. The radius of this zone is dependent upon occupant attributes (see Figure 8-18). The potency and therefore the extent of this zone of influence will be dependent upon the *seniority*, *identity* and *motivation* of the individual involved such that,

$$z' = z + \left(\frac{\alpha D_{\max} s_i + \beta D_i s_{\max}}{D_{\max} s_{\max}}\right) \quad (81)$$

where z' is the calculated radius, z is the initial value of the radius. After analysing the sensitivity of the model to a range of values for z, it was eventually decided that the default value of 4m would generate reasonable results. Obviously the means by which this figure was arrived at was not based upon empirical evidence, which would ideally form the basis of any simulated behaviour. However, in the absence of such data, approximations and assumptions have to be made that produce consistent and reasonable results. This initial value should ideally be available to user control. D_{max} and D_i represent the maximum motivation and the actual motivation of occupant i, s_{max} and s_i are the maximum seniority and the actual seniority of occupant i and α and β are coefficients that set the seniority of the occupant as being twice as influential as the motivation of the occupant. The range of z therefore approximately extends between 4.0 and 6.0m.

The extent of the zone is a compromise in the implementation of this algorithm within the buildingEXODUS model, being a mechanism to represent *communication*, rather than individual sensorial cues. Ideally the impact of aural and visual awareness should be dependent upon the enclosure and the environment, although little data is available on this topic [36].

The representation of the complex differences in the ability to communicate as purely physical, is a significant weakness in the method. However, given the complexity of the algorithm and the abundance of available evidence, initially a simplistic description was considered valid.

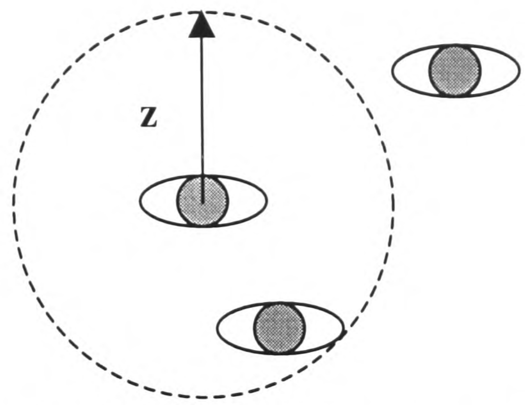


FIGURE 8-18: DEPICTION OF THE ZONE OF INFLUENCE. THE RADIUS, R, IS DEPENDENT UPON A NUMBER OF THE OCCUPANT'S ATTRIBUTES INCLUDING DRIVE AND SENIORITY.

A crude representation of visual awareness is also incorporated and is defined specifically in unison with the line-of-sight calculations described in Chapter 5. This is included as an initial step in representing the sensory perception of the occupant individually. If the occupants are in visual contact (see Section 5.4, Chapter 5) there is a possibility that they may perceive each other at greater distances than might normally be the case and act accordingly. The locations of the occupants involved are examined to determine whether they share the same *visibility index* (see Figure 8-19). This is a user-defined integer that determines whether locations are visible from particular vantage-points (for a full description of this process refer to Section 5.4, Chapter 5).

If the locations are deemed to be visible, then the occupants have the *possibility* of seeing each other. The likelihood of them doing so is also dependent upon the environmental conditions and whether either of the occupants is surrounded by other members of the occupant population, possibly restricting their visibility.

The visibility levels afforded to the occupant by the environment is extracted from the work of Jin [9,11], who established that the level of visibility is directly related to the extinction coefficient calculated for the smoke in the environment (see Section 2.5, Chapter 2 and Section 7.1, Chapter 7). The likelihood of the occupants being aware of each other is dependent upon these figures.

The physical impact of the surrounding population is implemented in a crude manner, assuming that if the occupant is surrounded by other occupants, then the occupant will *not* be visible. More complex geometrical calculations would require a three dimensional representation and a significant increase in the data available.

To introduce a stochastic and individual element into the calculation, the occupant's motivation is taken into consideration. Therefore, if both of the occupants are highly motivated, they are assumed to be actively seeking other members of their group and will therefore be more likely to be receptive to their presence. It might be argued that highly motivated occupants would be less likely to be interested in the existence of group members, given the perceived seriousness of the situation. However, given the existence of substantial evidence that social ties are not removed once occupants become motivated [1,4,85,58,207], the assumption is made that the position of the occupants within the group members is sufficiently important to encourage the reception of information, especially under conditions when this safety is most at risk. It is accepted that if the occupant is isolated within the enclosure then their receptiveness to the information relating to the location of other individuals may not be as elevated. Even under these conditions, a substantial amount of evidence exists suggesting the occupants still do not act in ignorance of the surrounding population. This representation of the occupant's ability to see the surrounding population requires a great deal more data.

For collective behaviour to occur, the method is therefore dependent upon the engineer to position the occupants in such a way that it is possible that they may influence each other's behaviour. In the current work, there is no means of actively 'searching' for absent or distant relatives. This development is left for future work.

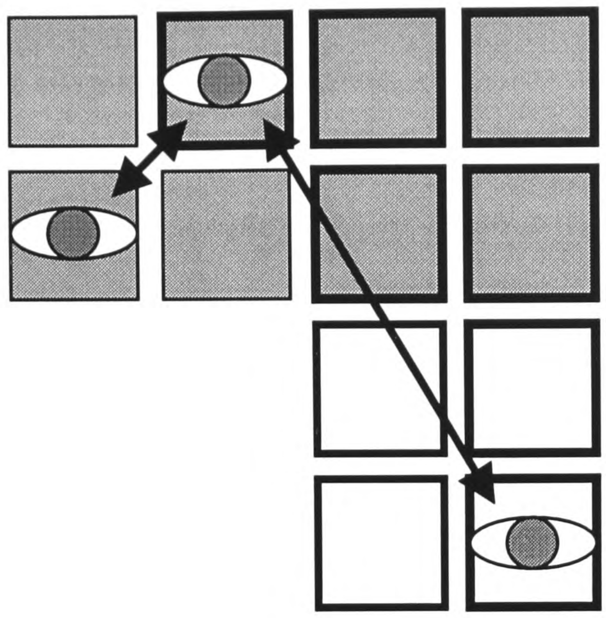


FIGURE 8-19: THROUGH IDENTIFICATION BY THE ENGINEER, NODES ARE DEFINED AS BEING VISIBLE. GIVEN THE APPROPRIATE CONDITIONS, THEY MAY THEREFORE COMMUNICATE. THE ARROWS REPRESENT VISUAL ACCESS BETWEEN OCCUPANTS.

As the existence of the unfamiliar is not considered by the occupant prior to the evacuation (or at least not in the same manner as the familiar), the relationships formed are *dynamic* and are considered continuously throughout the simulation. The occupant brings no information to the evacuation concerning an unfamiliar population other than the principles on which their everyday social life is based (these are the very principles that are continually overlooked in animalistic descriptions of occupant behaviour, see Section 2.1, Chapter 2). However, as the identity of the unfamiliar is by its nature less significant, the relationship is assumed to be *localised*, rather than being sought after. Any communication is therefore limited to those occupants who are adjacent to the object occupant's position. Within buildingEXODUS this implies that the occupants have to be within 0.5m of each other. This is important, as no memory of these occupants previously exists, precluding long distance or search calculations being commenced. This is a secondary means by which to represent the strength of the social ties between occupants.

COMMUNICATION: *THE PROVISION OF RELEVANT DATA*

A vital component in the response of familiar or unfamiliar occupant, is the ability to communicate with the surrounding population. This communication may provide the only information concerning a rapidly changing environment reflecting a more accurate and contemporary understanding of the situation in comparison with that provided by the signage or alarm systems.

Within the algorithm, the information that can be communicated between familiar and unfamiliar occupants (see Figure 8-20) involves

- The existence and the extent of smoke, according to the occupant's experience.
- The motivation of the occupant. This effect will be dependent upon the seniority of the individuals involved, so that more 'respected' members of the population will have a greater influence.
- The existence and use of otherwise unfamiliar exits, through the transmission of the door vector.
- The requirement to evacuate in response to the existence of a hazard, through the adoption of response times.

Although other information may in reality be communicated these were considered the most important in their impact upon occupant behaviour [199,218]. Communication is achieved through the transmission and reception of the above pieces of information. Once the occupants are deemed to influence each other (either by being adjacent or being within each other's zone of influence), their internal attributes are compared. If omissions appear in their knowledge of the incident, they may be corrected through the addition of new information. This is literally achieved through the copying of the details (be they numerical or logical) from one occupant to another. This might include the awareness of a new exit, the reduction of a lower response time, the recognition that there is a smoke hazard, etc.

Once communication has occurred, the occupant must decide upon the significance and accuracy of the information and select an appropriate response. That is once an omission is identified in an occupant's awareness, the source of this information is examined for both reliability and priority in comparison to other sources. The adoption of received information is strictly defined according to the occupant's position within the social hierarchy of the surrounding population. This is implemented using the *seniority* system described in Section 5.3, Chapter 5. In the familiar, this hierarchy will be shaped through day-to-day activities, such as in family life. In emergent social structures, these may be based around general social principles (such the assumptions based on gender and age) or through assumptions based on the location (the relationship towards staff, for instance). This method shares a number of common features with the examinations of

Johnson, Feinberg and Johnson [49,50,207] ,Klein [199], Fruin [220] , Hewitt and Jones [58], and Bales[219].

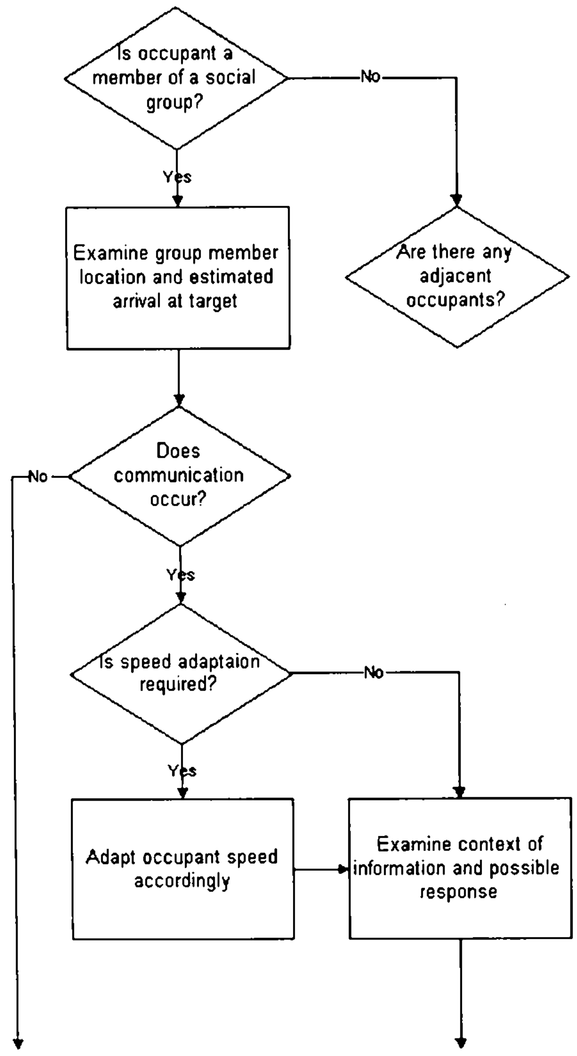


FIGURE 8-20: FLOWCHART REPRESENTING PROPOSED BEHAVIOUR

Although a simplification, the following hierarchical system is used to determine an occupant's reaction to new information (see Table 8-13). Rejected information is not discarded, but is stored. This allows information to be reinforced by the cumulative arrival of similar pieces of information from other sources. This point of view is reinforced by Feinberg and Johnson claim that,

"The time required for a decision is clearly a function of the clarity of the cues provided"[207]

If this is the case and if the cumulative arrival of information implicitly clarifies the situation, then the representation of the occupant reaction as a cumulative process is not unsupported.

Each arrival of new 'packets' of information increases the probability of the occupant accepting it as being accurate [1,4,57,58,93,218,219]. The influence of the subsequent sources of information will be dependent upon the perceived priority of the source.

The weight (perceived importance) of the information supplied by each occupant (w_i) is dependent upon their seniority (s_i, see Section 5.3, Chapter 5) and the seniority of the subject occupant ($s_{subject}$), motivation (D_i) and the motivation of the subject occupant ($D_{subject}$) and their relationship with the subject occupant (r_i,), such that

$$w_i = \alpha.\max(s_{i_i} - s_{subject}, 0) + \beta.\max(D_i - D_{subject}, 0) + r_i \quad (82)$$

where α and β are scaling coefficients, reflecting the relative importance of seniority. The relationship between the occupants is given highest priority. Therefore if the occupants are socially related and there is an appropriate discrepancy in the seniority levels, then the passing of information is guaranteed.

The priorities described in Table 8-13, are reflected in the figures produced by this equation, so that the eventual figure weights the likelihood of a piece of information being adopted according to the identity of the occupants involed. The probability of accepting a piece of information, given that it has been reinforced through continued levels of communication, at time interval $t+1$ is therefore

$$p_{t+1} = p_t + \sum_{i=1}^{n} w_i \theta \quad (83)$$

where θ is the default coefficient introduced to represent each packet of information (set to 0.01). This was derived through sensitivity analysis and is a purely internal coefficient. This probability, p_{n+1}, will then be compared against a random number generator at each time interval to determine whether the information has been adopted.

An example is provided to clarify this system. Two occupants are unaware of the existence of an emergency. One of the occupants (occupant A) is a junior member of a group (a child, for instance). The other occupant (occupant B) is not a member of a collective. A number of the members of occupant A's group pass the stationary occupants. Due to their proximity, occupant A is able to receive information from them. That is

$$d < \max(z_i) \quad (84)$$

where d is distance between the occupants and z_i is the radius of the zone of influence of the occupants involved (see equation (81)).

Given that the group members are senior to him, he accepts the information as being reliable and of a high priority. He therefore responds to the emergency and also adopts the same target. Occupant B however has a different reaction. He does not receive the information until the group members are *adjacent to him.* At this stage, the information imparted is stored but is given a low priority and does not engender a response. The continued reception of this information from the group members convinces occupant B of the seriousness of the incident (the probability of responding becomes sufficiently high) and he then responds. The information that is transferred in this manner can relate to the existence of the incident and the target of the occupants involved. This calculation is made according to

$$p_{t+1} > x \tag{85}$$

where x is a random number. That is not to say that this process is entirely random, as, on the contrary, it is dependent upon the identities and experiences of the occupants involved, as represented in equations (82) and (83). However, to generate a stochastic element to the algorithm, random number generators had to be involved in the calculation over which the engineer has no control.

Therefore as an occupant interacts with an increasing number of other individuals, who are aware of relevant information, the likelihood of adopting that information (and therefore acting upon it) increases cumulatively due to social reinforcement of the information.

TABLE 8-13: PRECEDENCE OF INFORMATION ADOPTION.

Status of Provider	Status of Receiver	Probability of Accepting Information	
		Pre-existing	Emergent
Senior	Junior/ Equivalent	Guaranteed	High Probability
Equivalent	Equivalent	Moderate Probability	Moderate Probability
Junior	Senior/ Equivalent	Low Probability	Low Probability

The relationship between occupants that are defined as sharing a gene will, due to the existence of an established relationship, be more influential than the other occupants [49-50,207,218]. An exception to this rule is the staff *in situ.* Staff members can be identified separately and are effectively related to the entire occupant population. The information that they impart is seen as more credible than that of the rest of the occupant population, due to their assumed local knowledge and expertise. However, the algorithm is flexible enough to represent the differing levels of assertiveness exhibited by members of staff, so that their motivation can provide an additional incentive to adhere to their advice [97]. The information that these occupants hold will therefore be likely to be imparted, and more likely to be adopted once received.

The motivation of the surrounding population has a different type of impact upon the individual, as it is not *used* by the subject occupant, but instead *affects* the subject occupant. The impact is again dependent upon the seniority of the occupants involved. Maintaining the logic discussed previously, senior occupants will have a greater influence than their more junior counterparts. The effect is calculated according to a weighted average of the drive figure of those occupants influencing the subject occupant. The final drive figure will be a composite of this weighted average and the occupant's original drive figure (see Figure 8-21).

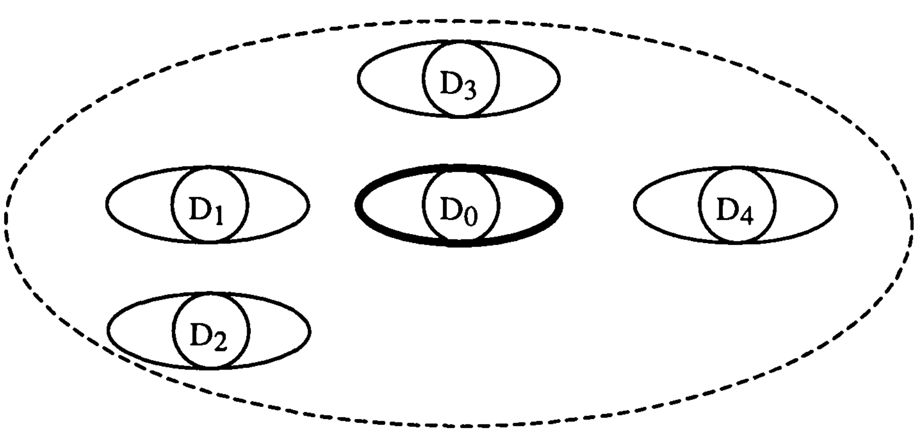


FIGURE 8-21: THE MOTIVATION OF THE SURROUNDING OCCUPANTS CAN INFLUENCE THAT OF OCCUPANT D_0.

The calculation of the weighted motivation of central occupant, given the existence of other occupants, is made according to

$$D_0 = \frac{(\mu - n)s_0 D_0 + n\sum_{i=1}^{n} s_i D_i}{s_0 \mu} \qquad (86)$$

where μ represents the maximum number of occupants, D_i represents the drive of occupant i and s_i represents the seniority of occupant i.

The system is information dependent. However, information is not distributed evenly throughout the population. Information location is dependent on the location of individual occupants in relation to the information sources in the environment. This disparity causes communication between occupants (familiar or unfamiliar).

The representation of the communication process within the buildingEXODUS model is a compromise in that physical restrictions are imposed upon what is essentially a social device. This is due entirely to the attempted representation of the priority given to the information received and the likelihood of initially receiving the information.

ADAPTATION: *THE PERFORMANCE OF AN ACTIVE RESPONSE*

The similarity of the information that can be passed between familiar and unfamiliar occupants is based upon the assumption that *occupants do not become anti-social when faced with extreme circumstances*. Instead the occupants maintain their social roles and general civility [51,55]. This extends to the initially unfamiliar population, but the extent of information passed may differ, depending upon the circumstances (both *proximity* and *priority*).

Once the occupant relationships have been processed and the relevant information has been communicated, the subsequent occupant actions can be determined. All occupants may

i. *Communicate* the information available to them
ii. *Redirect* their movement in response to new information
iii. *Respond* to the provision of information denoting the existence of an emergency
iv. *Modify their motivation* according to the perceived motivation of the surrounding population
v. *Adapt their travel speed* to maintain the group formation.

To maintain the integrity of the group, joint decisions have to be agreed upon, which generally converge to those of the most senior members of the group [51,52,207]. This is achieved through the adoption of the information from the most senior/motivated occupant available. Once faced with unexpected events, the group therefore reaches a consensus concerning their immediate choice of action, allowing the group formation to be maintained [51,52]. This information would then be disseminated throughout the group by its members in the manner described previously. This is important in relation to occupant redirection and the reaction of the occupant to the existence of a smoke barrier, or crowd formations (see earlier in this chapter). Although in emergent social relationships a unified approach may evolve due to the dissemination of relevant information, there is no responsibility initially on the senior members of the population to align their behaviour or maintain their proximity to less senior members.

The primary means by which the group formation is maintained is through the alignment of an action, e.g. adoption of the same target, responding at the same time, etc. To consolidate this, group maintenance is assisted through occupant travel speed adaptation. As noted by Feinberg and Johnson,

"Families move as units and remain together" [207]

The proposed development is based on two assumptions. Firstly, *the senior members of a group will generally maintain their role within the group and will continue a level of responsibility throughout the evacuation.* This is supported by a large amount of secondary data [51,52,57,58]. Secondly, *a significant manifestation of this responsibility is the continued close proximity of the group.* Therefore familiar occupants have an additional alternative open to them, namely that of adapting their travel speed to maintain the group formation.

The five behavioural actions highlighted are consistent with the developments in the response to the environment, familiarity and the response of the occupants to excessive crowding around exits, described in other sections. These activities are all reliant upon the communication of information, either from the environment or, from other members of the population.

The manifestation of these abilities within the buildingEXODUS model is now briefly addressed. The ability to transfer information was addressed at length in the previous section. It involves the copying of pieces of data between occupants. This data resides in the occupant's memory until it is confirmed through analysing the gravity of the situation and the seniority of the communicator or though cumulative reinforcement over a period of time.

The ability of the occupant to redirect is based around the reception of a new target, in this case the target is an exit. This process may be instant or through cumulative reinforcement, according to the identity of the occupants involved and their previous social relationship [57,58]. This might be accepted immediately or be calculated cumulatively according to equations (82) and (83). Once the decision to accept the information is made, this exit will be stored. Any future movement will then be made in respect of this goal. This is fundamental to the occupant reaction to crowd formations and environmental barriers, described elsewhere in this chapter.

The adaptation of the occupant's response time reflects two subtly different behaviours. Firstly, if an occupant is static and is passed by occupants reacting to the evacuation, the occupant may adopt a response time of zero. At the next simulated 'tick' ($1/12^{th}$ of a second), the occupant will then begin to evacuate. Again this process may be instant or through cumulative reinforcement. The adoption of another occupant's response time is also a secondary device to maintain group integrity. If a number of group members are not responding to the emergency and are able to influence each other, their response times will converge to that of the most senior member, therefore aligning these actions, allowing them to respond after an equivalent time.

Finally, the occupant's motivation is affected by the surrounding occupants [218]. This effect is calculated according to the attributes of the surrounding population. This can have an important impact especially when coupled with the dynamic behavioural regime described in Chapter 7.

The adaptation of the occupant to other members of their group (specifically relating to the alteration of their travel speed) is dependent upon the provision of new information concerning group members. Therefore in pre-existing relationships, occupants are also able to receive and transmit:

- *the existence and position of those group members within the zone of influence.*
- *the estimated time of arrival of the other group members.*

The location of other group members is examined at each $1/12^{th}$ of a second to determine whether the group members can be involved in an information transaction. The ability to estimate the arrival time of themselves and of others enables adaptation to occur. In this case the occupants can adapt their speed to maintain their proximity with the other group members. Those occupants who are not familiar with each other are not compelled to maintain their proximity to the other members of the population, as are the senior members of the collective. Their altruism extends to the relaying of important information that is itself vital for the outcome of an evacuation.

The maintenance of the group formation occurs though the self-regulation of the occupant's travel speed allowing them to communicate and interact with the other members of the group. This process is represented in Figure 8-22. Here the senior occupant is positioned closer to the shared exit target of the group (this unified goal may have been due to the communication of the door vector of a senior occupant, or through coincidence). The senior occupant estimates their arrival time at the exit, given their present speed and the distance that is to be covered. Other considerations may also be analysed, which are addressed later in this chapter. The occupant then performs this action for the rest of the members of the group from whom information can be received. *The senior occupant then adapts their travel speed to enable the delayed members of the group to reform.* As this calculation is performed frequently, other possible delaying mechanisms, such as the resolution of conflicts, are accounted for. This process is fuzzy, in that the estimations are not perfect, causing a slightly inaccurate response.

The estimated time of arrival of an occupant is calculated according to

$$t_i = \frac{d_i}{s_i} + \varepsilon \tag{87}$$

where d_i is the remaining distance to the occupant's target, s_i is the occupant's present travel speed and ε is a random number (0-0.1) reflecting the necessary inaccuracies of the calculation. The occupant then examines the estimated time of arrival of the occupants in the group from whom information can be received. The slowest of these times, t_{slow}, are stored such that

$$\max_{i=1,i\neq j}^{n}\left(t_1, t_2, \ldots t_n\right) = t_{slow} \tag{88}$$

This calculation is not made independently of the occupant's identity. Therefore, an occupant's arrival time will only be stored if the occupant is less senior than the observing occupant. This represents the more senior occupants taking responsibility for the more junior occupants. The occupant's new calculated speed is therefore

$$s_j' = \frac{d_j}{t_{slow} + \varepsilon} \tag{89}$$

Although this appears to endorse the social dichotomy so criticised previously, the algorithm subtly caters for social adaptation. Those members of the population to whom social significance is attributed can be adopted into the group. These are then equal members of the group and are involved in the calculations described previously. This is therefore completely consistent with the more civilised view of occupant behaviour adhered to by Quarantelli, Sime etc [4,55].

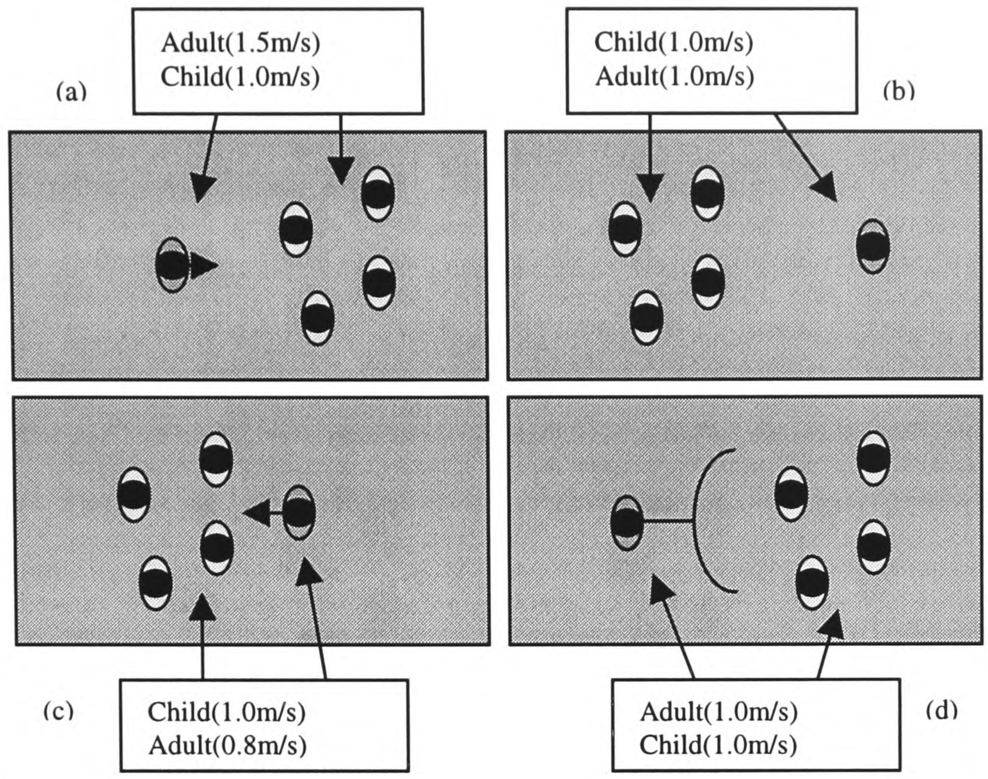


FIGURE 8-22: INITIALLY(A) ADULT IS BEHIND THE GROUP OF CHILDREN, TRAVELLING MORE QUICKLY. ADULT HAS OVERTAKEN CHILDREN AND REDUCES SPEED ACCORDINGLY (B). FURTHER REDUCTION OF SPEED IS REQUIRED(C). THIS CAUSES THE OCCUPANT TO FALL BACK INTO THE PACK. FINALLY, THE OCCUPANT REMAINS BEHIND CHILDREN, WHICH HAVE BEEN IDENTIFIED AS A RESPONSIBILITY.

An important difference between this definition of collective behaviour and a number of those used in other models [8] is that a collective is *formed* from a number of individuals. Once the collective is formed *the occupants still remain individuals*. It is therefore their propensity to align actions and respond in unison that defines them as a group; *groups are formed from and by individuals*. This differs radically from other representations in which the group is seen as a single entity that moves and makes decisions *en mass* [8]. The proposed method enables the type of analysis and communication cited in Beverly Hills Supper Club where the group 'discussed' potential group decisions. It also allows members to be added to the groups from outside.

The proposed system is based upon the assumption that a co-operative behaviour is common and may take a number of forms. It is not guaranteed in the general population, although if absent is not automatically replaced by selfish and competitive behaviour. Amongst familiar occupants, it is expected and is centred on the transferral of information and the subsequent behavioural responses. Groups therefore exist in the social relationships between members rather than as a separate entity. As such they may be dynamic in both membership and in structure.

8.3.4 VERIFICATION

Due to the complexity of the proposed behaviour, it is impractical to examine all of the facets outlined in a single example (see Table 8-14). It is important to demonstrate the effectiveness and the appropriateness of the different forms of behaviour where possible. The following cases are therefore designed to deal with a number of the most significant aspects of the behaviour described:

- 8.3.41 The ability of groups to maintain proximity given difficult circumstances
- 8.3.42 The extent to which occupants communicate given their social relationships and the introduction of occupant location as a factor in this process
- 8.3.43 The impact of relatedness and seniority upon the acceptance and perception of information
- 8.3.44 The ability of occupants to control the travel speed to reform the collective
- 8.3.45 The ability of separated occupants to perceive each other through line-of-sight and react accordingly.

TABLE 8-14: VERIFICATION CASES.

Case	Population	Geometry
8.3.41	44 occupants (8 group members)	Irregular, 1 exit
8.3.42	13 occupants	Irregular, 2 exits
8.3.43	24 occupants	20m x 5m, 1 exit
8.3.44	7 occupants (related/unrelated)	20m x 5m
8.3.45	81 / 2 occupants	20m x 5m

CASE 8.3.41

The ability of a pre-existing social group to maintain its formation during an evacuation is examined in verification case 8.3.41. The social structures present during the simulation are established prior to the simulation through the occupants being attributed with an identical gene. A complex asymmetric geometry has been designed expressly to provide difficulties for the group members to maintain their proximity with each other (see Figure 8-23).

An unfamiliar population of 36 default occupants is simulated. These are positioned centrally, approximately 25m from the exit. A small group of related occupants is positioned at the most distant location from the exit (approximately 30m from the exit) to ensure that they encounter this high-density group of unfamiliar occupants. This situation therefore produces another hindrance to the maintenance of the group.

The related group is made up of 2 senior and 6 junior members. The senior members of the group respond instantly. The junior members of the group do not initially respond to the event, with an attributed response time of 20 seconds. The senior group members are positioned such that they are able to communicate with the junior members of the group, *en route* to the exit.

The senior members of the group have travel speeds of 1.5m/s while the junior members of the group have travel speeds of 1.0m/s. This inequality is designed to increase the difficulty in maintaining the group formation. The other non-group occupants are all attributed with travel speeds of 1.5m/s and respond instantly.

Four severe bottlenecks are included to further test the group's ability to maintain their close proximity.

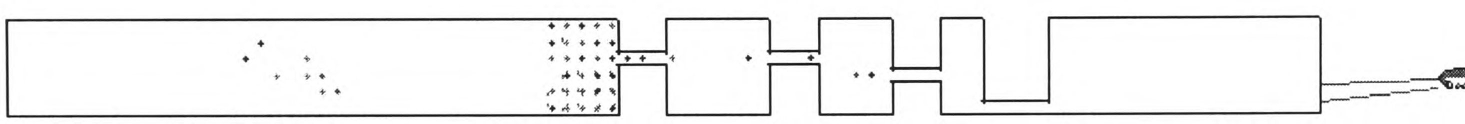


FIGURE 8-23: REPRESENTATION OF THE COMPLEXITY OF THE GEOMETRY INVOLVED.

Two separate scenarios are examined. Scenario 8.3.412 includes the 'group' behaviour, Scenario 8.3.411 omits this behaviour, but maintains the discrepancies in the occupant population concerning the response times. Each scenario is repeated five times in order to produce a range of results.

RESULTS-CASE 8.3.41

This case provides a means to ascertain the compactness of the grouping mechanism. The evacuation times and the evacuation position of related occupants are used as an index of compactness. These two figures will provide some indication of the eventual distance between members of the collective. If the members demonstrate large differences in the finishing position and their evacuation times, then the ability of the group to maintain its proximity under the proposed behaviour would be questionable.

If we examine Table 8-15, Table 8-16 and Table 8-17, a number of important developments can be observed. Firstly, the introduction of group behaviour has not *improved* the total evacuation time, indeed the opposite seems to be true. This can be seen from the 15% increase in the evacuation times of Scenario 8.3.412 over Scenario 8.3.411 (see Table 8-15).

TABLE 8-15: EVACUATION TIMES PRODUCED IN CASE 8.3.41.

Validation case	Evacuation times(secs)
Scenario 8.3.411	116 [115-119]
Scenario 8.3.412	133 [124-138]

In scenario 8.3.411, communication is not included, so that the former group members do not communicate and make no attempt to reform into a group. This is reflected in the final positions of the group members (see Table 8-16), demonstrating an increase in the distribution of finishing positions. The result is relatively modest due to the congestion preventing the senior occupants progressing further. However not only is the discrepancy increased, but the senior occupants, due to their faster travel speeds, finish *ahead* of the slower junior occupants. The evacuation times of the object occupants (latterly group members) have also altered reflecting the ability of the senior group members to maintain their optimal speed (see Table 8-17).

In Scenario 8.3.412, where the proposed behaviour is included, the group members do maintain a closer proximity than if no collective behaviour is included, even though they encounter a large degree of disruption to their egress route. This can be seen from examining Table 8-16 and Table 8-17. Here, the ability the group members to maintain their proximity is evident through the similarity in their finishing positions and in their evacuation times. These are far closer than under the present model where substantially larger discrepancies exist.

Also apparent is the fact that the senior members of the group consistently finish *after* the junior members of the group; effectively shepherding the junior occupants to safety (see Table 8-16). Initially, the senior occupants begin to evacuate. The movement of the senior group members and therefore the existence of a potential hazard is transmitted to the junior members of their group who in turn become mobile, responding to this information.

Once the junior occupants fall within the zone of influence of the senior occupants (approximately 6.0m, according to equation (81)), information concerning the need to respond is related. The likelihood of this information being adopted is increased due to the significant differences between the seniority levels of the group members. Given these factors and the small initial distance between occupant members, the junior members of the group are made aware of the evacuation within 5 seconds. Without this prompting they would have remained stationary for a further 15 seconds.

Therefore, all of the group members move off almost in unison. It is at the first 'bottleneck' (see Figure 8-23) that the occupants interact with the rest of the population. This initially causes the group to separate through the increase in the population density and the resolution of conflicts.

TABLE 8-16: AVERAGE FINISHING POSITIONS OF THE GROUP MEMBERS OUT OF A POPULATION OF 44

Status of Group Member	Behavioural Model	
	Present (8.3.411)	Proposed (8.3.412)
Junior	38.7 [35-41]	39.9 [39-41]
Senior	35.8 [31-42]	41.8 [39-43]

TABLE 8-17: AVERAGE EVACUATION TIMES OF THE GROUP MEMBERS

Status of Group Member	Behavioural Model	
	Present (8.3.411)	Proposed (8.3.412)
Junior	105 [98-109]	128 [120-130]
Senior	100 [92-111]	131 [118-135]

Once through the bottlenecks any disparity between the distances of the occupant from other members is corrected through the adaptation of the occupant's travel speed (according to equation (81)). This correction produces the relatively small discrepancies in the final positions of the group members (see Table 8-16) and the recorded evacuation times of the group members (see Table 8-17). This close proximity of the group members is all the more convincing as the junior members of the group are attributed with significantly slower travel speeds than the senior group members.

The comparison between the evacuation times suggests an important observation; *the imposition of group behaviour does not necessarily provide an advantage to all of the members of the group.*

It should be remembered that this geometry was specifically designed to increase the distances between the members of the group. The fact that there is still a difference between group and non-group members highlights the robust nature of this behaviour.

CASE 8.3.42

In validation case 8.3.42, the adoption and communication of the door vector and of the existence of the emergency is examined. This case is therefore dependent upon the use of the door vector described in Section 7.3, Chapter 7.

The geometry used has 2 exits, both of which are 0.5m in width. The use of these exits will not be uniform as one of them is defined as a fire exit (see Figure 8-24).

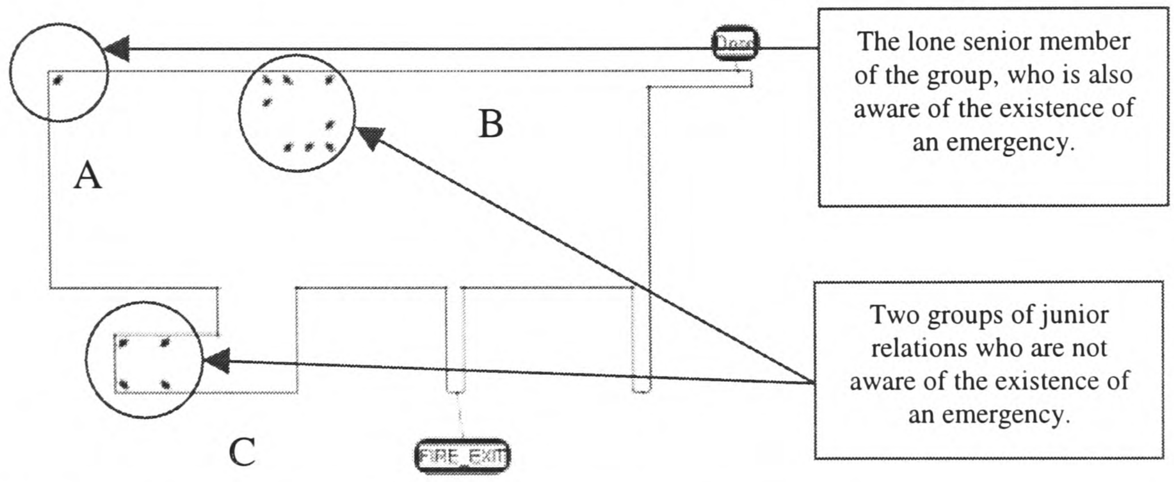


FIGURE 8-24: GEOMETRY USED TO EXAMINE IMPORTANCE OF COMMUNICATING EXIT INFORMATION

All of the 13 occupants that are simulated are attributed with the same social gene, identifying that they are all *socially related.* Of the 13 occupants, only one is senior enough to be aware of the fire exits. As the familiarity of the occupants is stochastic, the awareness of even the senior occupant of the fire exit cannot be guaranteed. This situation has been engineered to demonstrate the ability of occupants to communicate the existence of unfamiliar exits.

As an additional factor, the group is split into 3 distinct sub-groups (see Figure 8-24). The senior group member is positioned at the most distant point from the exits, at position A. The junior members of the group are positioned in separate locations (positions B and C), outside of the senior members' zone of influence. The senior occupant responds instantly, while the junior group members respond after 20 seconds.

Two scenarios are performed, Scenario 8.3.421 and 8.3.422. In Scenario 8.3.421, no communication is allowed, maintaining the present behavioural assumptions. In Scenario 8.3.422 the proposed behavioural developments are included. In both scenarios the occupant familiarity is reflected using the door vector system, allowing a more accurate comparison to be made between the results produced. Each scenario is repeated 5 times.

RESULTS-8.3.42

During Scenario 8.3.421 no communication occurred. As no communication occurred between the occupants, they respond at different times. The senior occupant responds immediately while the other occupants respond after 20 seconds. This is demonstrated in Figure 8-25, where the arrival times of the occupants is clearly affected by their initial response times. The time discrepancies for the first occupant evacuating can be explained through the senior occupant adopting different exits between the simulation runs, due to the stochastic nature of occupant familiarity. The variation in the arrival of the first occupant is therefore due to the differences in the distances covered to the two exits.

The junior occupants arrive after they have exhausted their initial response time. All of the junior occupants use the main exit, as they are unaware of the fire exit.

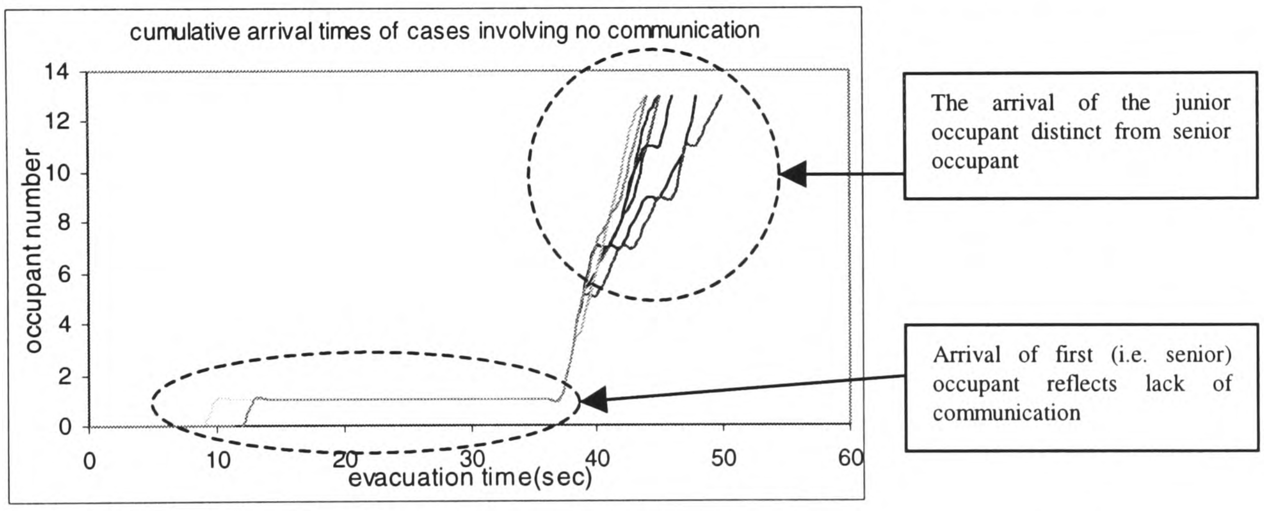


FIGURE 8-25: CUMULATIVE ARRIVAL CURVES OF SCENARIO 8.3.421.

This can be seen more clearly in Figure 8-25 where some variation in the eventual arrival of the junior occupants can be seen. This variation is due to the resolution of conflicts in the standard buildingEXODUS model.

In Scenario 8.3.422, if the senior group member is aware of the fire exit, he will move towards this exit, as it provides his closest point of exit. If this is the case, he will be able to communicate to *all* of the junior group members (situated at B and C) that they should evacuate, as well as of the existence of the fire exit. This is because the junior occupants are approximately located along his path of egress, falling within the senior occupant's zone of influence, enabling the senior occupant to communicate to all of them. The outcome of this is that the integrity of the group is established and then maintained, as the occupants move off almost simultaneously and move to the same target exit. This simultaneous response of the occupants is not the only mechanism maintaining the group proximity, as it is also affected by the adaptive speed calculations outlined in equations (88), (89) and (90).

If the senior group member is unaware of the existence of the fire exit, he will choose the nearest exit from the remaining exits in his door vector; that being the exit positioned at the top right-hand corner of the geometry (see Figure 8-24). In this case, one of the occupant groups (at position C) is isolated, falling outside of the senior occupant's zone of influence, preventing communication.

This behaviour is reflected in Figure 8-26 where two distinct patterns can be identified. The first pattern, which corresponds to evacuations requiring approximately 20 seconds, demonstrates the senior group member communicating to the entire junior population and shepherding them to the fire exit (see Figure 8-26 (a)). The occupants therefore exit in a smaller, more compact time period. The second pattern represents the lower degree of communication, therefore generating a greater distribution of evacuation times. Here one of the junior groups (position C) is not involved in the communication process and therefore responds after 20 seconds (see Figure 8-26(b)).

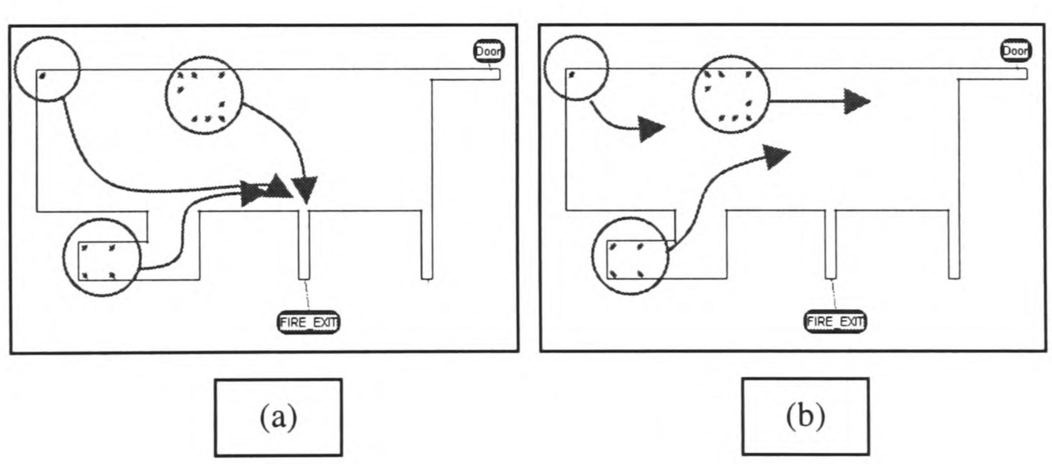


FIGURE 8-26: DIVERGENT OCCUPANT PATHS ACCORDING TO THE LEVEL OF COMMUNICATION.

The quantitative impact of the different levels of communication is represented in Figure 8-27 and in Table 8-18. The cumulative arrival curves fall into two categories reflecting the behaviour described previously. The first collection of curves is smooth and steep reflecting the small distribution in arrival times due to the general availability of information. The second collection of curves are far less even reflecting the large variety in the arrival times caused by the differences in the information levels.

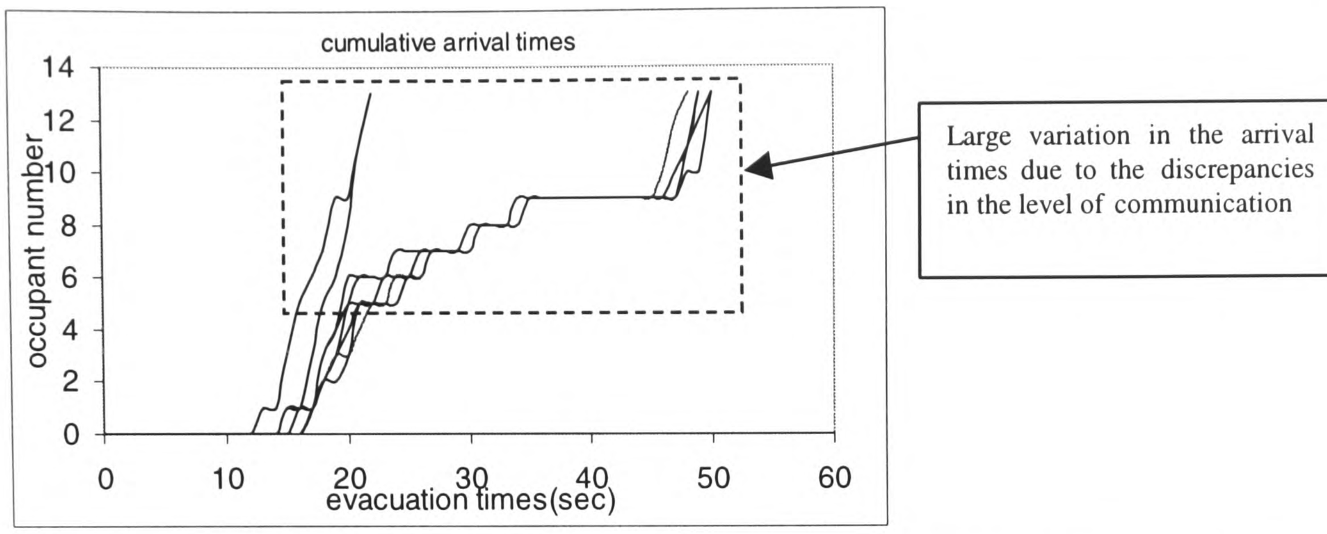


FIGURE 8-27: CUMULATIVE ARRIVAL CURVES OF SCENARIO 8.3.422

The evacuation envelope is significantly increased in Scenario 8.3.422. This is due to the impact of the extent of communication within the simulation (from Table 8-18). In Scenario 8.3.421 the envelope is reduced, with the variation being entirely dependent upon the resolution of conflicts.

TABLE 8-18: EVACUATION TIMES FROM 8.3.42.

	SCENARIO 8.3.421	**SCENARIO 8.3.422**
EVACUATION TIME(SECONDS)	44.9 [43.3-49.3]	44.3 [21.4-49.2]

The variation in evacuation times is due to the isolated occupants only responding after 20 seconds, therefore delaying their evacuation times significantly, once communication has not occurred during Scenario 8.3.422. The average is maintained, due to the advantages that communication, in this case, might bring.

This case has identified a number of important aspects of the proposed behaviour. Firstly, that the proposed behaviour doesn't necessarily reduce the evacuation times in comparison with reduced level of communication. Secondly, the behaviour exhibited is dependent on a number of factors including *familiarity, seniority* and *location*, all of which would be evident in an actual evacuation. Finally, the behaviour varies between simulations and these variations are not simply limited to fluctuations in the evacuation times, but reflect significant differences in the qualitative behaviour exhibited.

CASE 8.3.43

In these scenarios the impact of the exact identity and relationship of occupants is examined. The occupant awareness of the evacuation is used as an indication of the communication process. Initially, four occupants are evacuating from a simple 20m x 5m geometry with a single 1.5m exit. Their path of egress causes them to interact with 20 non-evacuating occupants. The relationship and identity of all of the occupants involved is examined to demonstrate the sensitivity of the algorithm to these factors and their impact upon the communication process and therefore upon the overall evacuation.

TABLE 8-19: DESCRIPTION OF THE DIFFERENT SCENARIOS EXAMINED IN 8.3.43

	Description		
Scenario	**Social Relationship**	**Identity of occupants**	**Behavioural model**
8.3.431	N/A	4 senior/20 junior	Present
8.3.432	N/A	24 junior	Present
8.3.433	Related	4 senior, 20 junior	Proposed
8.3.434	Related	24 junior	Proposed
8.3.435	Unrelated	4 senior, 20 junior	Proposed
8.3.436	Unrelated	24 junior	Proposed

From Table 8-19 the main variables examined are the existence of relationships between the occupants and the occupant position in the particular social hierarchy.

RESULTS- CASE 8.3.43

When no group behaviour is implemented in cases 8.3.431 and 8.3.432, no information is communicated. Therefore the identity and relationship of the population is irrelevant to the resultant behaviour as can be seen in Figure 8-28, providing no significant differences in the results of the two scenarios. The occupants react immediately to the call to evacuate (the four furthest from the exit), evacuate and pass through the remaining occupants causing the critical step in the arrival curve. After 20 seconds the static occupants then respond causing more conflicts to occur around the exit.

These results should be contrasted with the results produced once the proposed behaviour is enabled. If four related 'senior' occupants pass through a non-evacuating/related junior population who are unaware of the evacuation (case 8.3.433), efficient and immediate communication occurs, with the junior occupants moving off *prior* to the arrival of the senior occupants. Communication is *guaranteed* once the junior occupant falls inside the zone of influence surrounding the senior occupants. It should be remembered that once mobile, the junior members could also convey information, although the success of this communication is not guaranteed. They may therefore alert each other before receiving information from the senior occupant. The 'junior' occupants are effectively collected and shepherded to the exit, producing the shortest evacuation times, averaging 24.6 seconds (see Figure 8-28 and Table 8-20).

Although this collective action causes some congestion at the single available exit due to the close proximity of the group members, the disadvantage caused by the delaying effect induced is more than compensated for by the avoidance of the junior occupant's response times. This congestion is affected further by the faster moving occupants (in this case the senior occupants) delaying their movement, in order to shepherd the slower moving occupants.

If the same population is simulated, except that they are now unrelated (case 8.3.435, where the occupants do not share a gene), the occupants have to be closer together to allow communication to occur, due to the dynamic representation of non-collective altruism (see Figure 8-28). This produces an uneven evacuation arrival curve, as there is no guarantee that information will be acted upon or perceived, or indeed that the occupants will achieve adjacency, allowing communication. This therefore increases the overall evacuation time by 21.1% in comparison to the evacuation times of 8.3.433.

In 8.3.434 the population consists entirely of related junior occupants, a far less efficient evacuation is evident with a 47.5% increase in the evacuation time over 8.3.433. This is due to the increased time it takes for the information to be passed between occupants caused by the credibility gap of receiving information from a junior occupant [199].

TABLE 8-20: EVACUATION TIMES PRODUCED DURING THE SCENARIOS OF 8.3.43.

Scenario	Evacuation times (secs)
Case 8.3.431	34.8 [33.8-36.1]
Case 8.3.432	34.2 [33.3-35.3]
Case 8.3.433	24.6 [23.8-26.1]
Case 8.3.434	36.3 [34.4-37.8]
Case 8.3.435	29.8 [29.3-31.3]
Case 8.3.436	31.7 [31.2-32.8]

If the junior occupant population is now unfamiliar with each other (8.3.436) the communication is still further reduced. This causes the generation of a disjointed cumulative arrival curve. This curve is not dependent upon the exit attributes, as the occupants are even more dispersed in their arrival (see Figure 8-28). This also lessens the congestion evident at the exit and eventually slightly reduces the evacuation time in comparison to 8.3.434, although still 28.9% higher than 8.3.433.

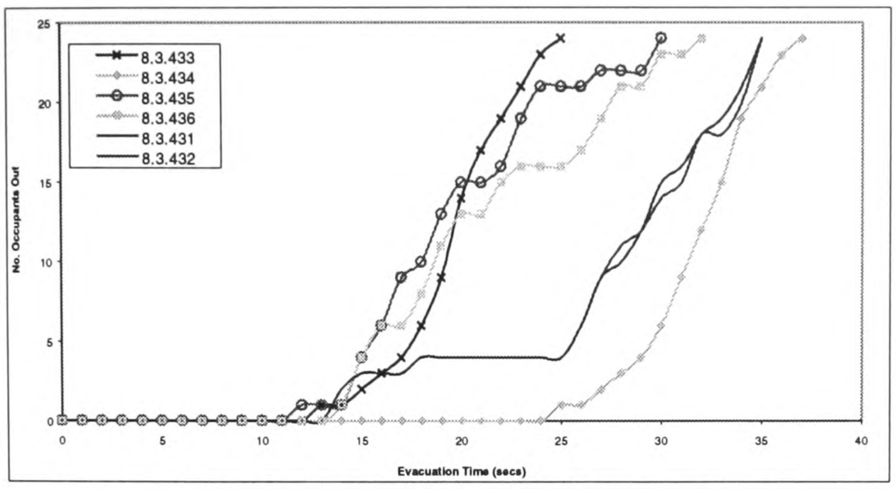


FIGURE 8-28: EVACUATION CURVES GENERATED IN THE SCENARIOS OF 8.3.43

The qualitative variations can be better appreciated from examining Figure 8-29. The manner in which the occupants interact is fundamental to the eventual form that their evacuation takes. In Figure 8-29, three distinct forms of occupant interaction take place:

- No communication occurs. (validation 8.3.431-8.3.432)
- Dependency interactions, where the senior occupants communicate and adjust their own actions accordingly (validation 8.3.433)
- Emergent Communication, where, according to the identity of the occupants, information is passed, but no other peripheral actions are taken (validation 8.3.434-8.3.436)

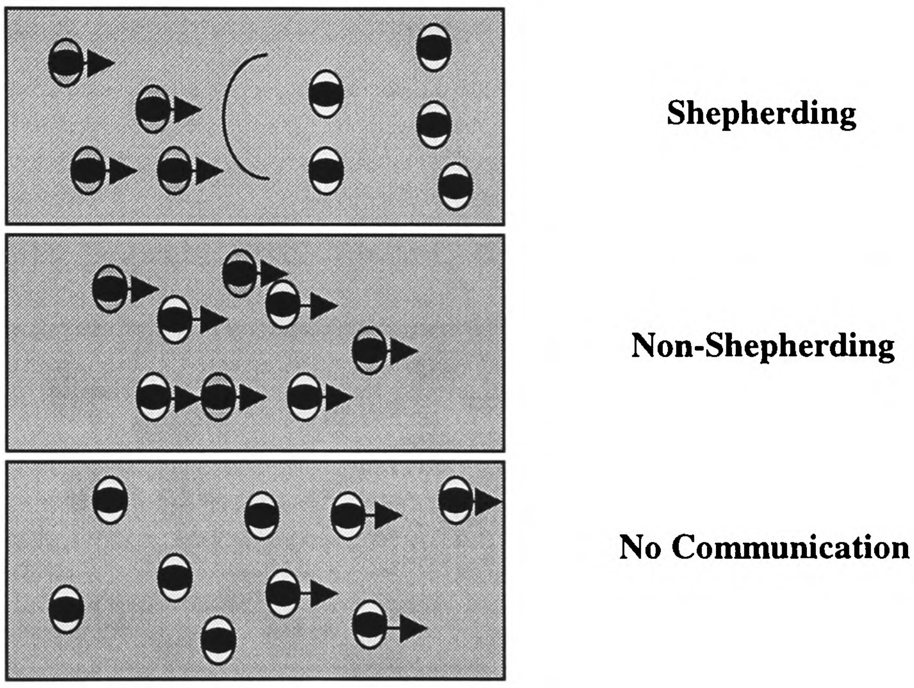


FIGURE 8-29: DESCRIPTION OF THE OCCUPANT BEHAVIOUR IN RESPECT TO OTHER OCCUPANTS. CASES 8.3.433(TOP), CASES 8.3.434-3.436 (MIDDLE) AND CASE 8.3.431-2(BOTTOM)

The significance of these results is that they demonstrate the extent and complexity of the behaviour that is generated through the introduction of the new behaviour. As stated before, the adoption of group/communicative behaviour is not necessarily beneficial to the occupants involved and in some of the scenarios examined, limited communication inhibits the evacuation.

The form of group/altruistic behaviour exhibited therefore has an impact upon both the quantitative and qualitative aspects of the evacuation.

CASE 8.3.44

The ability of an occupant with a higher travel speed to adapt according to slower and more distant group members is examined in 8.3.44. The single senior group member is placed approximately 12m from the available exit and has a travel speed of 1.5 m/s. The junior group members are placed approximately 20m from the exit and have a travel speed of 1.0m/s. The senior occupant is therefore placed some 8m closer to the single 1.5m exit, within a 20m x 5m geometry and travels significantly faster (see Figure 8-30).

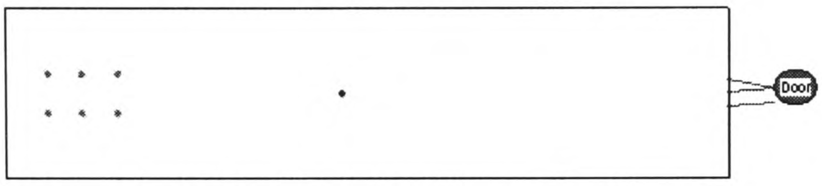


FIGURE 8-30: GEOMETRY USED IN VALIDATION CASE 8.3.44

Initially in 8.3.441, the present model is examined to produce a control case. No adaptation is applied. Secondly in 8.3.442, the proposed behaviour is then examined, where the occupant's ability to adapt his travel speed is analysed. All of the occupants are assigned the same social gene during the proposed model, denoting that they are socially significant.

All of the occupants respond instantly and progress towards the available exit. The examination of the simulated occupant's velocity at 1/12th second intervals throughout the simulation, as well as their finishing position, will give an indication of the adaptation process.

RESULTS- CASE 8.3.44

8.3.44 is designed to examine the ability of the occupants to sensibly adjust their speed in relation to other significant occupants. If we examine the results produced by the present model in 8.3.441, a number of factors are clear. No information was communicated between occupants, therefore reproducing the differences in the location of the occupants in the results. As the more senior occupant did not slow down for the occupants with a lower travel speed, an obvious discrepancy still existed between the arrival times (see Figure 8-31). This is apparent through the existence of a pronounced step in the cumulative arrival curve.

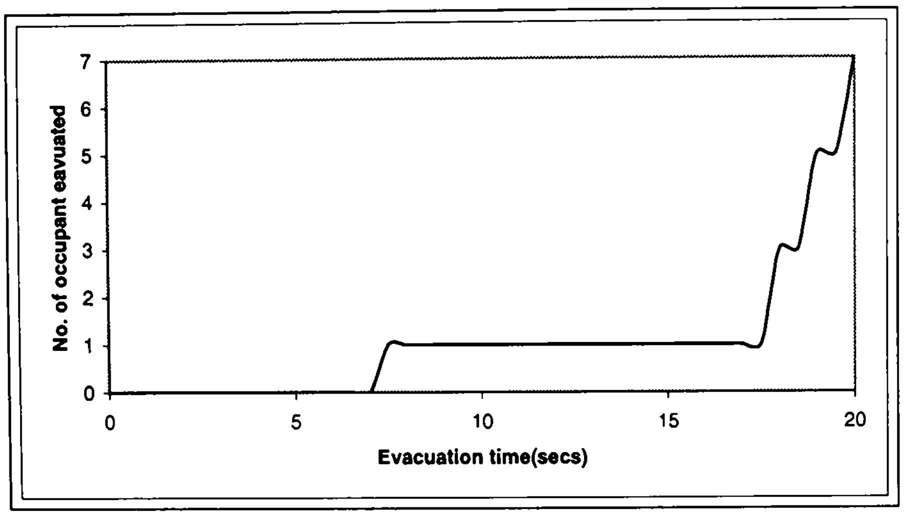


FIGURE 8-31: ARRIVAL CURVE PRODUCED SCENARIO 8.3.441

It should also be noted that the present model does not produce a distribution of results under any of the circumstances described (see Table 8-21).

TABLE 8-21: EVACUATION TIMES PRODUCED BY THE PRESENT AND PROPOSED MODELS.

	Evacuation Time (secs)	
	Present Model 8.3.441	Proposed Model 8.3.442
1st occupant out	7.3	17.6 [17.1-18]
Last occupant out	19.6	21.5 [21.1-22.0]

This is due to the deterministic nature of the model, as well as the limited/non-existent occupant interaction.

We now contrast these findings with the results produced through the use of the proposed model in 8.3.442. From Table 8-21 a consistent set of times is produced demonstrating that although the process is stochastic, the distribution is limited demonstrating no anomalies are present in the results.

Importantly the occupant arrivals are grouped into a small period of time, spanning only 3.9 seconds on average. This demonstrates the close proximity of the occupants to each other whilst they are exiting, reflecting the alteration of the faster occupant speeds to maintain their proximity and the ability of occupant to perceive other group members within their zone of influence.

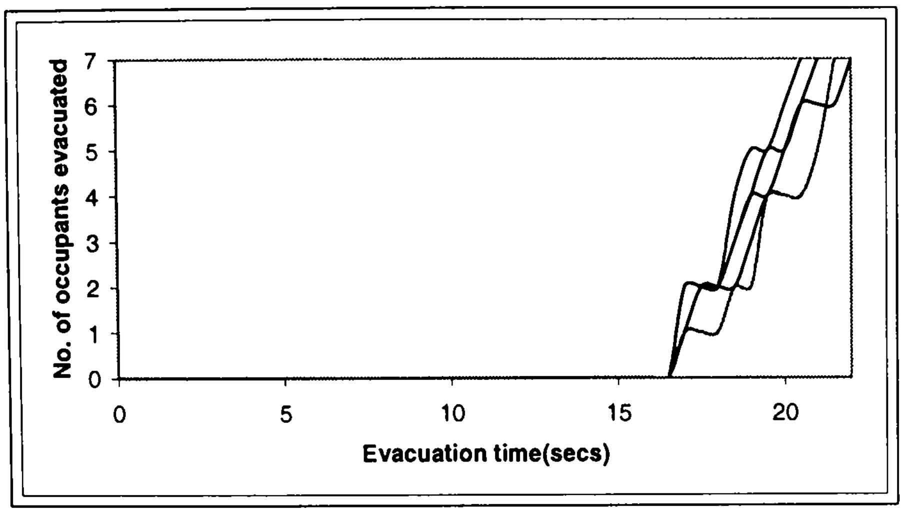


FIGURE 8-32: ARRIVAL CURVES PRODUCED IN SCENARIO 8.3.442.

This is more clearly demonstrated in Figure 8-32, where the gradient of the arrival curves are steeper, reflecting the rapid arrival rate of the occupants who do so *almost* simultaneously.

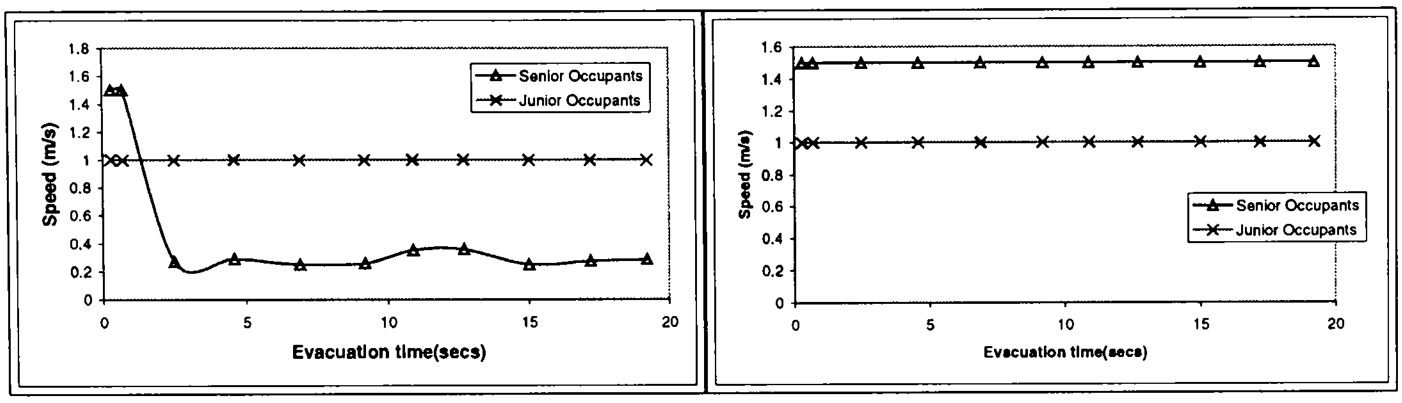


FIGURE 8-33: COMPARISON OF A SENIOR AND JUNIOR OCCUPANT TRAVEL SPEED IN THE SCENARIO 8.3.442 (LEFT) AND 8.3.441 (RIGHT).

From Figure 8-33 the ability of the occupants to adapt their speed is demonstrated. The senior occupant, who is located nearer to an exit, is constantly adjusting his speed in accordance with the approaching population under the proposed model (see Figure 8-33). The junior occupants, who are more distant, maintain their speed at 1.0m/s and only overtake the senior occupant at or very near the exit. This is more apparent once compared to the occupant behaviour under the present model.

CASE 8.3.45

The ability of occupants perceiving members of their group is examined in conjunction with a high population density and a smoke-filled environment in validation case 8.3.45. The simple 20m x 5m geometry is used again to prevent unnecessary complexity. In Scenario 8.3.451-2 two 'related' occupants are positioned inside the geometry. The senior occupant, who is attributed with a travel speed of 1.5m/s, is positioned 4.5 m from the exit. The junior occupant, who travels at a speed of 0.6 m/s, is positioned 15 m further away. However, 80 non-related occupants who initially completely shield the related occupants from each other surround the junior occupant. The distance between the related occupants is great enough for the junior occupant to fall outside of the senior occupant's zone of influence. The only method which can cause group-related behaviour is therefore observation. This is based on the same calculations described in Chapter 5, concerning the line-of-sight calculations.

TABLE 8-22: SCENARIOS EXAMINED IN CASE 8.3.45

Scenario	Geometry	Behavioural Model	Population	Environment
8.3.451	20m x 5m	Present	80 junior, 1 senior	N/A
8.3.452	20m x 5m	Proposed	80 junior, 1 senior	N/A
8.3.453	20m x 5m	Present	1 junior ,1 senior	0.3 /m
8.3.454	20m x 5m	Proposed	1 junior, 1 senior	0.3 /m

In Scenario 8.3.453-4, the 80 non-related occupants are removed and are replaced by a smoke-filled environment, with an extinction coefficient of 0.3 l/m. This then impacts upon the level of observation between the occupants.

In all of the cases, the simulations are each run 5 times. The present model is used as a control case in Scenarios 8.3.451 and 8.3.453.

RESULTS- CASE 8.3.45

Case 8.3.45 is designed to examine the ability of simulated occupants to observe related occupants who lie outside of the occupants' immediate range of influence. This is chiefly influenced by the existence of a high-density population around either of the two occupants involved, or the presence of smoke in the environment. Initially, the presence of other occupants is examined in Scenario 8.3.451-2.

From Table 8-23 and Table 8-24, the present model (in Scenarios 8.3.451 and 8.3.453) is shown to be insensitive to the influences examined, other than their physical impacts described in Section 3.1, Chapter 3. This is not the case in the scenarios involving the proposed model (Scenarios 8.3.452 and Scenarios 8.3.454). From Figure 8-34 and Table 8-23 the ability of the senior occupant to adapt to the presence of a junior occupant some distance away is clear. As the junior occupant lies outside of his immediate zone of influence the likelihood of the occupant seeing his group member is dependent upon the environmental conditions. In Scenario 8.3.452, the presence of some 80 other occupants hinders this likelihood.

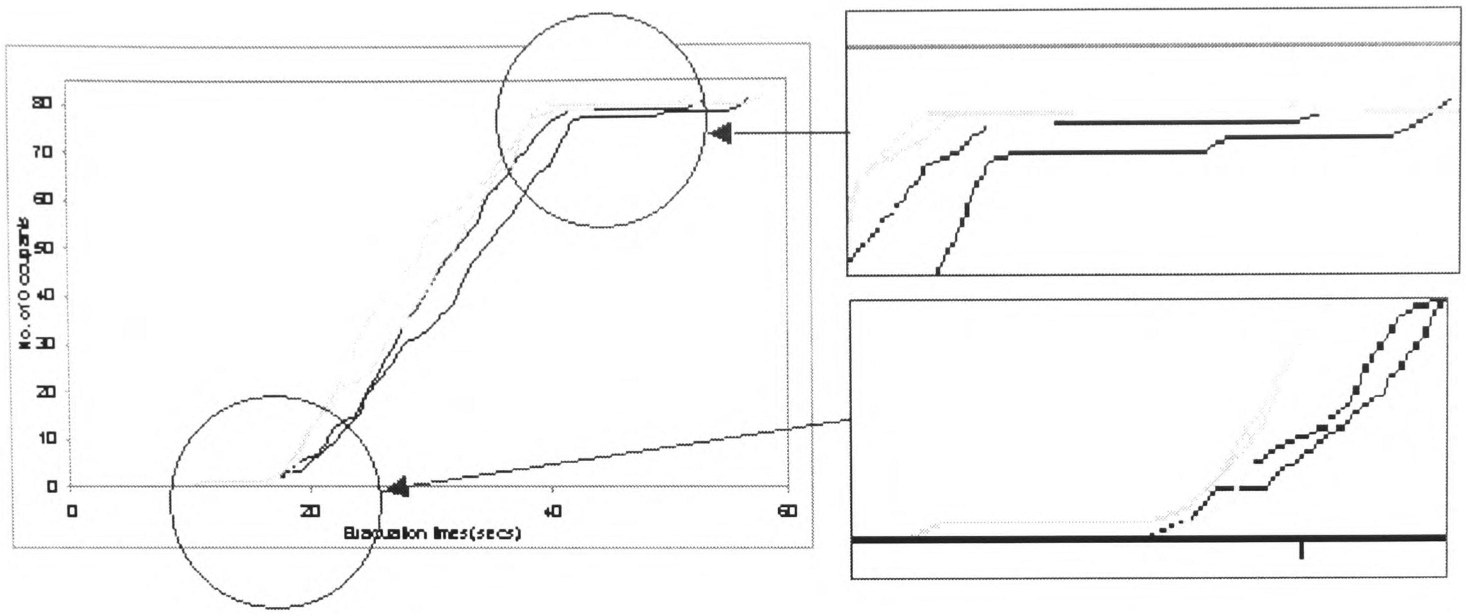


FIGURE 8-34: OCCUPANT ARRIVAL CURVES FOR SCENARIOS 8.3.452. THE SIMULATIONS INVOLVING OBSERVATION IS SHOWN IN DARK WHILE THE LIGHT CURVES REPRESENT A LACK OF OBSERVATION. ALL OF THE FIVE SIMULATIONS OF 8.3.452 ARE SHOWN HERE.

From Figure 8-34 two distinct types of behaviour can be seen during the implementation of the proposed behaviour. In those cases when the slower related occupant is not observed, the senior occupant, who is positioned far closer to the single exit, evacuates at full speed (1.5m/s). The senior occupant is therefore the first occupant out, after, on average, 10.9 seconds. This can be seen from the lightly coloured curves where an isolated blip can be seen early on in the evacuation (see Figure 8-34). Ultimately in these cases, the evacuation culminates in the junior occupant who is delayed and isolated, averaging a final evacuation time of 54.6 seconds. Indeed in these cases the occupant behaviour approximates that produced by the present model (see Table 8-23 and Table 8-24)

Once the senior occupant decides to wait for his slower group member his deceleration causes him to move back into the pack of oncoming occupants. This action delays the first occupant to evacuate, producing an average time of 16.4 seconds for the first occupant to evacuate. The first occupant under these circumstances is drawn from those occupants in the pack, rather than the senior occupant close to the exit. The senior occupant then joins his group member towards the back of the occupant population. Both of these behaviours can be seen in examining the dark curve in Figure 34. Here, the first occupant arrival is significantly delayed whilst the final occupant out is no longer isolated causing a more complex arrival curve, averaging 55.1 seconds. It should be remembered that these findings are averaged in the overall results of the proposed model, diminishing the overall effect. This analysis does highlight the increase in the variation and sophistication of the behaviour and the subsequent necessity for detailed analysis.

These qualitative observations are consolidated by the quantitative findings seen in Table 8-23.

TABLE 8-23; EVACUATION TIMES GENERATED IN CASE 8.3.451-2.

Evacuation times(sec)	Scenario 8.3.451	Scenario 8.3.452
1st Occupant out	10.9	14.4 [10.9-16.7]
Last Occupant Out	54.1 [52.1-56.9]	54.9 [51.2-57.9]

Again it is evident that adaptive communication behaviour is not necessarily beneficial to the individual occupant or to the overall evacuation time.

The second examination (in Scenarios 8.3.453-4) involves placing the junior occupant in a smoke-filled environment of an arbitrary extinction coefficient (0.3 l/m) to examine the impact upon communication levels. The difference in the resultant behaviour when the faster occupant perceives his slower group member is apparent from examining Table 8-24. Once the senior occupant is aware of the other's existence in a number of the cases in Scenario 8.3.454, he drastically reduces his speed, prolonging his overall evacuation by on average approximately 370%. Interestingly, no quantitative benefit is apparent to the junior occupant, other than that a senior and more mobile group member accompanies him. Once the senior occupant has observed his junior partner in Scenario 8.3.454, the evacuation time of the first occupant out is 46.6 seconds, while the evacuation time of the final occupant out is on average 48.3 seconds. In those runs of Scenario 8.3.454 where no observation takes place the behaviour approximates the present model, with the first occupant out arriving in 9.9 seconds and the final occupant arrives in 48.3 seconds. In these cases and in the present model (Scenario 8.3.453), no distribution appears in the results as no resolution of conflicts occurs due to the lack of occupant interaction.

TABLE 8-24: EVACUATION TIMES GENERATED IN CASE 8.3.453-4.

Evacuation times(sec)	Scenario 8.3.453	Scenario 8.3.454
1st Occupant out	9.9	39.3 [9.9-47.1]
Last Occupant Out	48.3	48.3 [48.2-48.3]

* no distribution is provided here as the occupants do not interact with other members of the population.

This scenario has demonstrated the ability of the occupants to perceive group members at some distance given the appropriateness of the surrounding area and the disadvantages that this perception can pose to the individuals involved.

8.3.5 Future Work

A substantial amount of work has been done concerning the exact size and dispersion of groups [1,163]. The results of this research might be represented within the model by relating the proximity of group members with their identities.

Most important, is the development of a search facility, where occupants attempt to find their less senior family members. This would significantly enhance the feature and would make it less dependent upon the user. It would also more effectively represent search and rescue behaviour that would enable the more effective modelling of the fire service during emergencies.

8.3.6 Conclusion

The introduction of social behaviour within the buildingEXODUS model reflects a significant advance in the capabilities of the model. As addressed in Chapters 2 and 3, no area of the evacuation process has been misunderstood more than that of the identity of and the relationship maintained by the occupant population. Occupants do not resort to barbaric selfishness when confronted with danger. Instead they attempt to maintain the social roles into which they normally fit, at least while still physically possible.

The features that denote this social position, are the quality, extent and credibility of the communication and the adaptation of behaviour in accordance with this information. In close social relationships, the condition of significant others is an additional factor in the possible success of a behavioural action. Unlike the accepted wisdom of the first half of this century, those that lie outside of the immediate social grouping are not irrelevant individuals. Instead they may have an impact upon the activities of unfamiliar occupants. However, their information may not be as high a priority as that of the immediate group members. *It is therefore a question of prioritisation rather than behavioural transformation.*

The cases examined demonstrate a number of the behavioural additions of the proposed model. These have outlined the complexity and consistency of the proposed features. Also, they have provided evidence for the *individuality* of the proposed behaviour. It is therefore dependent upon the occupant and their particular circumstances (social role, attributes, etc.) rather than some definition of collective behaviour.

8.4. THE ADAPTIVE RESPONSE TO APPROACHING A SMOKE-FILLED ENVIRONMENT

8.4.1 EXPECTED OCCUPANT BEHAVIOUR

As indicated previously, there are two distinct forms of behaviour that need to be addressed in relation to the environmental conditions. In Chapter 7, the occupant movement and decision-making process when *engulfed* in smoke was addressed. However, this did not account for the occupant's approach to the smoke-filled environment and the options available to the occupant. Ideally, these two behaviours would be combined. For clarity and for ease of verification this combination is left for future work.

A great deal of investigative work has been conducted concerning the occupant decision-making process in relation to smoke [52,54,57,58,64,65,91,106,107]. It has identified that a number of factors influence occupant behaviour in such circumstances. These factors include the occupant's *gender*, *age*, *familiarity* with the enclosure, *the extent and toxicity of smoke*, the occupant's *relationship to the structure*, the *time of day*, as well as several others.

These factors interact in a complex manner, and are not equally important in their influence over the subsequent occupant behaviour. Irrespective of this, the occupant is faced with a limited number of strategic options once faced by an environmental barrier of this type. These strategies can be broadly categorised as;

- Maintaining the present course of egress and passing through the smoke-filled environment. This might be forced upon the occupant if no other exit is available, or that the occupant has calculated that a safe passage still exists in this direction [60,163].
- Delaying further movement and maintaining their present position. This might be due to occupant curiosity/investigative actions, panic-based 'inaction' (described in

Section 2.1, Chapter 2 [52,60]), the occupant waiting for the conditions to improve or the occupant requires time to decide upon future actions.

- Redirecting their egress path away from the potential danger and heading toward another target. This movement may take the occupant back towards their initial position, cause the occupant to circumnavigate the problem or head towards an entirely new target. This action is based on the assumption that other routes exist and that the occupant is either capable of wayfinding or is aware of these other egress routes. It also assumes that the occupant has made the estimation for themselves or for a significant other, that the continuation of their present course would prove to be a significant risk to the well-being of those involved.

Obviously, these actions may be performed in a number of different contexts, each of which will influence their interpretation by an observer. Other forms of behaviour may be available to the occupant. However these are assumed to be either constructed through a combination of the three actions described, or are not significant enough, in egress terms, to be included in the model [24].

This form of decision process was clearly demonstrated by occupants in several cases. In Proulx's work concerning an incident in a 25 storey high rise, she found that,

> *"the response when encountering smoke ... was to 'kept going down' for 34%, another 31% 'reversed direction, and went up stairs', 11% indicated 'sought refuge' and 10% 'changed stairs, and reached outside by alternate exit stair' ".* **[221]**

This clearly indicates the three basic choices that occupants are faced with during the evacuation process when confronted with smoke, with additional sub-categorisation.

In Proulx and Fahy's examination of the New York Trade Centre evacuation [106], it was seen that 94% of one of the towers involved and 70% of the other tower, attempted to move through smoke. Nearly 50% of the respondents to their investigation claimed not only to have encountered smoke, but also to have moved through smoke all the way to their final exit. Of those attempting to move through smoke, 75% redirected due to the difficulty in breathing, lack of visibility, fear and other considerations.

In the Beverly Hills Supper Club [51-52] incident, similar evidence is available. As one occupant described, *"We came out of the entrance to the Viennese room which we entered through and tried to turn left because that was the only exit we knew of to the front but as soon as we turned left we saw smoke in that direction so we had no option but to turn right as the moment we came out."[52]*

These decisions are not generally made with perfect knowledge and as demonstrated by the Beverly Hills Supper Club incident they will therefore be susceptible to the adaptability of the occupant, the information available to the occupant and the ability of the occupant to carry out the desired actions.

This example demonstrates a group of occupants retreating immediately from the presence of smoke. However, in a number of cases, such as in the World Trade Centre incident [106] and the cases examined by Bryan, occupants were prepared to pass through a significant amount of high-density smoke. Obviously these behaviours can be combined, as described by an occupant involved in a fire in Ottawa, Canada who explained that,

"Many of the people from the upper floors who had evacuated at the first sign of smoke, were already coming back up the stairs, having found that the smoke in the stairwells too dense or too irritating to continue."[106]

Here, the occupants initially moved through smoke, but once they encountered more severe conditions on a stairwell they were forced to retreat and look for a more tenable exit route.

This example also highlights that the environment poses a physical barrier that might override the *desires* of the occupant. The occupant may wish to continue their present egress path, but due to the severity of the conditions, are unable to do so and are forced to redirect.

Finally, the individual history of the occupants will impact upon their egress paths. In the Ottawa example [106], occupants passed through a series of smoke-filled environments that eventually took their toll upon the occupants' health and prevented them from continuing. This process might be both psychological and physiological. In contrast, occupants may have previously experienced high levels of smoke and chose to avoid it. The existence of this smoke may encourage the occupant to move through less severe conditions at a later time [54,58].

8.4.2 PRESENT BUILDINGEXODUS IMPLEMENTATION.

At present, the effects of the environment upon the occupant are physiological rather than psychological. The occupants intake of toxins might reduce the occupants mobility but will not interrupt the passage to their chosen target. This representation is no doubt accurate for a proportion of occupants who are faced with the possibility of moving in smoke; that is under certain conditions, occupants will progress towards a desired target irrespective of the environmental conditions [1,9,11,57,58,60,106]. However, as highlighted, the decision to move through a smoke-filled environment is affected by a number of considerations including the perceived severity of the situation, the experience of the occupant, the actions of others, the physical condition of the occupant, the gender and age of the occupant, the availability of other exits and many more. It can therefore not be assumed automatically that an occupant will move through a smoke-filled environment irrespective of these conditions.

8.4.3PROPOSED BEHAVIOURAL ENHANCEMENTS

The proposed behaviour is very complex simply because of the numerous factors that influence the occupant behaviour and the flexibility required to cope with the occupant response. It was not felt sufficient to simplistically and arbitrarily enforce probabilities upon the occupant population reflecting secondary data. Although secondary data is utilised, it is combined with a variety of other data sources to make the algorithm as sensitive to the exact identity of the occupant as possible.

Several factors have been demonstrated in reality to affect the occupant's reaction to smoke. The simulated behavioural response to the environmental conditions could therefore be dependent upon these factors, given that they are already represented within the buildingEXODUS model. These options are dependent upon the following factors, currently represented within the model:

- *The severity of the environmental conditions*. For instance, are the conditions severe enough for the given individual to turn away?
- *The identity of the occupant involved (*including seniority/drive/gender/patience*).* A large amount of evidence exists [1,199,219] that suggests that the identity of the occupant can have important implications upon their confrontation with a hostile environment. The influence of these factors is dependent upon a number of new features, described in Section 5.2, Chapter 5, as well as existing occupant attributes.

- *The actions of significant others*, be they a staff member, a respected/senior occupant, or a related occupant, supplying information or otherwise can impact upon an occupants behaviour [9,11,54,58,97,] The influence of this factor is dealt with elsewhere in this chapter.
- *The existence and availability of other targets*. As demonstrated by Sime [4,101-102,118,200], occupants tend to move to the familiar. If this principle is extended logically, under conditions that force the occupant to redirect, they will move towards routes with which they are familiar or with which they have become familiar due to signage, information, etc. [101-102], given that these routes exist. The influence of this factor is dealt with in Section 7.3, Chapter 7. These options may also have included moving back towards a previously occupied area of refuge. Although this behaviour is acknowledged as being viable, it is left for future work to limit the complexity of the proposed behaviour.
- *The previous actions of the occupant*. The previous actions of the occupant, including previous interaction with hazardous environmental conditions, are an important consideration in the consistency of this behaviour [58,106,221]. The occupant history within the evacuation will influence the present and future decisions.
- *The expected distance that the occupant has to travel to their target*. This, in conjunction with the severity of the conditions, will form the basis for any estimation of the possible hazard provided by the environment. Although acknowledged as an important influence, this is left for future work.
- *The ability of the occupant to estimate the seriousness of the environmental conditions*. This calculation is made concerning the visible impact of the environment rather than the toxic or irritant impact of the smoke. This process is described in some detail.

It would have been possible to include a number of the other influences outlined in the relevant research [54,57,60]. The majority of these influential factors, such as the *enclosure type*, *the time of day*, etc., have been omitted, as they are not explicitly represented within the current buildingEXODUS model, although might be taken into consideration implicitly. As well as these omissions, a number of restrictions have been placed upon the algorithm to enable analysis. These are

1. The number of re-directive decisions available to the occupant has been limited, to guarantee that the occupant eventually commits to an exit (similar to the restrictions placed on the occupant when analysing congestion). Therefore, to prevent occupants rebounding between events, the re-directive capabilities are limited to a single instance.
2. The severity of the environmental conditions can only be examined if the occupant is in close proximity (adjacent) to the potential hazard. This is a compromise required for the implementation into the buildingEXODUS nodal system. Therefore, no long-term analysis exists at present.

The complexity of this behaviour might be improved in overcoming these compromises (for instance, removing the limitation on redirection). However, this would have meant the introduction of a number of new factors, not at present represented in buildingEXODUS, further complicating the initial analysis. It is therefore left for future work. The proposed algorithm, although including compromises, was felt sufficient to demonstrate the concept of behavioural adaptation in response to a worsening environment.

The factors outlined are therefore taken into consideration when the occupant is faced with a smoke-filled environment. They influence the decision-making process, given that the occupant is afforded with several options, when confronted with a *barrier* of smoke (see Figure 8-35). A means had to be derived to enable the occupant to perceive that a barrier of smoke exists. A barrier is deemed to exist if all of the potential locations that are closer to the occupant's target have a smoke-filled environment. (Obviously other environmental factors may influence the occupants decision, including heat, toxins, etc. However, smoke is initially chosen to represent this process, due to its visibility and the relative scarcity of relevant data-sets). Once detected, the behavioural response is triggered. The behavioural responses are based around the principles of *maintenance*, *delay* and *adaptation*.

Initially, as indicated by the relevant literature [106], the occupant can ***maintain their present course*** and move through the smoke, possibly triggering the behaviour highlighted in Chapter 7. This will cause the possible ingestion of significant levels of toxic products.

Secondly, the occupant can ***maintain their current position***, delaying future activity for a period of time. This may put the occupant at risk; the smoke possibly engulfing the occupant's present position or preventing passage through already worsening conditions, or it may allow the calculation of the best available option [221]. This action might be perceived as calculating future actions, examining the conditions, seeking refuge, etc. Irrespective of the interpretation, the occupant will be faced with a similar decision once the delay period has elapsed.

Finally, the occupant may ***redirect to another exit*** in an attempt to avoid interacting with a potentially toxic environment. This is dependent on the occupant being aware of other exits and that these exits do not also entail the occupant immediately moving through an equivalent smoke barrier.

If distant smoke barriers exist that are not immediately visible from the occupant's position, it is possible that they may provide an unanticipated hindrance [221]. *The occupant will not reflect upon this possibility in their analysis.* This movement may take the occupant back towards their initial position, although no searching algorithm is included for the occupant to intentionally seek refuge in a previously safe area.

The likelihood of the occupants performing these actions is extracted from several pieces of research [9,11,57,60,107]. Ideally, the algorithm should not be reliant upon probabilities derived from secondary data, with the obvious difficulties that this reliance brings (dependence upon unknown researchers, different motives for the collection of data, the necessity of adapting the data, etc.). All of the data described, including that of Wood, Brennan, Jin and Bryan [9,11,57,60,107] required manipulation to make it useable within the algorithm. Primarily this is because the original research was never intended for use in the modelling procedure and therefore either lacked the precision or the scope required.

Another important factor that should be considered is that the information derived from these data-sets tends to describe an *entire* evacuation. The algorithm addresses behavioural actions on a much smaller time interval (usually $1/12^{th}$ of a second).

Therefore the data extracted from the literature had to be restructured so as to be useful in a more continuous environment.

Most importantly, the data extracted is not used in *isolation*. It is either combined with other data sources, or interacts with buildingEXODUS occupant attributes, within the equations used in the algorithm. This is to make the algorithm sensitive to a number of occupant-based factors that might not be considered in the data-sets provided. It would therefore be unrealistic to expect an *exact* replication of the original results. For the model to be expected to accurately emulate the data-sets used, more significant adjustment to the buildingEXODUS model would be required, as well as some simplification of the methods used. Indeed, given that the original results tend to be averages across a variety of circumstances (e.g. domestic, experimental, industrial incidents), it is probably not desirable to replicate them exactly. The results produced by any verification cases should instead fall within the expected boundaries set by the original data. *The simulated results should therefore approximate the trends distilled from the original data, rather than emulate the data precisely.*

Eventually, sophisticated occupant behaviour should be produced according to the individual, the environment and the options available, without the requirement of detailed data extraction. This would represent a truly bottom-up behavioural system that was generating occupant behaviour according to individual traits and not according to imposed probabilities. However, even in this situation, secondary data may provide an *initial* position from which the occupant behaviour may emerge. This type of behaviour would require a vast amount of development and would also need to be shown to produce stable and consistent results. *Therefore, the algorithm discussed is a provisional rather than definitive measure designed to improve the representation of occupant behaviour and demonstrate the concepts described.*

The proposed algorithm will now be discussed with brief descriptions of the data-sets used and their specific limitations (see Figure 8-35).

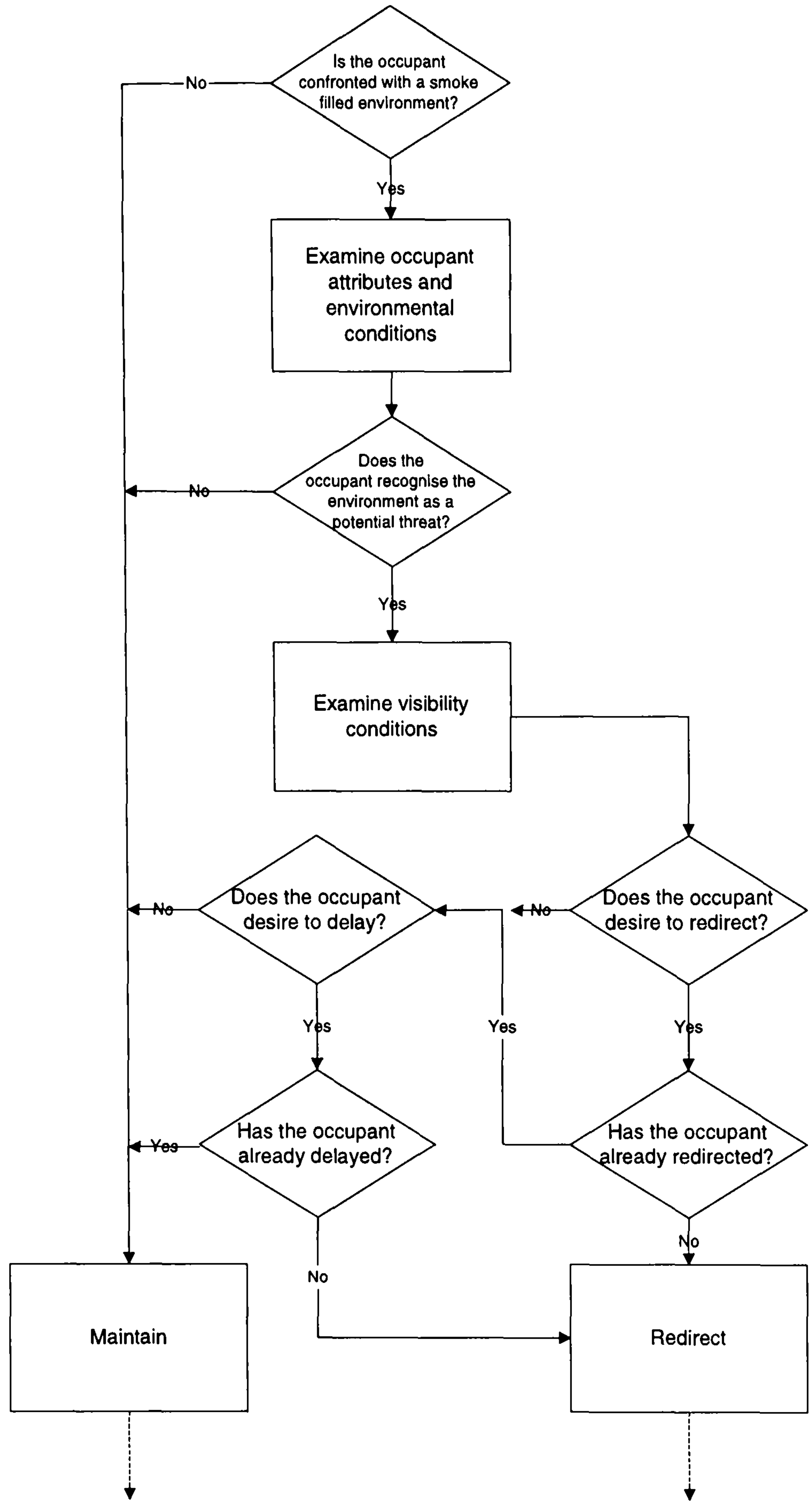


FIGURE 8-35: FLOWCHART OF THE PROPOSED BEHAVIOUR

As it is in the present model, the occupant's *physical* reaction to the extinction coefficient of the surrounding environment is extracted from the work of Jin [9,11], and then related to the possible visibility levels of the environment. Another less familiar aspect of Jin's work concerns his approximations of the tenability of the environmental conditions given the ***familiarity*** of the occupant with the enclosure. This therefore reflects upon the potential psychological influence that familiarity may bring over the occupant's interpretation of the hazard. These also have an impact upon the occupant's decision-making process (see Table 8-25). Jin (through his analysis of the wide array of available literature) explicitly links the occupant's familiarity with the perceived tenability of the environmental conditions [9,11]. This literature included the work of Kingman [222], Rasbash [223], Kawagoe [224], Togowa [11] and the Los Angeles Fire Department [225] and involved a variety of situations and incidents.

The inclusion of this data is done with some caution, as this factor is also partially addressed in the occupant's general familiarity with the building. Therefore, the occupant familiarity with the enclosure may already indirectly influence the possible exit choices of the occupant, irrespective of whether they are faced with smoke-filled environments. Given this fact, the occupant familiarity with the enclosure is an *influential* factor within the decision-making process, rather than being a *determining* factor.

Some supportive evidence is provided for the observations of Jin by Wood [57]. Wood investigated 952 fires in the United Kingdom, interviewing 2,193 occupants who were involved in residential and industrial incidents (see Table 8-26 and Section 2.5.1, Chapter 2).

TABLE 8-25: MINIMUM VISIBILITY REQUIRED FOR SAFE-KEEPING AS CALCULATED BY JIN[57].

Degree of familiarity with building	Visibility	Smoke Density (Extinction Coefficient)
Familiar	**3-5m**	**0.4 –0.7 /m**
Unfamiliar	**15-20m**	**0.1/m**

Several problems are apparent in the use of the Wood data in conjunction with the Jin data. Firstly, difficulties exist in the categorisation of the familiarity levels (what exactly constitutes less than complete familiarity?). Secondly, differences exist in the results produced due to the majority of the cases in Wood's sample being drawn from residential incidences [57].

TABLE 8-26: IMPACT OF FAMILIARITY AS CALCULATED BY WOOD [57].

Familiarity with Building	Percentage Moving Through Smoke(%)	Proportion of sample
Complete	**61**	**988 out of 1618 deemed completely familiar**
Less so	**51**	**145 out of 282 deemed less familiar**

For either Wood's or Jin's work to be used in this context, a working definition of 'familiar' and 'unfamiliar' is required within the proposed algorithm. In this instance, an occupant is considered familiar if they are aware of *all* of the exits (i.e. theirs door vector is equivalent to that of the global list of exits, (see Section 7.3, Chapter 7)). An occupant who is aware of all the exits is assumed to be familiar with the entire structure. Otherwise the occupant is not considered to be completely familiar with the enclosure (termed 'less familiar' by Wood [57]).

The influence of the occupant's ***age*** upon the occupant's reaction, is taken from the work of Brennan (see Table 8-27) while the influence of ***gender*** is taken from both the work of Brennan and Wood (see Table 8-28 and Table 8-29) [57,107].

Brennan examined the accounts of 29 occupants who were forced to move through smoke during an evacuation from an office building in Australia (see Chapter 2). Although a cross-section of the population existed within the Brennan data-set, the work of Brennan is on a small-scale and may be considered unrepresentative. At present however, it provides some of the only data available.

TABLE 8-27: LIKELIHOOD OF REDIRECTION ACCORDING TO THE INFLUENCE OF AGE AS CALCULATED BY BRENNAN [107].

Age	Percentage(%)
20-39	**50**
40-59	**40**
60-79	**53**

TABLE 8-28: LIKELIHOOD OF REDIRECTION ACCORDING TO GENDER. CALCULATED BY BRENNAN [107].

Gender	Percentage(%)
Male	**40**
Female	**53**

TABLE 8-29: LIKELIHOOD OF TRAVELLING THROUGH SMOKE ACCORDING TO GENDER. CALCULATED BY WOOD [57].

Gender	Percentage(%)	Proportion of sample
Male	64	684 out of 1064 male occupants
Female	54	448 out of 836 female occupants

As can be seen from Table 8-29, although the sample sizes are quite large in the Wood data-set, they suffer from similar inequalities in the constituent sample sizes that were evident in Table 8-26, which might bias the eventual results.

A degree of similarity exists between the two sets of results displayed in Table 8-28 and Table 8-29, with male occupants in both samples appearing more likely to interact with the smoke hazard.

Again these factors have proven influential over the occupant reaction to the smoke hazard. Therefore, they will also be included as *influences* rather than determining factors. As with all of the secondary data included, the consistent portrayal of the trends evident in the data is considered far more important than the precise repetition of the figures.

The likelihood of the occupant ***moving through smoke*** as well as the distance that the occupant is willing to travel through the environment is extracted from the work of Bryan and again from Wood [57] (described earlier). Bryan analysed data from 335 incidents, involving 584 occupant interviews originally conducted by fire personnel. The incidents examined by Bryan all occurred in residential enclosures (see Chapter 2).

Bryan's analysis of occupant behaviour confronted with a smoke-filled environment produced probabilities relating to the *likelihood of redirection*, given the perceived smoke density and the expected travel distance (see Table 8-30 and Table 8-31). The occupant here is making decisions according to the *estimated* time that the occupant will be subjected to a potentially injurious environment. Bryan's work is supported by similar findings in the Wood investigation. Differences between the two data-sets are due to discrepancies in the sample sizes, as well as differences in the occupancies of the incidents examined.

TABLE 8-30: INFLUENCE OF VISIBILITY (AS AN INFLUENCE OVER AN ENTIRE POPULATION) ON MOVING THROUGH SMOKE [57,60].

Visibility Distance (feet)	Visibility Distance (m)	Wood (%)	Bryan (%)	Avg. (%)
0-2	0-0.76	12	10.2	11.1
3-6	-1.98	25	17.2	21.1
7-12	-3.81	27	20.2	23.6
>13	>3.81	37	52.4	44.7

TABLE 8-31: INFLUENCE OF VISIBILITY UPON OCCUPANT REDIRECTION [57,60].

Visibility Distance (feet)	Visibility Distance(m)	Wood (%)	Bryan (%)	Avg. (%)
0-2	0-0.76	29	31.8	30.4
3-6	-1.98	37	22.3	29.7
7-12	-3.81	25	22.3	23.7
>13	>3.81	9.0	23.6	16.3

The final category in these data-sets (namely '>13m') has been formed from combining several categories from the original data-sets. This was initially to overcome problems concerning inequalities in the class sizes used, as well as attempting to overcome the sparseness of the data-set. It also simplified the calculation process somewhat, so that the functions generated were less complex than might have otherwise been the case. This process would have had no impact upon the results, as the categories combined refer to relatively moderate conditions. These data-sets are described in more detail in Chapter 2.

A number of valid criticisms exist concerning Wood and Bryan's techniques, especially in the context in which they are being used. Specifically, the nature of the categorisation and the division of behavioural actions without reference to their cause and context are debatable. However, this data, albeit imperfect, still provides a test-bed upon which to examine the concept of representing occupant behaviour in relation to smoke. It should be borne in mind that the *concept* of this behaviour and the development of the algorithm overall is of utmost importance. The replacement of this data, although tiresome and requiring sensitivity analysis, is a matter of simplicity; developing a consistent and coherent algorithm that is able to generate acceptable results given the identity of the occupants concerned, is less trivial.

Having analysed these pieces of research it is necessary to adapt and interpret the work so as to make it consistent within the model. For instance, a number of the pieces of research used are in the form of sparse or scattered data-points, with large gaps in the data-set. Therefore the original categorisation used in the work cited (especially that of Wood and Bryan), required adaptation to be of use in the algorithm. To be of use, the data-sets referring to behavioural probabilities have been converted into functions that can then be easily used within the overall algorithm. These functions are intentionally simplistic allowing a greater understanding of their impact and enabling the identification of particularly influential factors. The influential factors have been adapted so that they can exert their influence over these functions.

It is apparent from Table 8-30 and Table 8-31 that although general similarities are evident, there are some differences in the data-sets provided. To 'smooth' the data-sets removing what might be considered extreme data-points, a function representing the average of the Bryan and Wood data-sets is calculated. This is only intended to simplify the modelling process and is not meant as a criticism of the original data. However, the original data-sets (see Chapter 2) do suggest some counter-intuitive behaviour that may have been due to the recording procedures used, rather than the first-hand interpretation of the behaviour by the occupant. These anomalies are removed during the truncation and averaging of the data.

Briefly then, the implementation is described. The occupant is faced with the three choices outlined (namely to maintain their position, to maintain their course or to redirect). The calculation as to the choice of action will initially be dependent upon the information available to the occupant. In the proposed algorithm, if the occupant is unfamiliar with any other routes (that is no other options are available), the algorithm will be ended and the occupant will not attempt to redirect irrespective of the density of the smoke in the environment. It is understood that this is a compromise and that in actuality occupants may well redirect into the unfamiliar or to an alternative form of refuge. This is left for future research.

Given that the occupant has a number of routes available (see Chapter 7), the density of the smoke barrier encountered is approximated, as is the expected travel distance. *If the distance expected to travel is less than the visibility afforded by the conditions, then the occupant automatically attempts to continue.* This is based on the assumption that if the occupant can see the exit through the smoke, then he will continue on towards it. Therefore if the occupant is within a small distance of the target exit (or if the smoke is sparse) and the environment allows visibility of the target exit, the occupant will continue on through the smoke. Otherwise, these variables are compared using functions derived from the experimental work highlighted to determine their next course of action (see Figure 8-36).

It is assumed that the occupant has no ability to determine how much of the future egress route will be through the smoke, unless the target exit is visible. If the occupant is faced with a dense smoke 'barrier', 20 m from their exit, calculations are made on the basis that the smoke will continue at the perceived level until the exit. The assumption therefore forced upon the occupant is that given that they are faced with a smoke-filled environment, that this potential barrier will continue until reaching the target exit. ***The occupant therefore assumes the worse possible scenario.***

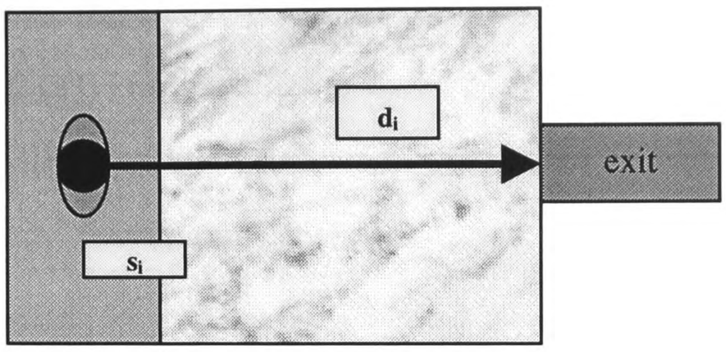


FIGURE 8-36: REPRESENTATION OF THE CALCULATION MADE BY THE OCCUPANT ONCE FACED BY SMOKE

Given that the occupant is adjacent to the smoke barrier, the occupant initially determines whether the barrier poses a threat. Given the attributes of the occupant (age (A_i) ,gender (G_i), familiarity (F_i), motivation (D_i), visibility (v) etc.[11,57,60,200]), the barrier posed by the environment is examined to see if it warrants consideration. These factors are derived in a simplistic fashion from the data retrieved from the research literature of Jin, Brennan and Wood. Simplifications are made to represent the data-sets in order to overcome omissions or vague descriptions, or to compensate for small data sets. The derived function therefore relies on these factors being converted into probabilities. These are provided in Table 8-32.

TABLE 8-32: THE INFLUENCE OF THE BEHAVIOURAL FACTORS USED IN THE PROPOSED FUNCTIONS

Factor	Gender (G_i)		Familiarity(F_i)		Age(A_i)		
	Male	Female	Complete	Incomplete	<20yrs	<60yrs	60yrs+
Impact Upon Calculation	1.0	0.8	0.8	1.0	0.5	0.7	0.5

These probabilities have been distilled from the individual data sets to be included into the *overall* redirection algorithm. Although possible distortions exist on close comparison against the original data, the use of the new figures has been analysed so as to generate similar trends given similar conditions.

In Table 8-32 the impacts of individual factors are presented. These are used in Equation (90) and (91). The occupant examines the visibility levels afforded by the smoke (v) and compares this to the distance to their desired exit (where $P = [x_{pres}, y_{pres}]$ and $Q = [x_{exit}, y_{exit}]$).

$$v > \|P - Q\|_2 * F_i \qquad (90)$$

Equation (90) determines whether the occupant can see the chosen exit given the position and the level of visibility, or that smoke affords a visibility level sufficient to continue. The familiarity of the occupant (F_i) is also an influence upon this calculation, biasing the required level of visibility. If the exit is deemed visible from the occupant's vantage-point (the inequality in (90) is satisfied), then no further examination is made and the algorithm is ended. Therefore if the occupant is afforded visibility that is greater than the remaining distance to the exit, the occupant then continues. This prevents occupants from redirecting when particularly close to their target exit. An occupant who is familiar with the structure is more likely to satisfy this equation, given the influence outlined in Table 8-25 and Table 8-26 and has a greater probability of passing through the smoke in accordance with the data provided in the available literature [11,57,98].

If this inequality is not satisfied, it must then be determined whether the occupant *perceives* the smoke barrier as a threat. A calculation is made according to

$$A_i . G_i . \frac{D_i}{D_{\max}} > r \tag{91}$$

where r is a random number [0.0-1.0], A_i is the occupant's age, G_i is the occupant's gender and D_i and D_{max} represents the occupant's present motivation and the maximum occupant motivation achievable, respectively. According to the influence of the occupant attributes, from Table 8-32, men who are motivated and are aged between 20 and 60 will be less likely to perceive the smoke as a threat, and will be more likely to pursue their present course of action, than other occupants. If the inequality is satisfied then the occupant does not perceive the smoke as a threat and continues the movement towards the exit. The calculation may then be halted at this point.

It is recognised that this initial stage does implicitly influence redirection, in that if the occupant does not recognise the smoke barrier as a threat, they will not be eligible to redirect. However, it is considered separately as occupants distinguish between not recognising the environment as a threat and considering the environment as a threat, but still moving through it [52,106].

Once the occupant acknowledges the existence of the threat, the situation is analysed, as described previously. The occupant may *redirect* (see Table 8-31), *delay* or *maintain* the route, irrespective of the perceived threat.

The occupant is faced with what is perceived as being a threatening situation. Initially he determines whether the conditions, ***although deemed hazardous***, permit passage.

This is calculated according to a number of factors.

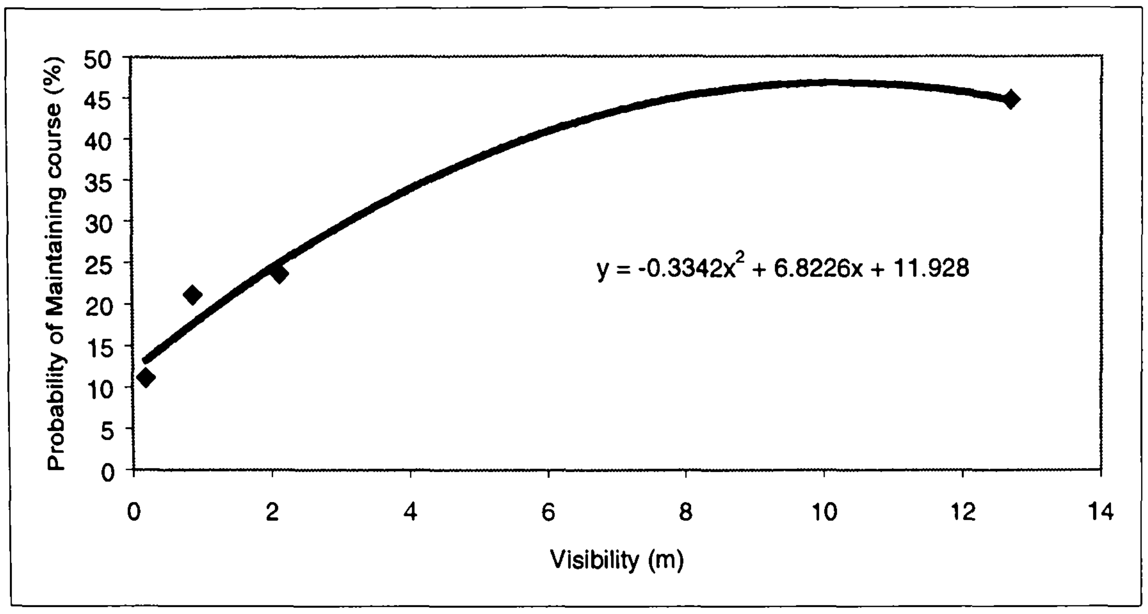


FIGURE 8-37: DERIVED TREND-LINE REPRESENTING LIKELIHOOD OF THE OCCUPANT MAINTAINING COURSE ACCORDING TO THE DATA OF WOOD AND BRYAN [57,60]. ONLY VISIBILITY LEVELS EXAMINED ARE SHOWN.

The data of Wood and Bryan in Table 8-30 *is averaged*, to produce a single function (see Figure 8-37) formed from a line of best fit. Again, it is acknowledged that this process is questionable. However, in this instance it is the behavioural *concept* based around noted pieces of research, rather than the precise accuracy of the implementation that is felt to be important. (In a complete implementation of this behaviour, the user might be able to switch between appropriate data-sets according to the simulated circumstances, or indeed the calculation may be influenced by the type of enclosure in which the evacuation occurs, switching between the data-sets automatically). Given that a number of other factors outside of the Bryan and Wood data-set are included and that the data-sets themselves cover a variety of situations, it was felt that the use of a general trend derived from their work, instead of strictly adhering to the exact data-points, was sufficient.

The influence of the occupant attributes of drive (D_i) and seniority (S_i) are included in the function. This is another reason why the exact accuracy of the probabilities derived from the work of Wood and Bryan are not considered essential. Instead they are used as a *trend* that influence occupant behaviour rather than a determining factor, with the experience and identity of the occupant being introduced as a factor. Through seniority, a number of the occupant's other attributes (including *Age* and *Gender*) are represented in a numerical form (see Chapter 7). These factors are then combined to produce (92).

$$r \leq \left(\frac{-0.33(v)^2 + 6.82v + 11.93}{100}\right) + \left(\frac{S_{\max} D_i + D_{\max} S_i}{5.S_{\max}.D_{\max}}\right) \tag{92}$$

where v represents the visibility afforded by the environmental conditions D_{max} and S_{max} are the maximum drive and seniority, D_i and S_i is the present occupant drive and seniority, and r is a random number between 0 and 1.0. The denominator of the fraction relating to seniority and motivation is increased to control the impact of this aspect of the equation.

This equation is intentionally simplistic. This is to simplify the process of analysis, the maintenance of control over the results and the eventual sensitivity analysis. It also derives from the lack of a basis on which to justify more complex composite functions.

According to this function, the more senior and the more motivated the occupant is, coupled with better levels of visibility afforded them, the greater the likelihood of the occupant moving through the smoke-filled environment. *If this inequality is satisfied then the occupant will pass through the smoke and the algorithm is exited.*

This process, although involving a random number generator forming a probabilistic representation, is not arbitrary. It involves a number of factors derived from secondary data [57,60,107], concerning the likelihood of occupant actions, as well as assumptions based on the exact identity of the occupant. These trends are adhered to through the establishment of probability levels of performing specific action that are then compared against a random number, producing a general likelihood of sections of the population performing particular actions, although still being sensitive to the individual.

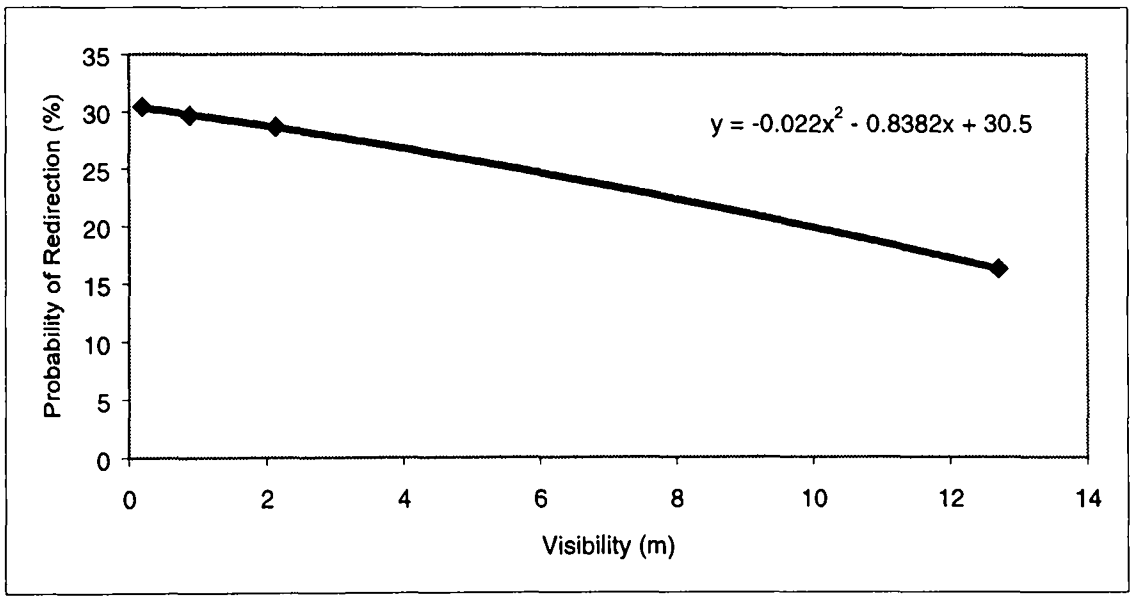


FIGURE 8-38: TREND-LINE DERIVED FROM TABLE 8-31 IN ORDER TO REPRESENT THE OCCUPANT REDIRECTION (ACCORDING TO THE DATA OF WOOD AND BRYAN [57,60]).

Given that the occupant fails this condition in equation (92) and is deemed to require an alternative route, it is then determined whether the occupant is *able* (i.e. other routes are available) and *willing* to redirect (see Table 8-31). The ability of the occupant to redirect is largely based on whether alternative routes exist (see Section 7.3, Chapter 7). The willingness to redirect is calculated in a similar manner as the perception of the threat.

Again, the data derived from the work of Wood and Bryan (see Table 8-31) produces a function (see Figure 8-38). In a similar manner to the previous function, this is combined with the occupant attributes of drive (D_i) and seniority (S_i) in (93).

$$r \leq (\frac{-0.02(v)^2 - 0.84v + 30.5}{100}) + (\frac{S_{max} D_i + D_{max} S_i}{5.S_{max} .D_{max}}) \quad (93)$$

If the inequality in (93) is satisfied then the occupant does not consider redirection. The motivation and seniority of the occupant is a *negative* influence upon the likelihood of redirection, as is an increasing level of visibility. Therefore an adult male occupant who is faced with smoke that affords him with 10m visibility has a relatively low probability of redirection, in comparison with a female child who is faced with smoke that affords her with 5m visibility.

If both of these options are rejected (continuing and redirecting), the occupant is assumed to delay the decision [106] for between 0.0-10.0 seconds according to equation (94).

$$t_{delay} = 5.0 * (1 + r - \frac{D_i}{D_{max}}) \quad (94)$$

Here, t_{delay} is the delay time and r is a random number between 0 and 1.0. The default position of 5 seconds was calculated after a degree of sensitivity analysis, although it is open to user control and is otherwise not based on empirical evidence. To prevent anomalies, the occupant is only allowed to delay this decision once. This is an implementational compromise that requires further development.

Once the occupant has completed the delaying procedure, if still appropriate (i.e. the occupant is not now engulfed in smoke), the occupant will pass through the decision process again, without the availability of the delay option. The relevant probabilities will therefore be normalised to accommodate this change.

As highlighted earlier, much of the incident/experimental data available concerns isolated cases or is based upon a single factor, such as the type of occupancy. *Therefore the comparison and the use of the experimental data is less than ideal.* For instance, it was necessary in the case of the Bryan and Wood data, to combine several of the original data-points to form a consistent data series. As well as this, the categories provide an incomplete set of information and therefore some interpolation was required.

In addition, other occupant attributes are also examined and are considered important, such as the occupant's motivation. Although much anecdotal evidence exists for such a consideration [52,93,98] it is rarely quantitatively examined. Therefore the exact replication of the data-sets provided is not attempted. Indeed given the diversity of the research available this would appear inappropriate. Instead these factors are included as *influences* upon the occupant behaviour, rather than determining occupant behaviour and are examined accordingly.

The development or replacement of these probabilities would be a trivial matter. For instance, the user may wish to use the U.S. data described by Bryan rather than the U.K. data. This would simply be a matter of replacing one data set by another. The model would then require some sensitivity analysis and verification to determine the effectiveness of the introduction of the new data. Indeed, It might also be of some experimental use for a user to be able to influence the data used in such a situation. This is left for future work.

The proposed developments are not an attempt to reflect the *exact* findings of individual instances or even individual data-sets, but instead to allow the simulated occupants to react according to general expectations, given the existence of environmental difficulties, their particular attributes and their individual cognitive abilities. The proposed behaviour is therefore an initial step towards a more complete and more accurate description of occupant behaviour in relation to a smoke-filled environment. It is crude in that it is overly restrictive and might be criticised for the manipulation of the secondary data. However, this is due to the lack of consistent data and the restrictions of the existing buildingEXODUS model. ***All that can be achieved under the present circumstances is that the proposed behaviour produces trends that are consistent with the data available and that given this fact, it does so without producing anomalies.*** This would be seen as providing an improvement over the existing methods available, legitimising the introduction of the proposed behaviour, even in this limited form.

8.4.4 Verification

It is important to demonstrate the appropriateness of the committal of the actions outlined in the previous section (see Table 8-33). The verification cases are therefore designed to examine whether the behaviour is performed consistently given the data available. It is impossible to examine all of the aspects of the behaviour, due to its complexity, therefore the cases are designed to represent the main features of the algorithm. These include

- 8.4.41: A simple geometry of 3 exits, used to demonstrate the probability of performing the actions outlined, when confronted with a smoke barrier, as well as investigating certain behavioural influences upon these actions.
- 8.4.42: The conditions are maintained from 8.4.1, except that the occupant is now only credited with a limited familiarity of the enclosure, affecting their awareness of individual exits and therefore the eventual behavioural choice, and, to a lesser extent, their understanding of the threat posed.
- 8.4.43: The algorithm is tested for anomalies in the adoption of new targets.
- 8.4.44: The algorithm is applied to a complex geometry, producing a more realistic example.

Table 8-33: Validation cases demonstrating the proposed behaviour

Scenario	Population	Environment	Geometry
8.4.41	50, varied make-up, instant response	0.3-0.9/m	2 exits, full awareness
8.4.42	50, varied make-up, instant response	0.3-0.9/m	2 exits, partial awareness
8.4.43	30, default, instant response	0.7	3 exits
8.4.44	150, varied make-up, instant response	1.0+	Irregular

Case 8.4.41

In 8.4.41, a simple geometry is examined with two 1.5m exits. The geometry is populated with fifty occupants who are completely familiar with the enclosure. These are positioned so as to prefer the exit blocked by the smoke barrier. This is necessary to provide a consistent comparison for the occurrence of occupant redirection between the scenarios examined (see Figure 8-39).

A number of variables are examined to determine their impact upon the simulation. These include the gender, age and motivation of the occupants and the density of the smoke barrier. These factors are examined independently. For instance, a population may contain male occupants who are 25 years old, highly motivated and are faced with a smoke hazard of 0.9 l/m. the next population will contain different factors.

The examination of this behaviour is reliant upon the introduction of the Seniority and Door Vector attributes (see Section 7.3, Chapter 7), with no other proposed behaviour influencing the results produced. This then allows us to examine whether the results are consistent with the experimental work.

RESULTS- CASE 8.4.41

The impact of the environment upon the occupant behaviour was examined whilst implementing the present model (in Scenario 8.4.411). From Table 8-34 no obvious trends or differences can be discerned from the numerous variables examined. All that can be said is that in this case the evacuation *times* generally increase in accordance with the physical effect of the environment and due to the complete absence of redirection. This then promotes excessive crowding around the primary exit, as all of the occupants, somewhat unrealistically, head for the same exit.

From the experimental and real-life data analysed, the factors examined should influence the likelihood of passing through smoke. From Table 8-35 these factors have a significant impact over the occurrence of redirection, once the proposed model has been implemented (in Scenario 8.4.412). As the occupants were completely familiar with the exit positioning in this scenario, this was not a factor in exit adoption or in the occupant's perception of the hazard.

The occupants are simulated as having variable levels of motivation. It would be unlikely that occupants confronted with difficult environmental conditions would be relatively unmotivated. However, the assumption of these conditions provides a useful comparison.

TABLE 8-34: EVACUATION TIMES (IN SECONDS) GENERATED FROM THE PRESENT MODEL (SCENARIO 8.4.411).

Male Occupants

Ext. Coeff. (l/m)	Age			
	25 years		12 years	
	Motivation			
	5	20	5	20
0.3	76.8 [70.1-81.3]	71.8 [70.1-73.9]	81.9 [72.2-87.8]	77.7 [65.6-78.2]
0.6	74.3 [70.8-86.2]	79.5 [70.8-86.3]	76.4 [71.4-82.1]	79.8 [78.4-81.9]
0.9	82.2 [80.9-84.1]	79.5 [77.9-82.1]	77 [63.3-85.4]	74.5 [71.3-77.6]

Female Occupants

Ext. Coeff. (l/m)	Age			
	25 years		12 years	
	Motivation			
	5	20	5	20
0.3	73.2 [68.1-75.1]	74.1 [70.3-78.6]	81.2 [77.6-83.2]	80.1 [75.6-82.6]
0.6	74.2 [75-2-77.6]	77.6 [75.6-80.2]	77.8 [75.6-82.0]	76.8 [72.6-79.6]
0.9	78.9 [75.6-81.1]	81.0 [75.6-82.6]	76.2 [72.9-78.9]	78.3 [75.3-79.6]

In line with expectation, *females are more likely to redirect than males*, with 50.6% of females choosing to redirect as compared to 41.7% of males (with females on average 1.2 times more likely to redirect). These results should be compared against those produced by Brennan and Wood, who found that females were approximately 1.19 times more likely to redirect than males [57,107]. Obviously this level of accuracy is purely attributable to the scenario and would not be expected in all circumstances.

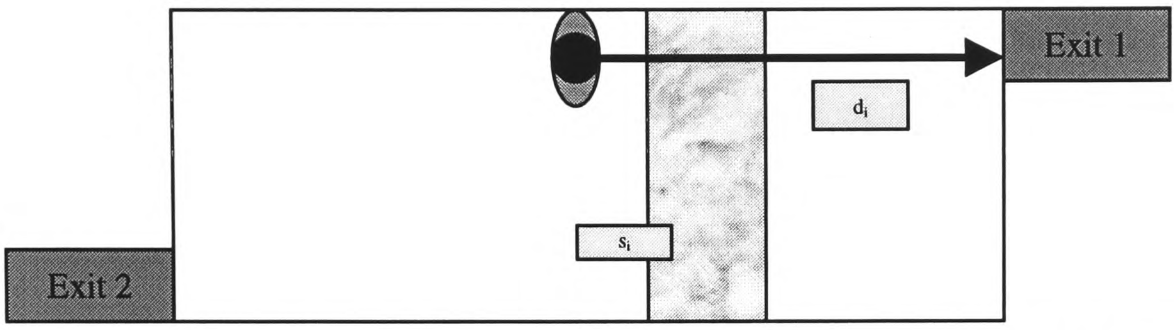


FIGURE 8-39: GEOMETRY USED IN THE VALIDATION CASE 8.4.41 AND 8.4.42. IF AWARE OF EXIT 1, OCCUPANT COULD APPROXIMATE DISTANCE D_1. HE WOULD BE AWARE OF THE EXTENT OF S_1.

Age also has an impact upon the behaviour of the occupants with the elderly and the young being more prone to redirection than others (see Table 8-35). It should be remembered that in this case, the young are used as a comparison and effectively represent the both the young population as well as the elderly. In these scenarios, the young are seen to be 1.15 times more likely to redirect. This again reflects the findings of Brennan, whose results suggest that the elderly and young are 1.3 times more likely to redirect [107]. Again, this result would not be expected, nor desired in all of the scenarios that might be examined.

Finally and most importantly, *the likelihood of all of the occupants redirecting increased as the density of the smoke increased.* This directly reflects the findings of Bryan[60] and Wood[57], as well as more anecdotal evidence [52,58,106] and is clearly shown in Figure 8-40.

TABLE 8-35: REDIRECTION PERCENTAGES PRODUCED FROM VALIDATION CASE 8.4.412.

Male occupants

Extinction coefficient (l/m)	Age			
	25 years		12 years	
	Motivation			
	5	20	5	20
0.3	42.6% [38-48]	14% [10-20]	55.4% [48-62]	23.4% [20-26]
0.6	55.6% [50-62]	23.4% [18-32]	56.6% [46-62]	28% [22-32]
0.9	67.6% [62-72]	29.4% [24-38]	69.4% [66-72]	35.4% [30-40]

Female occupants

Extinction coefficient (l/m)	Age			
	25 years		12 years	
	Motivation			
	5	20	5	20
0.3	60% [54-64]	24% [20-30]	60.6% [60-62]	28.6% [20-38]
0.6	70% [66-76]	32% [28-40]	70% [68-72]	33.4% [26-38]
0.9	71.4% [64-80]	37% [26-58]	80.6% [78-84]	39.4% [36-46]

The evacuation times generated provide a complex pattern (see Table 8-36). This is due to the number of different factors impacting upon the times generated. In this example, due to the possibility of occupant delay and the physical impediment of the environment, the redirective behaviour seems to *reduce* the evacuation times (see Figure 8-40).

This will certainly not always be the case, as the evacuation times will be dependent upon the distance to the exit that is the object of the redirective behaviour. Even in this example, the general level of redirection impacts significantly upon the success of the individual occupant's redirection. This is due to distant congestion at the secondary exit, delaying the occupant's progress (i.e. once the occupant has redirected they find that their secondary choice is congested).

TABLE 8-36: EVACUATION TIMES (IN SECONDS), PRODUCED FROM VALIDATION CASE 8.4.412.

Male Occupants

Ext. Coeff. (l/m)	Age			
	25 years		12 years	
	Motivation			
	5	20	5	20
0.3	61.0 [58.8-66.4]	67.5 [63.1-71.8]	59.3 [56.4-61]	61.4 [59.3-63.9]
0.6	67.7 [66.1-70.1]	69.1 [65.4-74.6]	61.6 [59.3-64.1]	60.5 [53.8-65.9]
0.9	67.4 [61.9-73.3]	63.5 [57.9-71.8]	72.3 [66.6-76.9]	56.2 [46.8-67.1]

Female Occupants

Ext. Coeff. (l/m)	Age			
	25 years		12 years	
	Motivation			
	5	20	5	20
0.3	57.7 [53.8-60.1]	58.4 [52.8-62.1]	62.5 [59.1-64.6]	52.1 [44.9-57.1]
0.6	73.3 [66.9-81.6]	59.2 [47.9-66.6]	68.9 [62.1-78.3]	50.1 [46.9-56.3]
0.9	72.3 [65.3-85.4]	57.9 [48.8-64.6]	75.1 [66.6-81.4]	58.7 [52.8-65.6]

Similar to the behaviour cited in Hewitt and Jones [58], occupants can make *incorrect decisions*. Here, in a simplistic geometry, occupants could easily have passed through the smoke without serious danger but instead redirected. This behaviour was replicated in the Hewitt and Jones examination, where several occupants refused to pass through smoke and instead redirected, encountering far more difficulties than if they had continued [58].

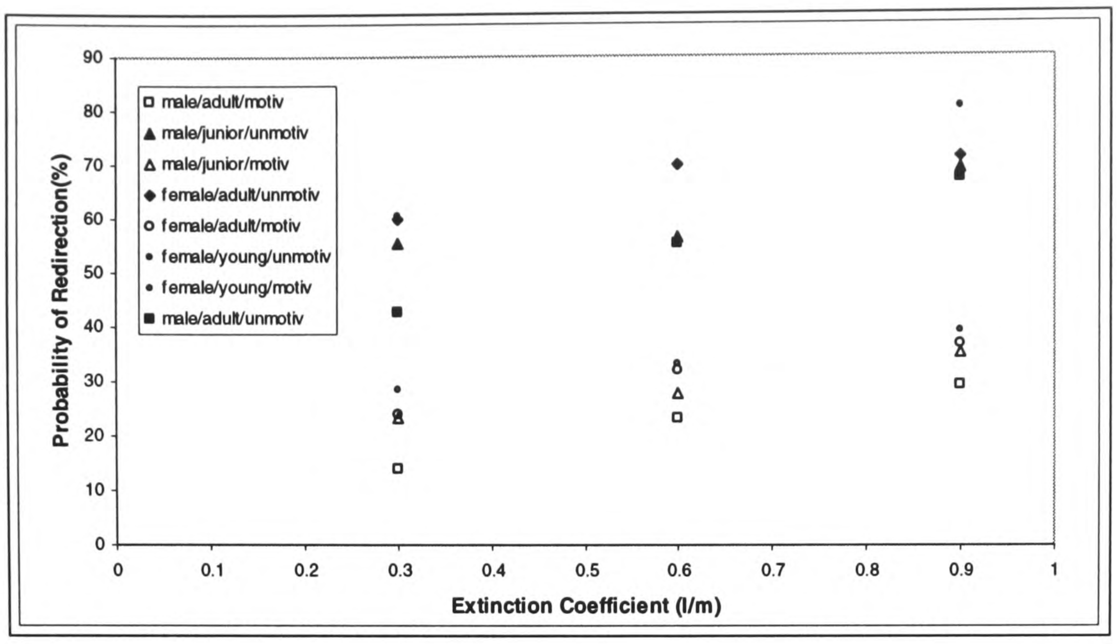


FIGURE 8-40: GRAPHICAL REPRESENTATION OF THE VARIABLES IMPACTING UPON THE REDIRECTION TO A SMOKE-FILLED ENVIRONMENT IN SCENARIO 8.4.412.

From Figure 8-40, the importance of motivation upon the occupant decision is evident, although still adhering to the general trends identified by Bryan et al [60]. These figures also reaffirm the importance of the extinction coefficient upon the probability of redirection.

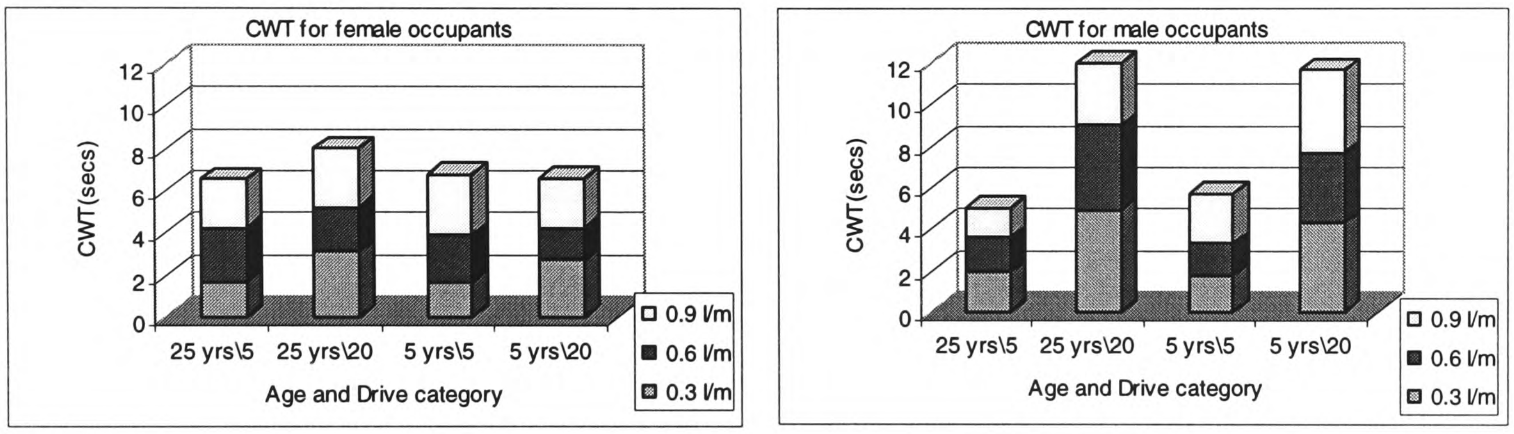


FIGURE 8-41: CUMULATIVE WAIT TIMES PRODUCED IN THE SIMULATIONS OF 8.4.412

It is possible to get a more detailed picture of the occupant activity from examining the figures generated and the cumulative wait time experienced by the occupants. From Figure 8-41 the impact of the variables (age, drive, gender and extinction coefficient) upon the occupant experience can be ascertained. *Those simulations that comprise of occupants less likely to redirect tend to have populations who have experienced longer wait times*. This is due to the greater occupant congestion around the main exit.

CASE 8.4.42

Case 8.4.42 is identical to the previous case except this time only a proportion of the occupants are aware of the more distant exit. This required the use of the door vector feature described in Chapter 7. The comparison is made between highly motivated adult males, as they are *most* likely to be fully aware given the mechanisms used in the production of the door vector, therefore reducing the impact of familiarity.

Approximately 20% of the population were aware of all of the exits, although this figure fluctuated between runs. The importance of this case is therefore to demonstrate the impact that occupant familiarity and subsequent behavioural developments can have upon this proposed behaviour.

RESULTS-CASE 8.4.42

The introduction of familiarity as an influence on redirection has important consequences. From Figure 8-42 a significant difference can be seen between the adoption rates of the alternative exit, with an average 78.9% reduction in the level of redirection exhibited between this case and the equivalent situation in 8.4.412. This is entirely due to the changing familiarity levels of the occupant population, as no other alterations were made in the conditions in this scenario.

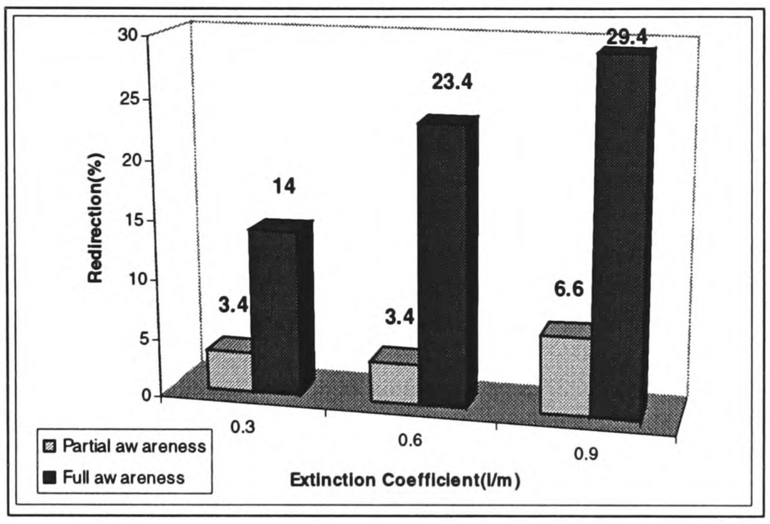


FIGURE 8-42: COMPARISON BETWEEN REDIRECTION INVOLVING FULL AWARENESS AND REDIRECTION INVOLVING PARTIAL AWARENESS.

A number of interesting observations can be made from examining Table 8-37 and Figure 8-42. Firstly, the distribution of the evacuation times has increased, as the environment conditions worsen. This is due to the delaying action of the occupants who do not immediately redirect, subsequently alleviating the crowding around the exit used. Due to the stochastic element involved in the occupant selection of actions, there is also a great degree of variation amongst the percentage of occupants redirecting. This distribution increases in relation to the extinction coefficient.

TABLE 8-37: RESULTS FROM EVACUATIONS INVOLVING A DISTRIBUTION OF EXIT FAMILIARITY (8.4.42).

Ext. Coef. (l/m)	Evac. Time (secs)	Occ. Redirection (%)
0.3	75.7 [73.3-78.6]	3.4 [2-6]
0.6	73.5 [69.6-78.3]	3.4 [0-6]
0.9	72.7 [58.9-81.8]	6.5 [4-10]

Note: the increase in the distribution of evacuation times is due to the additional impact if occupants did not redirect caused by immobilising effect of the smoke.

There is a progressive *reduction* in the evacuation times generated as the extinction coefficient is increased. In the previous scenarios crowding occurred at one or both of the exits which may have counteracted any advantage produced through redirection. In these cases, the reduced level of redirection, although providing some crowding at the secondary exit, alleviated the crowding at the primary exit without extending the overall evacuation time due to increased travel distances or secondary crowding.

CASE 8.4.43

The purpose of 8.4.43 is to demonstrate the sensible adoption of exits given that the occupant has redirected. An *anomalous* decision on the part of the occupant is deemed to be one where the occupant who has decided to redirect from their present course due to the presence of smoke, then redirects to another exit that *also* means travelling through the *same* area of smoke. This may be appropriate if other conditions prevailed, such as extensive crowding around one of the exits [52]. However, if the only influence upon the decision is the existence of a smoke barrier, then the expected behaviour would be to redirect away from the smoke.

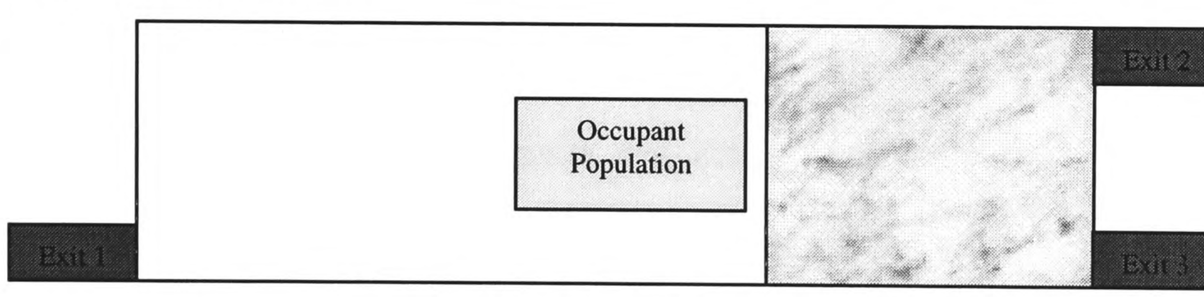


FIGURE 8-43: GEOMETRY USED IN 8.4.43.

The geometry has three 0.5m exits, two of which are beyond the smoke barrier. The occupants are familiar with the exits available. In this instance the exact dimensions of the exit are not irrelevant. Thirty occupants are positioned so that they desire to move through the smoke barrier towards their initial target exit (either exit 2 or exit 3). The density of the smoke is kept constant at an extinction coefficient of 0.7 l/m, as this has no impact upon this anomaly. A default population is used.

RESULTS-CASE 8.4.43

In this case, the actual evacuation times generated are relatively insignificant (although on average the occupants were evacuated within 36.7 seconds, ranging between 35.9 and 37.6 seconds). Far more important in this case, is the ability of the occupants to make sensible decisions in relation to the environmental conditions.

The occupants redirected, due to the presence of the smoke barrier, in the direction of exit 1 (positioned in the bottom-left hand corner of the geometry). Approximately 15.4 occupants, ranging from 14 to 17 occupants, redirected away from the smoke to exit 1. **There was no *redirection* towards exit 2 or exit 3** (see Figure 8-44), which would have meant the occupant changing direction and still passing through the smoke barrier.

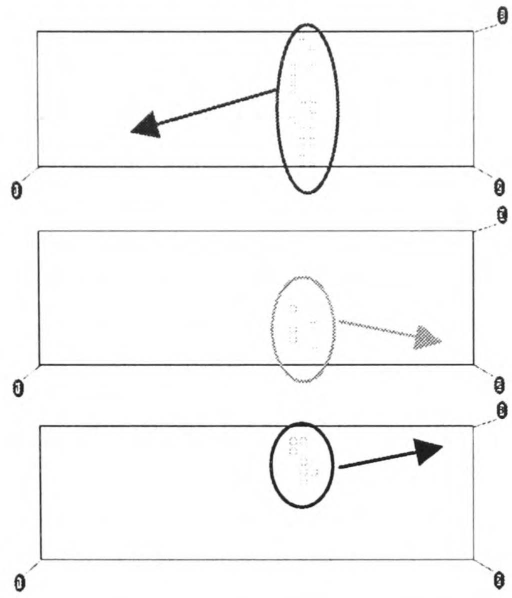


FIGURE 8-44:THE EXITS ADOPTED DURING A SIMULATION RUN. NOTICE THAT ONCE THE OCCUPANTS HAVE DECIDED TO MOVE THROUGH THE SMOKE THERE IS NO REDIRECTION TO A CLOSER EXIT.

Those occupants who were situated near to exit 3 either maintained their route or redirected to exit 1, avoiding the hazard altogether. The occupants nearest to exit 2 exhibited similar behaviour. On average 7.4 occupants used exit 2 (ranging between 6 to 9 occupants) while 7.2 occupants used exit 3 (ranging from 6 to 8 occupants). No 'cross over' was evident amongst the occupants and therefore no irrational exit choice was produced. This demonstrates that the algorithm does not allow *completely* irrational behaviour at an individual level, whereby occupants, who have decided to avoid the short-term contact with smoke, then redirect to another exit that also means passing through the same area of smoke.

CASE 8.4.44

A more complex enclosure is examined in 8.4.44. This has four exits, approximately 30 rooms and is populated by 150 occupants, who have a different relationship to the enclosure and therefore have different levels of familiarity. A smoke barrier is placed across the main exit to examine the impact of the adaptive decision-making process upon the evacuation time and the survival rates of the occupant population. This is initially set at an extremely high level of smoke density (1.0 l/m), simulating what might be expected in a real-life event. This then gradually increases throughout the evacuation (see Figure 8-45 and Figure 8-46). The exit closest to smoke-filled environment is deemed to be the main exit, therefore attracting the majority of occupants.

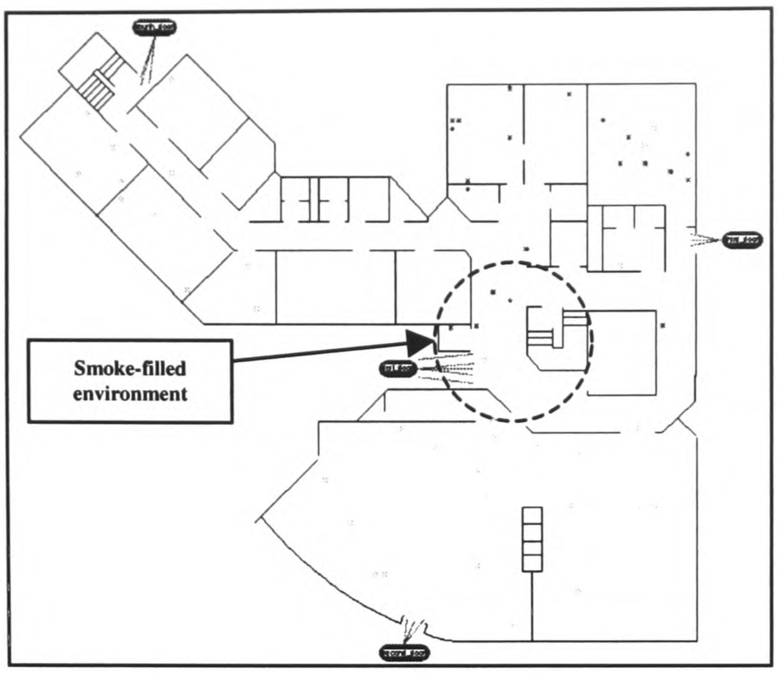


FIGURE 8-45: THE GEOMETRY USED IN 8.4.44.

The other three exits within the geometry are fire exits, and are biased so that their familiarity is not guaranteed to all of the occupants (see Chapter 7).

The method used to reflect the behaviour of the occupant population is altered to examine its impact upon their interaction with the smoke barrier (see Table 8-38). Initially, the present buildingEXODUS implementation is examined to provide a control case (Scenario 8.4.441).

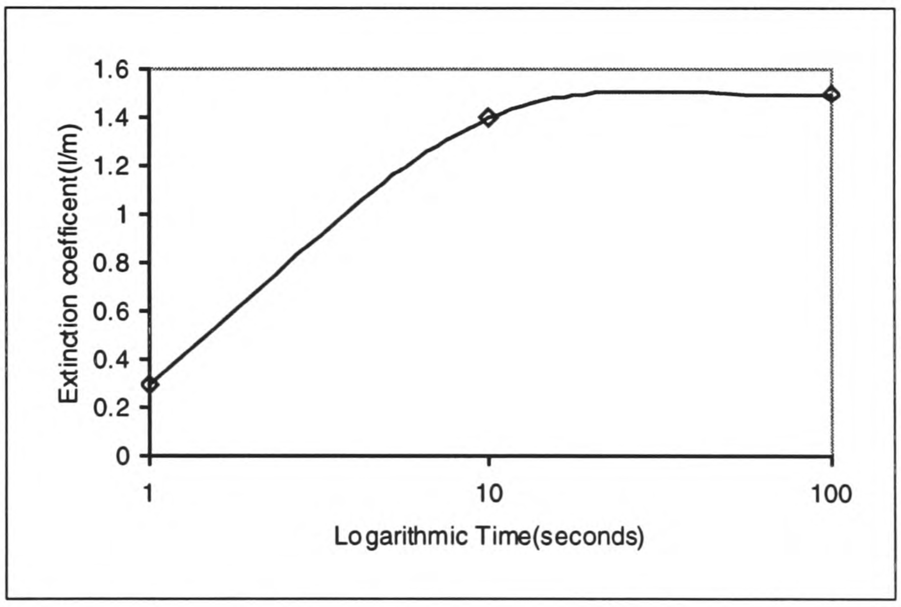


FIGURE 8-46: CHANGE IN THE SIMULATED EXTINCTION COEFFICIENT IN VALIDATION CASE 8.4.44.

The proposed behaviour is examined in four separate cases. In Scenario 8.4.442 a default population is implemented. Whilst implementing the proposed behaviour, the level of behavioural sophistication is increased in Scenario 8.4.443, allowing the occupant population to *communicate* the existence and availability of alternative exits. No explicit social grouping is imposed upon the population (i.e. none of the occupants are attributed with the social gene, see Chapter 5), so that the communication is based entirely upon emergent social behaviour, limiting the impact of communication upon the results.

TABLE 8-38: DESCRIPTION OF THE SCENARIOS EXAMINED IN 8.4.44

Scenario	Behavioural Model	Communication	Population
8.4.441	**Present**	**N/A**	**Default**
8.4.442	**Proposed**	**None**	**Default**
8.4.443	**Proposed**	**Emergent**	**Default**
8.4.444	**Proposed**	**None**	**Young/Female/Unmotivated**
8.4.445	**Proposed**	**None**	**Adult/Male/Motivated**

In the final cases, the population is made up of either unmotivated, young, female occupants (Scenario 8.4.444) or motivated, adult, male occupants (Scenario 8.4.445). This provides two extreme populations whose reaction to the smoke barrier should differ accordingly. Neither of these cases includes the communication behaviour.

Although the results produced are expected to be complex and scenario specific, they will allow us to examine the impact of the redirective behaviour upon a more realistic scenario. It also demonstrates the manner in which some of the more complex proposed behavioural developments interact with each other.

RESULTS-8.4.44

To provide a simple control case, the present version of buildingEXODUS is used to simulate the evacuation (see Table 8-39). Here the occupants initially head towards the main exit and encounter the smoke barrier. However no redirection occurred, increasing both the evacuation times and the time spent waiting by the occupants Table 8-39.

TABLE 8-39: RESULTS GENERATED THROUGH USE OF PRESENT MODEL IN REPRESENTING 8.4.441

Scenario	Percentage of occupants redirecting	Evacuation times(secs)	Avg. CWT(Secs)
8.4.441	0 [0-0]	125.9 [124.3-129.1]	4.1 [3.9-4.2]

In Scenario 8.4.442, where the proposed behaviour is implemented upon a default population, (see Table 8-40), 23.5% of the population are seen to redirect away from the smoke-filled area. Given the severity of the conditions, this is a relatively small proportion of the population redirecting away from the hazard. It should be remembered that the smoke is in close proximity to an exit. This would have affected the occupant's tenability calculations. In reality the occupant decision to redirect will be influenced by the actions and communication of others. Therefore a reduced figure should be expected. This level of redirection increases significantly (to 62.7%) once the occupants are allowed to communicate in Scenario 8.4.443. Even though there are no social relationships explicitly defined, due to the innate diversity of the population, significant communication occurs (described earlier in this chapter).

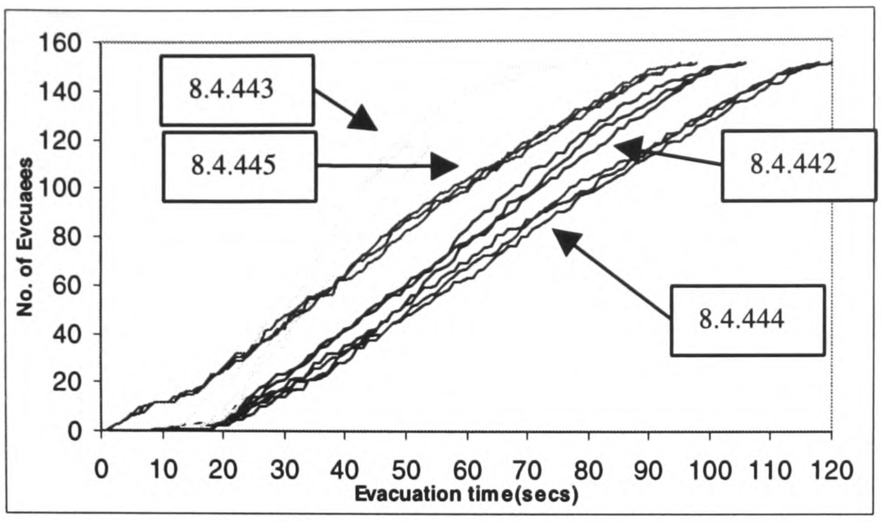


FIGURE 8-47: COMPARISON OF THE CUMULATIVE ARRIVAL CURVES FOR CASE 8.4.44.

It should be remembered that during scenario 8.4.443 no alteration was made to the level of familiarity within the occupant population of scenario 8.4.442. Therefore the increased redirection of the occupants is entirely due to the process of communication.

The final two scenarios (8.4.444 and 8.4.445) provide unexpected results. Paradoxically, the higher levels of redirection occur in Scenario 8.4.445, due to the greater familiarity of the more senior occupants with the enclosure. This compensates for the reduced likelihood of them redirecting (Table 8-40).

A number of factors can be observed from the cases described. In Scenario 8.4.445, the occupant arrivals begin earlier (see Figure 8-47). Due to the increased occupant familiarity, some occupants were able to initially adopt routes that prevented their interaction with the hazard, as they aware of fire exits positioned close-by.

The three cases implementing the proposed behaviour but not involving communication (Scenarios 8.4.442, 8.4.444 and 8.4.445) produce basically parallel arrival curves, as the redirection is determined according to the probability of occupants reacting to the smoke. In 8.4.443 however, the occupants may be redirected due to an interaction with the environment, or through the communication that may have occurred anywhere within the geometry. This factor accounts for the non-linearity in the arrival curves generated in Scenario 8.4.443 (see Figure 8-47).

This also provides some explanation as to why the occupants simulated in 8.4.443 have a relatively high waiting period (CWT), given the reduced evacuation times produced. These are due to the occupants arriving at the exits in close proximity. This is caused by the high degree of communication between occupants, unifying the direction of occupants in a small period of time, causing congestion once they arrive at the exit.

TABLE 8-40: RESULTS GENERATED IN VALIDATION CASE 8.4.444

Scenario	Percentage of occupants redirecting	Overall Evacuation times(secs)	Avg. CWT (secs)
8.4.442	24 [20-29]	105 [104-105]	1.7 [1.63-1.76]
8.4.443	63 [61-66]	75 [72-80]	2.3 [1.74-2.53]
8.4.444	13 [12-16]	119 [117-119]	2.9 [2.86-3.14]
8.4.445	19 [17-20]	96 [95-97]	2.3 [2.2-2.4]

The low CWT figure generated by Scenario 8.4.442 may be partially explained by the reduced level of conflict resolution, due to the greater distribution of drive levels within the population.

8.4.5 Future Work

It is important for the simulated occupants to decide the number of redirective activities performed. In this incarnation, the proposed behaviour only allows one redirection in an attempt to control the existence of anomalies within the algorithm. This is obviously an over-simplified view of the occupant behaviour seen in reality [57,60]. However, more research is required concerning the relationship between occupant motivation and the number of times the occupant is prepared to redirect before it is introduced into the model.

The method could also involve the impact of heat and of toxins upon the occupant decision making process. The impact of this effect would be more subtle, relating to either specialist knowledge of the materials involved in the fire, or to physiological effects.

As highlighted previously, it might be useful to have occupants turning away from smoke filled environment even if no other alternative targets exist. This may involve a more complex wayfinding algorithm to be implemented, but would provide a useful asset that might be used in other behavioural features. This type of algorithm should also be capable of allowing the occupant to move back towards areas previously occupied. This requires storing previous locations and the environment at those locations, reflecting the tenability of that position. It should also be possible to redirect to another *route* rather than to another exit. Here the occupant may still head towards the same external exit, but may adopt a more circuitous route to get there, avoiding the environmental difficulties.

Instead of imposing probabilities upon the occupant that influence the performance of individual actions, these actions should be entirely dependent upon calculations involving internal occupant attributes. Initial conditions may be dependent (although not entirely) upon acquired probabilities, but would not determine the eventual behaviour. The likelihood of redirection would therefore be influenced far more by the individual history of the occupant as well as the context of the decision, rather than the general expectations of the entire population. Therefore, the decision-making process in response to the environment might be based around similar considerations as those used in the response to congestion.

The algorithm highlighted is only able to obtain information concerning the environment once the occupant is adjacent to a node affected by smoke. The ability of occupants to determine the density of smoke at a distance, would be a significant improvement. This might be based around the line-of–sight calculations in Section 5.4, Chapter 5, but would involve either the seat of the fire or of the smoke environment being described and recorded.

The distance that the occupant has travelled to reach the smoke-filled environment [106] should influence the occupant's decision. If the occupant has committed a large amount of resources into attaining a particular goal (e.g. travelled a large distance to reach an exit), then it is assumed that they are more likely to maintain their present direction rather than recommit to a new target [4,101-102,200]. Due to the present complexity of the behaviour, this is left for future development.

8.4.6 Conclusion

It is conceded that the proposed behaviour is an initial step in representing the occupant reaction to a potential smoke hazard. It certainly requires a number of advances similar to those relating to collective behaviour and queuing behaviour (refer to earlier in this chapter). However, the validation cases have demonstrated that the proposed behaviour does significantly increase the functionality of the model. It does this inline with the existing experimental and real-life data-sets.

The proposed behaviour also credits the simulated occupants with the ability to analyse their surrounds and adapt their egress accordingly. This is not a precursor to optimal evacuation, as the occupant is in possession of a limited knowledge set. It is, however, dependent upon the information levels of the occupant who may then evacuate according to local knowledge, rather than evacuating rationally according to global knowledge.

It should be reiterated that the appropriateness of the proposed behaviour is dependent upon the secondary data on which the behaviour is based. As new and more sophisticated evidence arises, so the proposed behaviour can evolve. The behaviour should not be expected to reflect the research findings exactly. This is due to both the differences in the mechanisms used in producing the behaviour and the inevitable differences in the scenarios examined. All that can be expected is that if dominant trends and influences exist within the research then they should also be reflected in the proposed behaviour.

8.5 The adaptation of the occupant to the evacuation: Concluding Remarks

The adaptive process described in this chapter marks a qualitative shift in the representation of the occupant and the subsequent behaviour (see Table 8-41). Instead of seeing the occupant as passively responding to the events around him, he is represented as anticipating and producing a response that is suitable to the conditions perceived. The ability of the occupant to perform such a task is obviously not represented as being uniform, but instead takes into account the heterogeneous quality of the population. Not only is the occupant now credited with the ability to proactively shape their immediate future, but is now seen in context with the social structures around them. These structures and the relationships that they represent influence the levels of communication, the perception of the information and the subsequent decisions of the occupant. Instead of the occupant reacting to the physical environment, they now perceives, interprets and engages in an environment shaped by sociological, psychological and physical influences that surround him.

Table 8-41: Summary of the behavioural developments in this chapter

Section	Development	Description
8.1	Adaptive Response to Crowd Formation	Enables occupants to select egress route according to exit congestion
8.2	Adaptive Response to Crowd Formation From Afar	Enables occupants to select egress route according to exit congestion prior to reaching the exit
8.3	Adaptive Response to Information	Enables the occupants to be sensitive to the provision of information via communication
8.4	Adaptive Response to the Environment	Enables occupants to adapt their egress route according to the environmental conditions

CHAPTER 9 THE BEVERLY HILLS SUPPER CLUB CASE

Until now the cases used for verification of the new behavioural features have generally been hypothetical, specifically designed to investigate the developments *individually*, or have involved simplistic real-life incidents that were used to demonstrate a *single* behavioural feature. Only in isolated cases was more than one behavioural feature examined simultaneously. This was largely due to the more complex behavioural developments requiring the less sophisticated behavioural features described in Chapter 5 to function properly and therefore to be investigated thoroughly.

In this chapter, a real-life incident has been selected to examine all of the new behavioural features simultaneously. The case selected is the Beverly Hills Supper Club incident of 1975. Information concerning this incident is based on several sources, primarily the post incident report, "*Reconstruction of a Tragedy*"[52] and a number of relevant papers by Feinberg and Johnson, as well as several newspaper articles on the subject [49-52,187,207,226]. This case has been selected because of the relatively exhaustive analysis that was conducted concerning the development and outcome of the incident. The existence of a relatively complete data-set allows a detailed analysis of the new behavioural features and, due to the complexity and scale of the incident, will require the use of the majority of the behavioural features in order to replicate the observed behaviour. However, even in this case, it is unlikely that all of the new behavioural features will be activated simultaneously. Indeed, part of the verification process is to demonstrate that the behavioural algorithms are activated at appropriate times.

The main purpose behind this chapter is to demonstrate that the developments outlined in this dissertation maintain or *improve* upon the ability of the model to simulate actual evacuation behaviour. Due to the nature of the data-set, a thorough quantitative comparison is prevented. However, the behavioural developments are expected to improve upon the qualitative aspects of the behavioural activities of the simulated occupants. Clearly the ability of the model to qualitatively represent the occupant behaviour will have an impact upon its quantitative capability. Most importantly, the model is examined to determine its sensitivity to the changing conditions within a simulation and the decision-making process that is utilised in response to the changing environment. The behavioural actions of the occupants are therefore investigated, as a reflection of these processes, examining the context in which actions are performed, the processes through which the occupant passes, the decisions made and the effects of these decisions on the decision-maker and upon those around him. The ability of the behavioural developments to be utilised simultaneously is also examined for anomalies and for unforeseen eventualities.

9.1 The Incident

On the 28th of May 1975, in the early evening, an electrical fire started in the 'Zebra Room' of the Beverly Hills Supper Club [52] (see Figure 9-1) . The two-storey enclosure was a well-known night-spot (known as the 'the Showplace of the Nation') and was a popular destination for famous cabaret entertainers [52]. The club was a large, complex structure (covering approximately 65,500ft^2), being formed from numerous dining rooms, cabaret rooms, function rooms and lounges. Although it was designed to be occupied by approximately 1500 occupants (being classified as a place of assembly), at the time of the incident between 2400-2800 patrons were located on the premises.

On the evening of the 28th, the fire and smoke spread rapidly throughout the building, eventually leading to 164 fatalities. Of these fatalities, 162 were situated in the Cabaret room, where between 1200 and 1300 patrons were awaiting the evening's entertainment (see Figure 9-1). These fatalities were situated around two previously unfamiliar exits (see Figure 9-2), the use of which was forced upon the patrons by the conditions (see Figure 9-3). The Zebra room, which was the seat of the fire, was an unoccupied 'cubby hole' [52], allowing the fire to develop for an extended period of time prior to the fires discovery. Due to the rapid evolution of the incident, the two fire exits in the Cabaret room (exit A and exit B, see Figure 9-3) proved incapable of coping with the huge occupant load placed upon them (between 1200-1300 occupants) in the short passage of time permitted. Extensive congestion arose around these exits, especially the northern exit (exit A in Figure 9-3) due to the difficulties presented by the structure's geometry. These occupants were overcome by the arrival of smoke and toxic gases causing incapacitation. The other fatalities in the building were situated on the second floor, caused by the isolation of the position and a complete lack of egress routes at that stage.

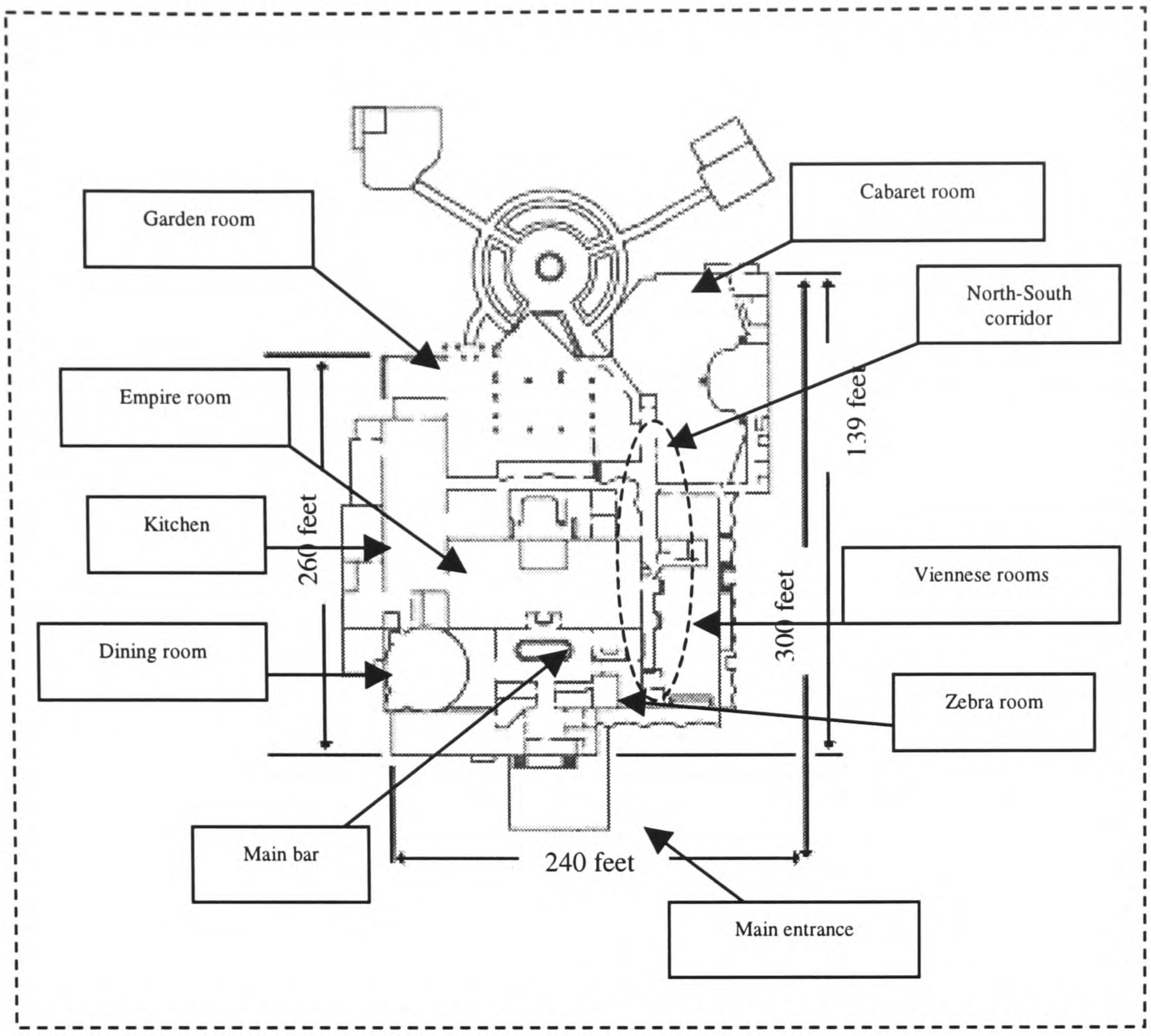


FIGURE 9-1: PLAN VIEW OF THE GROUND FLOOR OF THE BEVERLY HILLS SUPPER CLUB [226]

The high death toll of the event was attributed to a number of factors [52], including

1. The lack of a sprinkler or alarm system
2. The materials used in the enclosure contributing to the spread of the flames
3. The excessive number of occupants in the enclosure not being catered for by sufficient means of egress
4. The delay in informing the patrons of the incident due to the attempt of the employees to extinguish the fire.
5. The lack of an evacuation plan or employee training

The complexity of the enclosure and the limiting effect that it had upon communication also certainly contributed to the high death toll (see Figure 9-1). However, a more horrific tragedy was avoided by the actions of the employees, who eventually guided and informed patrons to a safe exit. Without this information, the death toll would have certainly been higher. The event was most notable by the dedication and selflessness of the employees [49-50,52]. As recorded in the original report

"A definite pattern was observed in the employee actions described in the transcripts – that employees, when made aware of the fire emergency, returned to the room and party that they had been serving prior to the notification. Employees made certain that their rooms or their parties exited to safety, and seemed to assume a responsibility for those customers they were serving, but not necessarily for customers in other parts of the building." [52]

The chronology of the event was relatively complex. A brief account is provided, although some simplifications are made. On the evening of the incident, patrons began to arrive at the club between 7p.m. and 7.30p.m. The fire was discovered at approximately 8.45p.m. by members of staff who attempted to fight the fire prior to informing the patrons. Some of the patrons who were situated near to the Zebra room also became aware at this stage. The majority of the occupants in the main rooms (the Viennese, the Empire and the Garden room) were notified by employees by approximately 9p.m., prior to serious environmental deterioration (see Figure 9-4). Those in the Cabaret room only became aware of the incident at 9.06p.m. The Cabaret Room was completely engulfed by smoke by 9.11p.m., at which stage no means of escape was available without significant interaction with the smoke. Details of the progression of the smoke and the consequent reduction in the availability of egress routes can be seen in Figure 9-5.

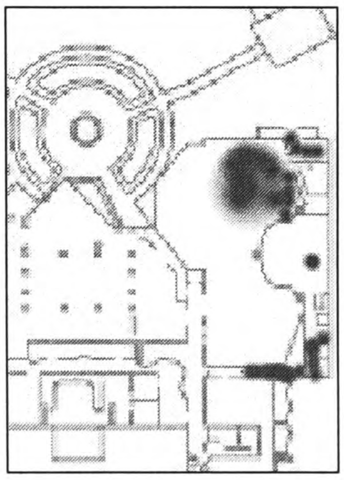


FIGURE 9-2: POSITION OF FATALITIES IN THE CLUB (DENOTED BY DARK AREAS).

A geometric feature that is frequently referred to due during the following text is the north-south corridor (see Figure 9-1). This leads from the main bar area from the Zebra room, past the Viennese room and the Empire room up to the Garden room and the Cabaret room. This provided the means of smoke and fire spread during the incident. It is particularly important in the decision-making process of the patrons, as it provides access to the main entrance at the south end of the structure. This was the only means of exit familiar to the vast majority of the occupants of the Beverly Hills Supper Club on the evening of the incident.

9.2 THE NATURE OF THE DATA COLLECTED

A detailed questionnaire and interview procedure was conducted to ascertain the evolution of the incident and the patron response. Some 1117 of the patrons responded to the questionnaire, 630 patrons were interviewed and 18 staff members were also approached. Therefore a *relatively* comprehensive understanding of the experiences of those involved were obtained. Most notably lacking in this data was the exact path adopted by the majority of occupants (e.g. the exits used), the exact starting locations of the evacuees involved and the evacuation times, especially relating to individual exits. However, the detailed qualitative understanding of the behaviour somewhat compensates for these omissions (see Figure 9-3, Figure 9-4, Figure 9-6, Figure 9-8 and Figure 9-9).

The omissions in the data collected prevent a detailed *quantitative* analysis. As described in Section 9.2.1 these omissions were not limited to the collection of data from the occupant population, but extended to the data available concerning the environmental conditions. The omissions concerning the environmental conditions were largely caused by technical practicalities such as the difficulty in recording environmental data without specialist equipment. The omissions concerning the data extracted from the evacuees was influenced by the design of the questionnaire but was also hindered by less avoidable problems such as the impossibility of a complete evacuee record where fatalities are involved.

The detailed responses to both the interviews and the questionnaires, as well as the experimental findings concerning the environment, enable a detailed *qualitative* examination of both the model currently used and the new behavioural features. It is still possible to perform modelling with the information provided but the quantitative accuracy of the results cannot be demonstrated, as relatively few comparisons can be made to determine the accuracy of the results.

In the remainder of this section, details are supplied concerning the three main areas examined during the simulation process. These are the Cabaret room, the Garden room and the Main bar and Dining room area. The original report should be examined for details on the other areas of the structure [52].The following information was gleaned from the response to occupant survey, as well as other sources [49-52,187,207,226].

9.2.1 The Fire

The progression of the smoke throughout the structure was rapid (see Figure 9-7). The rapidity of the environmental decline caught both the staff and the patrons unaware. Most significant was the limited time it took for the arrival of the fire after the smoke had first been spotted (see Figure 9-9). The arrival of smoke, especially in the areas some distance from the seat of the fire, denoted the imminent arrival of fire and the consequent increase in fatalities. The progression of the smoke and fire had reduced the number of viable (i.e. not encountering a deteriorating environmental conditions) egress routes from 43 prior to the fire, to 5 by 9p.m., and zero after 9.05p.m (see Figure 9-5 and Figure 9-9). After this time, the evacuees would experience declining environmental conditions. The occupant response in each of these areas will now be detailed.

Post-incident experiments were conducted to determine the possible intensity and toxicity of the smoke generated. Obviously these experiments did not describe the conditions that specific locations experienced or at which time-frame this might have occurred. This would have been an extremely difficult task, except under controlled conditions, with the necessary equipment in place prior to the incident. The post-incident experimental results do however, present some information concerning typical concentrations of toxins that may have been present during the latter time-frames of the incident. From this, an approximation of the environmental conditions can be ascertained. These conditions derived from the experiments are a *corrected* optical density of between 95-580/m, a HCl concentration of between 0 and 12 ppm, a HCN concentration of 2-31 ppm and a CO concentration of 1000-1500 ppm. Again, the experimental results do not adequately describe the conditions to which the patrons would have been exposed. The original report describes the type of impact that the smoke may have had upon the patrons,

"This smoke would have appeared to be dark-almost black- to the occupant. In addition, it would have been extremely irritating, causing tearing to the eyes and a burning sensation to the nose".[52]

This effect may have been more immediate and important to the egress of evacuees than the other aspects of the deteriorating environment. The experimental results therefore can only be seen as providing guidelines as to the toxicological effluent of specific materials, rather than providing an adequate description as to the tenability or the psychological impact of the environmental in general.

9.2.2 The Garden Room

The Garden room was adjacent to the Cabaret room at the north end of the structure, some distance from the seat of the fire (see Figure 9-1, Figure 9-3 and Figure 9-11). Approximately 200-300 patrons were already located in the room, by the time the incident occurred. These patrons were seated, having already started or awaiting dinner. Several patrons were queuing outside of the Garden room, in the North-south corridor, waiting to be seated within. The occupants in the Garden room would have entered the enclosure via exit D at the southern end of the enclosure, moved along the main corridor (the North-south corridor) and into the Garden room at the eastern side of the room (see Figure 9-3).

Members of staff were originally moving towards the Main bar but returned due to the presence of smoke to notify the patrons within the Garden room of the incident (see Figure 9-1 and Figure 9-4) [52]. The patrons in the Garden room were previously unaware of the incident and were relatively inexperienced with the use of the fire exits available to them (see Figure 9-1 and Figure 9-4). These were then evacuated through exits H, F and G and out through the kitchen to Exit E (see Figure 9-3 and Figure 9-11). To the majority of the patrons these would not have been familiar routes, prior to their communication with the member of staff. Normally, they would have used the internal exit leading to the North-south corridor to move around the enclosure. Although potentially obscured by drapery and other obstacles, Exits F,G and H may have been visible to the patrons in the room. However, the exit reached by travelling through the kitchen was not visible to the patrons (see Figure 9-3). No data is available concerning the exact numbers of occupants using the exits available. All that can be noted is that during questioning of those involved, all of these exits were reported as being used by the patrons as escape routes.

Due to the prompt action of the staff, the patrons in the Garden Room evacuated without significant interaction with the environmental conditions (see Figure 9-6) and prior to the loss of all of the potential egress routes (see Figure 9-5). Therefore the main events affecting the outcome of the evacuation of the Garden room was the interaction between the staff and the environment, a decision by the staff members to return to the patrons, their notification of the event, the patrons accepting the authority and advice of the staff and the potential evacuation routes and their eventual usage.

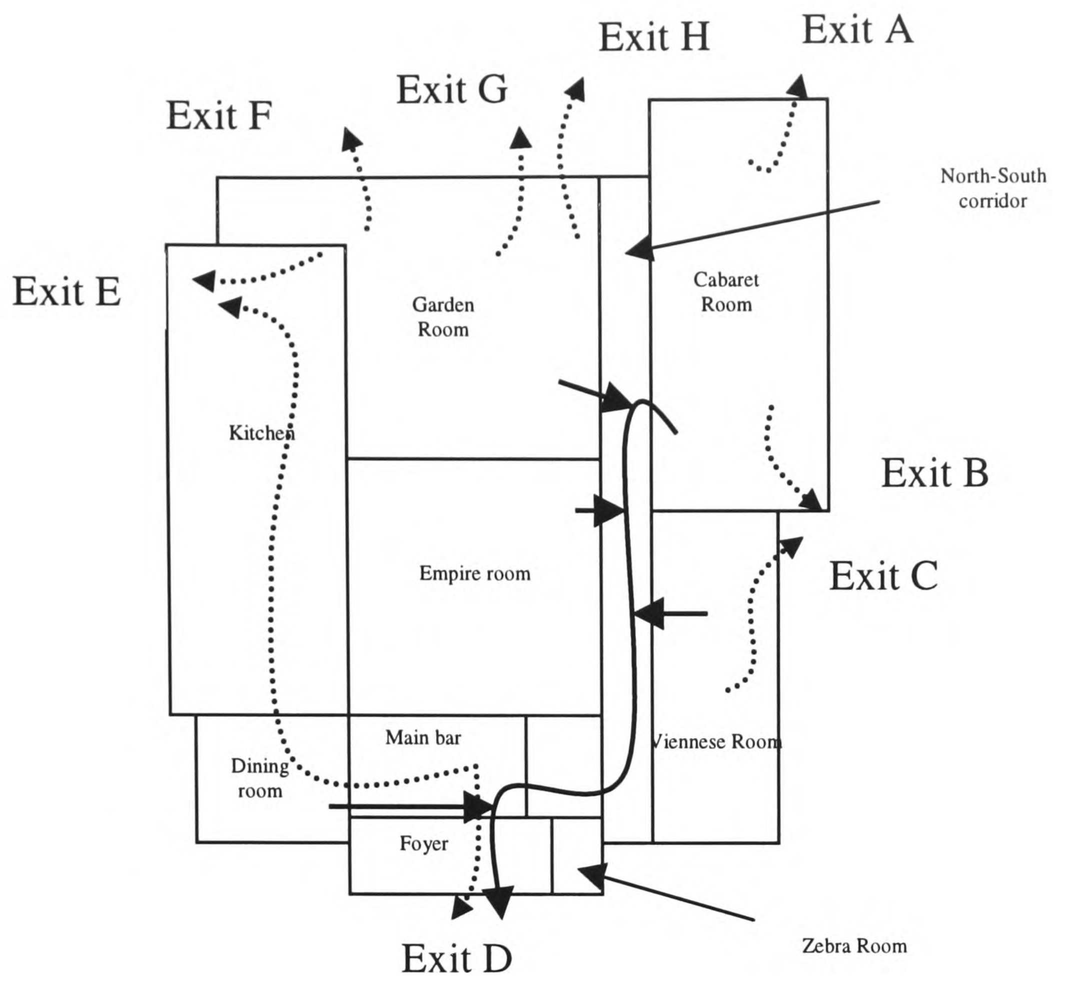


FIGURE 9-3: BOLD MARKINGS INDICATE THE ROUTES FAMILIAR TO THE PATRONS. THE DASHED MARKINGS INDICATE THE EVACUATION ROUTES ADOPTED BY PATRONS

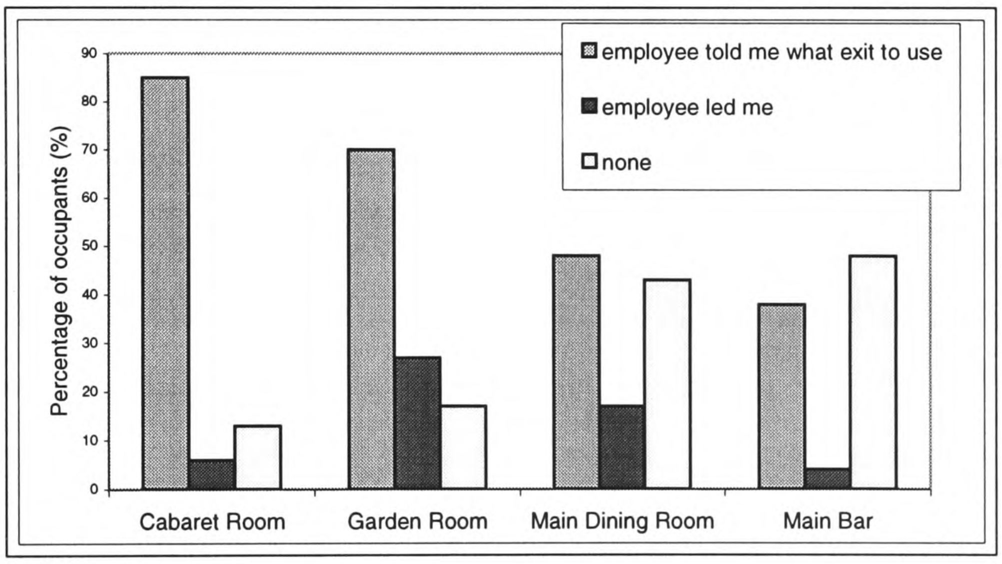


FIGURE 9-4: EMPLOYEE ACTIONS ACCORDING TO AREA [52].

9.2.3 MAIN BAR, DINING ROOM AND KITCHEN AREA

The Main bar, Dining room and Kitchen area (see Figure 9-1) was particularly interesting because of the complexity of the behaviour demonstrated. Approximately 100-125 occupants in the Main bar were evacuated relatively early on in the incident, due to their close proximity to the incident and through staff intervention. These patrons would have previously been enjoying drinks or refreshments in the Main bar and Dining room area. The kitchen would have only been occupied by staff members and would previously have not been used by members of the public.

Almost a quarter of these patrons first became aware of the incident through contact with smoke [52], although the vast majority of them were not hindered by its presence (see Figure 9-6 and Figure 9-7). This allowed them to be sensitive to the existence of the incident and to be aware of the potential danger that it posed. These patrons then evacuated through the main exit; the exit through which they would have entered the building, experiencing some congestion due to the large number of evacuating people (see Figure 9-3).

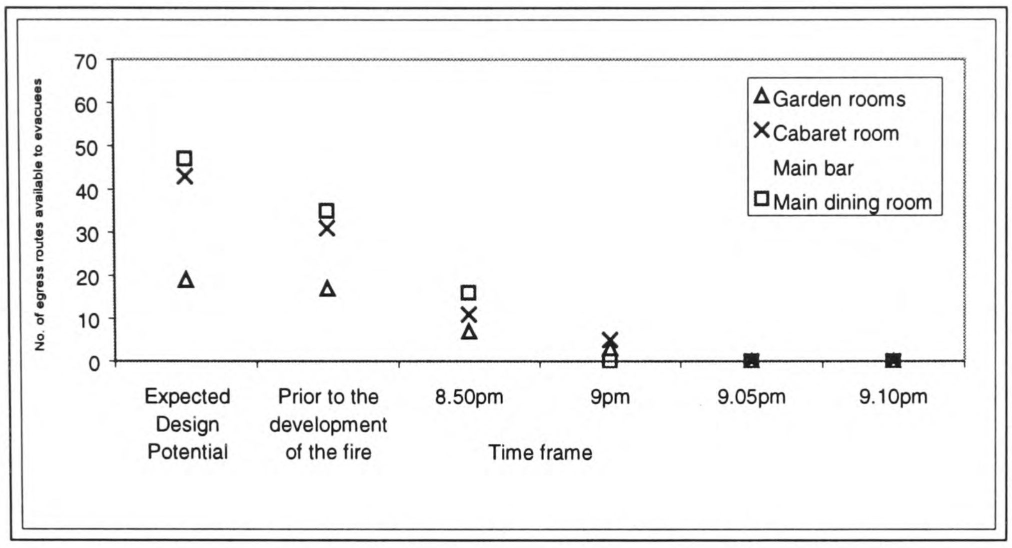


FIGURE 9-5: DEGRADATION OF ESCAPE ROUTES FROM PARTICULAR LOCATION

Again, between 100-125 patrons were originally situated in the Dining room, who were eating or preparing to eat their evening meal. Several patrons from the Dining room became aware of the situation and moved into the Main bar. These were repelled back into the Dining room due to congestion and the increasing presence of smoke (see Figure 9-6). At this stage, the employees arrived, informing the 100-125 patrons of the incident and guiding them out through the kitchen area, an area with which they would have previously been unfamiliar (see Figure 9-3). Without this information, these patrons would have eventually been alerted by the worsening conditions, but would have only been able to evacuate out through the main exit where congestion was already present (see Figure 9-4).

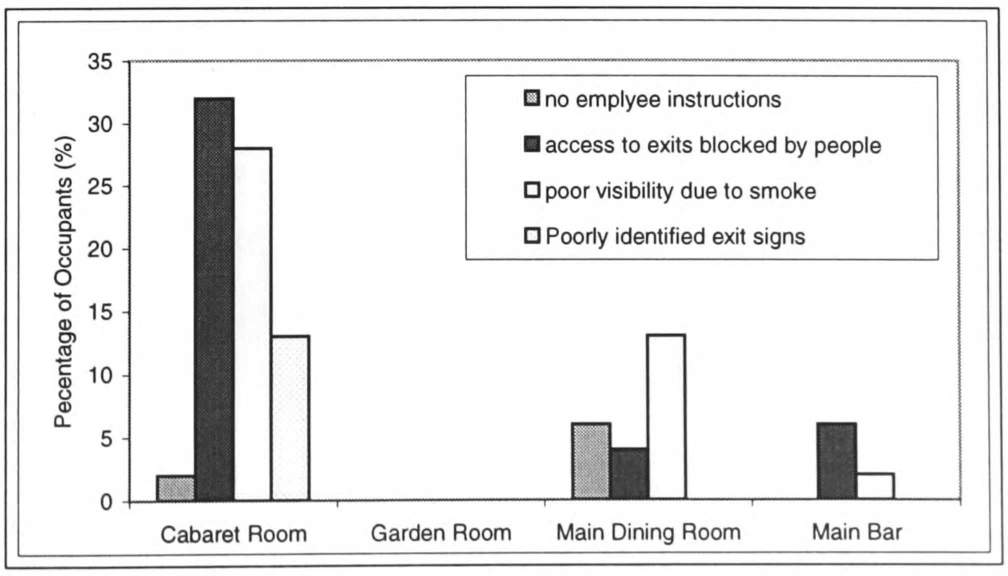


FIGURE 9-6: EXPERIENCES OF PATRONS EVACUATING [52].

9.2.4 The Cabaret Room

The Cabaret room was a complex enclosure, containing many tables, chairs, a raised stage area, railings that separated portions of the room and different levels. The exits available from the Cabaret room were exits A and B (that lead directly to the outside of the enclosure) and the internal exit into the North-south corridor, of which only the internal exit would have normally been used by the patrons (see Figure 9-3). To arrive at the Cabaret room, the patrons would have normally entered via exit D at the southern end of the structure, and moved allow the North-south corridor until they reached the Cabaret room.

The Cabaret room had approximately 1200-1300 patrons occupying the room when the incident occurred. This room was situated at the northern end of the structure, some distance from the fire source (see Figure 9-1). Due to its relative distance and isolation, the patrons in the Cabaret room were dependent upon the employees for information concerning the incident prior to it becoming a serious threat (see Figure 9-4). Without this information, the patrons would only perceive the incident through personal contact, at which stage the fire would have been fully developed and would have posed a significant threat to their well being. Even with the early warning provided by the member of staff, the large occupant load caused significant delays to the evacuation of the patrons in the Cabaret room.

The patrons were initially notified by a member of staff (the busboy Walter Bailey [52,226]), whose intelligent reaction undoubtedly saved hundreds of lives. He climbed onto the stage in the centre of the room and informed the crowd of the incident (see Figure 9-4). This information was not immediately accepted as being important by the patrons who had previously been enjoying dinner and entertainment. Patrons either believed that it was part of a drill, that the incident was not particularly serious or (worst of all) that Walter Bailey was part of the comedy act that had been interrupted [52]. One patron estimated that only between 30-40% of the patrons perceived the information as being serious enough to evacuate immediately [52].However, after further prompting, the patrons began to move off.

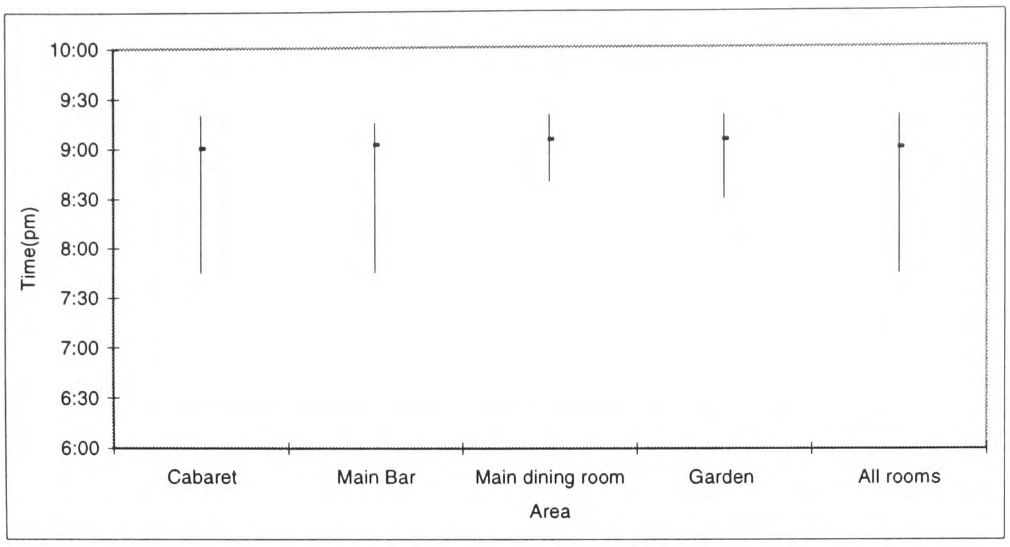


FIGURE 9-7: FIRST ARRIVAL OF SMOKE. THE BAR REPRESENTS THE DISTRIBUTION OF TIMES, THE TICK, REPRESENTS THE MEDIAN.

The majority of the patrons within the Cabaret Room cited instruction by a staff member as their reason for leaving (see Figure 9-4). The actions of the busboy [52] enabled the *majority* of the patrons to evacuate prior to the degradation of the environmental conditions, giving them priceless additional evacuation time, amounting to several minutes, before the environmental conditions became critical (see Figure 9-6). He also informed patrons of previously unfamiliar exits that by this stage were the only viable routes of exit (see Figure 9-3 and Figure 9-4). Until this point the patrons would have generally only used the main entrance, which was now blocked because of the arrival of smoke. Not only did Walter Bailey point out the existence of the fire exits but gave instruction as to which sections of the population should use which exit

The patrons were encouraged to use these newly familiar exits to evacuate given the rapid decline in the availability of alternative routes. The design of the structure (limited signage and complex geometry [52,226]) also restricted the likelihood that occupants would become aware of exits on their own, although some cases of this were still recorded (see Figure 9-6). Exit A was accessible by passing through a bar and a single internal exit. This was to prove important in the subsequent tragedy. Access to Exit B, although still involving movement through internal exits, did not present such a bottleneck as the approach to Exit A, as more than one internal exit lead to Exit B, alleviating the congestion.

Although the patrons were generally calm, congestion occurred at Exit A and Exit B, caused by the complex configuration and the excessive occupant load (see Figure 9-6). Patrons were seen to redirect between potential routes, especially around the barriers and to avoid congestion. Indeed the level of congestion was noted in the questionnaires, where 32% of the patrons confirmed that they had difficulty evacuating due to congestion (see Figure 9-6).

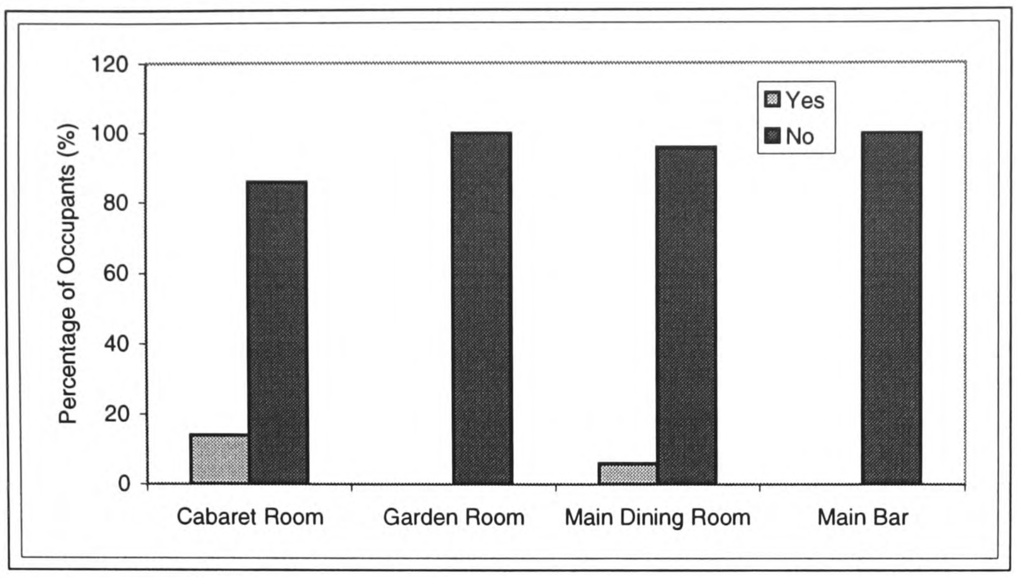


FIGURE 9-8: REPRESENTATION OF WHETHER THE PATRONS EXPERIENCED DIFFICULTY LOCATING AN EXIT [52]. SORTED ACCORDING TO LOCATION.

These problems were compounded by the arrival of smoke, which had progressed along the north-south corridor. This arrival made the attempts at evacuation more desperate and erratic [52]. Of the patrons located in the Cabaret room, 28% reported that they had interacted with smoke (see Figure 9-6). This therefore increased the level of urgency of the patrons and impeded the evacuation process. Eventually the conditions led to 162 fatalities in the room (with approximately 70% being situated around exit A).

Although initially clear, the room was completely engulfed in smoke within approximately 5 minutes (see Figure 9-7) [52]. After this period of time, the majority of occupants who remained inside the Cabaret room were killed due to the arrival of acrid smoke or the rapid later arrival of the fire itself that had spread along the north-south corridor. From Figure 9-9 it is apparent that the occupants in the Cabaret room tended to have approximately 5 minutes between the arrival of smoke and the arrival of flames. Of the 164 people that were killed during the incident, the vast majority perished in the Cabaret room [52,226]. One hundred and twelve victims were located around Exit A. Twelve victims were found trapped behind the bar area. Thirty-five victims were found around Exit B. (The other victims died in hospital or in hospital facilities [52,226]).

Most notable of the behaviour in the Cabaret room, was the initial lack of structural familiarity of the patron population, their lack of awareness of the incident, the arrival of an information source, the acceptance and use of this information, and the eventual occurrence of congestion and declining environmental conditions.

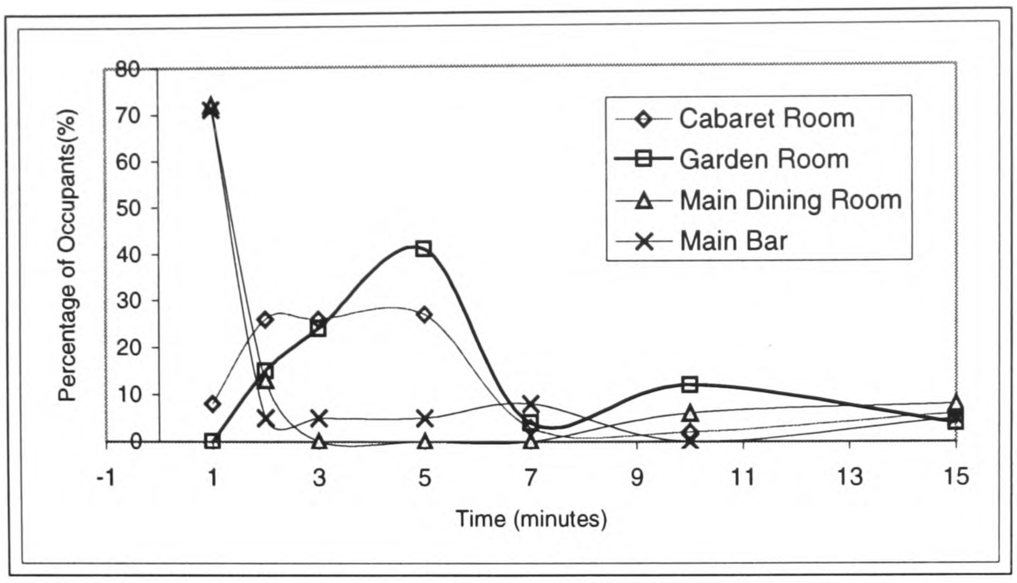


FIGURE 9-9: TIME BETWEEN PATRONS EXPERIENCING SMOKE AND THEN FIRE [52].

9.3 VERIFICATION CASES

It would have been possible to model the entire structure within the buildingEXODUS evacuation model (both that presently available and the new model). This process might have detracted from the detail required for behavioural analysis, due to the complexity of the enclosure and the number of evacuees involved. Therefore, only three of the major structural components are included here to demonstrate the new behavioural features and the advancements that they may provide. This enables a more rigorous analysis of the occupant response and the context in which it occurred. For further details on the other areas of the structure, the reader is encouraged to refer to the original report [52].

The three areas that are examined are the Garden room (in Case 9.41), the Main bar area (in Case 9.42) and the Cabaret room (in Case 9.43). These have been selected because of the behavioural complexity of the occupant response. Indeed behaviour exhibited by the patrons from the components that are not simulated, form a subset of those represented. This required the maximum number of the new behavioural features to be implemented to reflect the occupant behaviour and therefore allows an analysis of nearly all of the new features simultaneously.

Due to the lack of specific details concerning the exit usage and the evacuation times, the analysis concentrates upon the *behaviour* of the simulated occupants, the situations in which the behaviour occurred and how the simulated behaviour compares to the original behavioural actions. An indicator of this behaviour will, of course, include exit usage and the eventual evacuation time, but only limited comparison between this and the original data will be made.

Each of the cases are repeated ten times to generate a distribution of results. The randomisation procedure is conducted such that the numbers of occupants within each of the specified areas remain the same. The cases are now described.

In each of the cases the current release version of the buildingEXODUS evacuation model is initially used to simulate the occupant response. This is followed by the analysis of the results provided by the new behavioural model.

In all of the cases (see Table 9-1), a default occupant population is used (unless otherwise stated), taken from the population panel facility within the buildingEXODUS model (see Chapter 3 and 4). The response times implemented varied according to the behavioural features used and the assumptions upon which the specific verification case was based. Due to the lack of a detailed information set concerning the make-up of the occupant population, no grounds were identified upon which a more refined representation of the population could be made. The release version of buildingEXODUS is not able to take into account the passing of information between evacuees. However, given that the patron response to this information is broadly available, the approximate response times of the patrons can be attributed, indicating the arrival of new information. Where possible the exits are biased in order to approximate the exit usage and the passage of the occupants. Where the actions of the members of staff can be represented, whilst using the new behavioural features, they are represented, otherwise the members of staff are represented as evacuees allowing the maintenance of a similar congestion levels.

In all of the scenarios using the new behavioural model, rough 'social' clusters were generated to crudely account for the existence of social groups (see Chapter 8). The size of these clusters ranged form 5-20 occupants depending on the exact nature of the population and their position within the structure. It was not possible to extract the exact nature of the original population, nor their precise starting position. However, by crudely implementing social groupings (using the gene mechanism outlined in Chapter 5) the behaviour of the occupants involved may more closely represent the original occupants.

TABLE 9-1: BRIEF DESCRIPTION OF THE SCENARIOS EXAMINED

Scenario	Area	Population	Environmental Conditions
9.41	Garden	200, 1 member of staff	North-south corridor filled with smoke. This encroaches upon room after 120 seconds
9.42	Main bar/ dining room	125, 1 member of staff	Environmental conditions worsen after 30 seconds
9.43	Cabaret	1200 occupants, 1 member of staff	Deteriorates after 120 seconds

During the use of the new behavioural features, nearly all of the new behavioural features are utilised. Specifically

- Communication
- Group behaviour
- Adaptive behaviour (to congestion and smoke)
- Route inefficiency due to smoke
- Familiarity
- Dynamic motivation
- Population and wall proximity*

*One of the new behavioural developments, that of the delay area, was not implemented, as no appropriate use for it could be found within the scenarios described. Therefore although the behaviour was enabled, as no delay nodes were included, it had no effect upon the outcome.

The evacuee behaviour represented by the majority of these features is referred to specifically in the original report [52]. Those that are not (namely those concerning the correction of the egress route according to wall and occupant proximity) might not have been deemed noteworthy by those questioned and are assumed to have occurred, according to the weight of evidence available in general evacuation literature (see Chapter 2). All of the new features will be enabled throughout the simulations, allowing the sensitivity of the entire model to be examined, rather than requiring the user having to switch behavioural features on and off according to the needs of the situation.

Two types of simulations are generally possible when modelling evacuation behaviour. In the first simulation method, all of the known behavioural actions of the main protagonists are *imposed* upon the scenario and the repercussions of these actions are examined (specifically relating to evacuation times and exit usage). For example, the return of a staff member to the patron population once smoke has been encountered might be assumed and an egress route imposed upon the simulated members of staff.

A second type of simulation would allow the modelled individual to react to the conditions and select their own course of actions, according to local conditions and according to a simulated decision-making process. For example, staff may or may not choose to return and warn patrons of the incident on interacting with smoke; a decision made according to the perception of the simulated patron rather than being imposed by the engineer. This decision is therefore made locally rather than being imposed by the engineer.

The second option requires a sophisticated behavioural model that is capable of producing a rich variety of behaviours. This method is particularly useful as it can be used to investigate potential results from a particular set of initial conditions. The latter is the strategy adopted when examining the performance of the new behavioural features whilst the former strategy is adopted when using the release model. *It should be emphasised that both of these options are valid engineering practices.* Indeed, in reality a user would produce results based around both strategies (where possible), enabling comparison and detailed analysis. It would not therefore be true to say that the introduction of a more sophisticated behavioural model greatly *simplifies* the process of evacuation modelling. Using the first method, the user would require expertise in the construction of relevant scenarios. In contrast, when using the second strategy, expertise would be required concerning the assumptions behind the model and the process involved in the more sophisticated behavioural model, and an ability to interpret the richer qualitative results produced.

During the implementation of the new behavioural features, an attempt is made to reproduce the behavioural actions of the protagonists involved (hence following the second method outlined above). Due to the probabilistic nature of a number of the behaviours, a distribution of outcomes will be produced. All that can be expected of the new algorithms is that similarities may be observed *within* the distribution of results produced and the actual events; i.e. that the behavioural actions produced during the actual events are included in the distribution of outcomes described in the simulated event

It must also be acknowledged that a number of simplifications and composite characters have been made. For instance, the actions of a group of staff members may have been condensed into a single member of staff, or the time-frames of events may have been condensed to aid simulation. This has been both due to gaps in the data-set available (the exact direction that an occupant was moving, the precise environmental conditions, etc.) and to better analyse the results generated. The three cases examined do not occur at exactly the same time-frame. Time-frames were selected for their importance to the outcome of the evacuation. Therefore the scenarios involving the Main bar area (due to its proximity to the incident) start at a relatively early time-frame, approximately 8.50-8.55p.m. The simulation of the Garden room and the Cabaret room start at the slightly later time-frame of approximately 8.55-9.00p.m.

9.3.1 Description of the Simulated Environmental conditions

Some general reference will now be made concerning the environmental conditions imposed during the scenarios examined. The smoke hazard used in several of the scenarios is not intended to be an exact replication of the conditions experienced during the original event, due to the limitations in our understanding of these conditions. Although some experimental results are available, these alone are insufficient to describe the entire event. Instead, while reflecting the experimental results, the hazardous conditions used are intended to be a simplistic representation of those evident during a large-scale incident, rather than simply being based on the limited experimental data available.

The hazard is represented within the buildingEXODUS model to reflect the details that are provided within the report (location, time-frame, etc.). However, some extrapolation had to be made concerning other facets of the environmental conditions as they were not fully described in the original report. Given the lack of specific details provided concerning specific localised conditions, the hazard used during all of the scenarios examined will be identical. Only the location and duration of the environmental conditions will alter, according to the time-frame simulated.

In these scenarios the following fire hazards will be used: temperature (C), smoke (K), CO_2 (%), HCN (ppm) and CO (ppm). The irritant gases are not included in this analysis. These hazards will operate over pre-defined regions of space or zones (see Chapters 3 and 4) and will evolve over time.

The temperature of the smoke hazard is represented by the linear function

$$T\,(^{o}C)=20+0.2t,$$

where T is the temperature is in degrees centigrade and t is the time in seconds.

The smoke is represented by

$$Smoke\ level\ \ (K,\ 1/m)=0.7+0.2t$$

where smoke is measured in terms if its extinction coefficient.

The carbon dioxide content is represented as

$$CO_2(\%)=0.004t$$

All of these functions are conservative estimates of what might have been expected. The representation of the other facets of the environment (HCN and CO), broadly reflect the original findings of the report (see Section 9.3.4 and Table 9-2). This hazard will come into effect within the scenarios, according to the description in the original report. It should be emphasised that the representation of the environmental conditions in this case is specifically to determine their impact upon the patron behaviour rather than to make toxicological comparisons.

TABLE 9-2: SIMULATED ENVIRONMENTAL CONDITIONS

Case	Zone	Time
9.41 Garden Room	1 3	0 seconds 120 seconds
9.42 Main bar area	4 5	30 seconds 60 seconds
9.43 Cabaret Room	2	120 seconds

9.3.1.1 THE SIMULATED ENVIRONMENTAL CONDITIONS IN THE GARDEN ROOM

During the representation of the Garden room, environmental deterioration along the north-south corridor (Zone 1, see Figure 9-10) is assumed to be evident from the beginning of the simulation. Any evacuee moving south along the North-South corridor would then eventually be confronted with smoke. After 120 seconds the smoke is assumed to have become serious in the Garden room (Zone 3, see Figure 9-10) reducing the likelihood of survival. Anyone situated in this area would then be subject to the environmental conditions.

9.3.1.2 THE SIMULATED ENVIRONMENTAL CONDITIONS IN THE MAIN BAR, DINING ROOM AND KITCHEN AREA

During the representation of the Main Bar area, the Main Bar (Zone 4, see Figure 9-10) was simulated as having a deteriorating environment after approximately 30 seconds.

This progressed in an easterly direction towards the Dining room (Zone 5, see Figure 9-10) after 60 seconds. The main entrance and foyer was not simulated as having declining environmental conditions.

9.3.1.3 THE SIMULATED ENVIRONMENTAL CONDITIONS IN THE CABARET ROOM

Finally, during the representation of the Cabaret room (Zone 2, see Figure 9-10), the environment in the room begins to decline after 120 seconds. More details are provided concerning the exact location of the environmental deterioration during the presentation of the results.

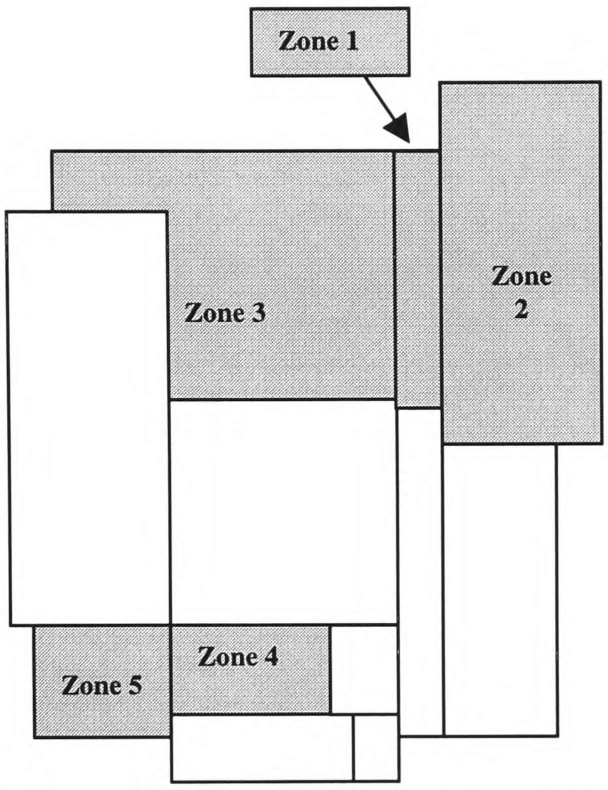


FIGURE 9-10: LOCATION OF ENVIRONMENTAL ZONES

These representations are simplifications of the original events. This is not expected to seriously impact upon the outcome of the simulation, as it is the interaction of the patrons with the environment and the consequent decisions that are of interest rather than the toxicological impact of the environment.

The scenarios derived for the validation process are now described individually in sections 9.3.51-3.

9.3.2 DESCRIPTION OF THE GARDEN ROOM SIMULATIONS

In scenario 9.41 the Garden room is represented. No internal obstacles or barriers are included, as no reliable or detailed information was available concerning this data [52]. This omission is considered relatively unimportant to the eventual results produced (in this instance) as the relatively low population densities that are evident and the overall simplicity of the room itself (see Figure 9-11), allow for the evacuees to compensate for the presence of such localised complexity. In scenario 9.411 the present model is used to simulate the Garden room from approximately 9.00p.m, at which time the staff informed the patrons of the incident. The patrons are assumed to have response times between 30-90 seconds reflecting the seriousness with which they perceived the incident and the approximate time that information was relayed to them [52]. This time distribution is relatively arbitrary, as no comparison can be made against the original evacuation times. However, it does demonstrate the means by which the present buildingEXODUS model is able to represent the perception of information, the seriousness with which it is regarded and the subsequent delay in responding to it. These patrons then evacuate through the four available exits (exits F, G, H and the exit through to the kitchen area). The familiarity of the patrons is constant throughout the scenario. This compromise is essential during the use of the present model, to approximate the original behaviour of the patrons.

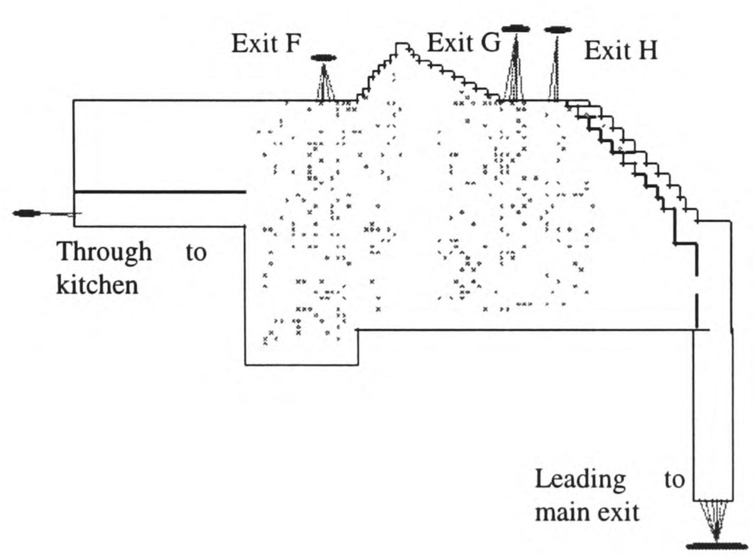


FIGURE 9-11: THE GARDEN ROOM

During the original incident, staff members entered the room to inform the patrons of the incident and guided them out through a number of exits. This action occurred after the staff members interacted with smoke in the north-south corridor [52]. Without this knowledge, the occupants of the Garden room would have been delayed significantly, possibly causing fatalities.

In Scenario 9.412, utilising the newly developed algorithms, a member of staff is located in the corridor travelling towards the main bar, reflecting the original behaviour. The staff member then interacts with the smoke-filled environment that is progressing northbound along the north-south corridor towards the Garden room (see Figure 9-10). The decision of the staff member at this stage determines whether he returns to the Garden room to alert the occupants or continues onwards towards the Main bar, where he is assumed to play no further part in the evacuation of the Garden Room.

During the simulations using the new behavioural features, the patrons situated in the Garden room are attributed with response times of 1000 seconds (i.e. an arbitrarily extended period of time), denoting their initial ignorance of the situation and desire to stay within the enclosure. They also have a limited awareness of the exits available to them, initially only being aware of the main entrance available through the north-south corridor. In the original incident, several patrons may have had more extensive familiarity. However, to better demonstrate the concept of communication and to simplify the simulation process, the patrons are assumed to only be aware of the exit at the end of the north-south corridor. The staff members are assumed to have a complete awareness of the structure. However, the increased awareness of the patrons and therefore their future actions are dependent upon either the provision of information by the member of staff or the worsening environmental conditions forcing them to evacuate through the worsening conditions.

In Scenario 9.413, the member of staff is assumed absent and is replaced by an informed member of the public, positioned within the Garden room. This patron is a motivated adult male who is aware of the seriousness and existence of the incident (see Chapter 5,7 and 8), but has only a limited familiarity with the enclosure, not being familiar with the fire exits. Hence, the evacuees cannot be made aware of all possible exits through the actions of this individual. The evacuees have the capacity to learn of the new exits through line-of-sight calculations. However the likelihood of this diminishes with the arrival of smoke and increasing population densities.

The transmission and the perception of the information provided will be different, according to the impact of the presence/absence of a staff member. Although a hypothetical example, this is intended to demonstrate the impact that the absence of a staff member might have had and the ability of the new behavioural model to cater for this absence.

9.3.3 Description of the Main Bar, Dining Room and Kitchen area simulations

In Scenario 9.42 the Main bar and Dining room area is examined (see Figure 9-12). Using the present model in Scenario 9.421, the patrons in the main bar are attributed with a response time of *zero*, representing their immediate evacuation of the main bar, at the time-frame simulated. This is not intended to demonstrate a weakness in the present model. This time-frame has simply been selected as the start of this scenario as it is pivotal to the survival of the patrons in the Dining room. Again, this time-frame is selected purely for convenience. Therefore the patrons in the Main Bar are assumed to be aware of the incident and head towards the only available exit to them; the main exit.

The patrons situated in the Dining room respond after 30-90 seconds. This is to simulate the cascading effect of the information evident in the original incident from either becoming aware of the worsening environmental conditions or being informed by a member of staff [52,226]. The exits are left unbiased during this scenario, simulating the *eventual* familiarity of the patron population. Therefore the patrons in the Dining Room are assumed to be familiar with the exit that is available by passing through the kitchen. The environmental deterioration is initially limited to the Main Bar area and begins after 30 seconds. Therefore the patrons initially situated in the Dining Room can expect to interact with deteriorating environmental conditions, which arrives after 60 seconds (see Figure 9-10 and Table 9-2).

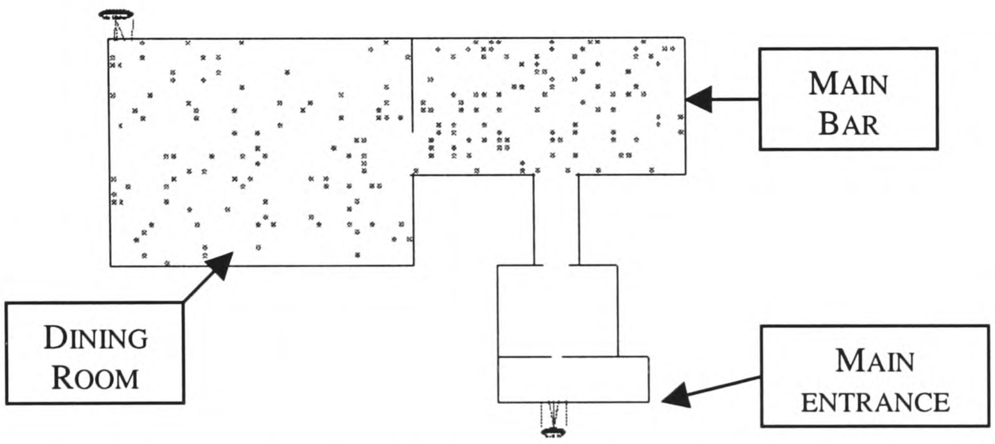


FIGURE 9-12: BUILDINGEXODUS REPRESENTATION OF THE MAIN BAR AREA.

In scenario 9.422 the member of staff is assumed to be *absent*, whilst still using the present model. This therefore forces the patrons to move towards their only familiar exit; the main exit at the south of the building. This is represented by biasing the exit leading to the kitchen making it unattractive to a patron within the Dining Room. This should therefore lead to greater levels of congestion and a greater interaction with the worsening environmental conditions, which will be the only means by which the patrons become aware of the incident.

The Main bar area is then represented in scenario 9.423 using the new behavioural features, from approximately the 8.50 p.m. timeframe. At this stage during the original incident, a member of staff who was travelling southwards along the north-south corridor (to both investigate the incident and to alert patrons) informed the patrons situated in the Main bar that an incident had occurred. This is simulated by a member of staff located in the Main bar area, who reacts instantly to the situation. Due to the differential in the information levels, the member of staff then attempts to inform the patrons to evacuate immediately. Again, the staff member has a greater familiarity with the available exits. This can be transferred to the patron population. These patrons are again initially attributed with extended response times of 1000 seconds. They are therefore dependent upon the actions of the member of staff positioned in the main foyer to alert them of the incident prior to its arrival. However, in reality the proximity of the patrons to the seat of the fire, in the Zebra room, would have enabled another means of access to the incident prior to its substantial development or its widespread progression through out building, limiting the number of available exit routes [52].

The patrons situated in the Dining room area are similarly (if not more so) dependent upon the provision of information, again having a response time of 1000 seconds, but being further away from the original incident. A second staff member is positioned in the doorway between the main bar and the dining hall. This member of staff responds after 30 seconds, reflecting the movement towards the worsening environmental conditions [52]. This response time is arbitrary, although is designed to guarantee the interaction of the staff member with the smoke within the simulation. This is a concession, as the response time could and should have been randomly attributed (as should the exact location of the staff member). This figure remained constant to limit the size of the result distribution for the purpose of this analysis.

The second staff member's actions and his awareness of the situation determine the outcome of the simulation. The member of staff initially moves towards the Main bar where he encounters smoke. He has the option of either passing though the smoke or redirecting away from it. The patrons situated in the Dining room will have entered by the main exit to the south and will certainly not have initially been familiar with the exit available through the kitchen area. Their paths out of the enclosure will therefore be dependent on the provision of information

Information relating to the internal complexity of the Main bar, Dining room and Kitchen area were not provided in the original report [52] in sufficient detail. Therefore no obstructions (such as furniture, etc.) could be included in any of the geometric modelling of the structure. No mention was made during the post-incident investigation relating to the presence of obstacles as a significant delaying factor. Therefore the absence of obstacles is assumed to have a minimal effect upon the decision making process of the patrons involved.

9.3.4 DESCRIPTION OF THE CABARET ROOM SIMULATIONS

In Scenario 9.43, the Cabaret room is simulated, approximately starting from the 9.06 p.m. time-frame (see Figure 9-13). This case consists of five scenarios. In Scenarios 9.431-3 the present model is used. In Scenario 9.431, no environmental difficulties are included and patrons are simulated as *immediately* moving towards their nearest exit (for instance, exit A). In Scenario 9.432 response times of 30-120 seconds are included as well as biasing patron movement towards the northern exit (exit A) and the southern exit (exit B, see Figure 9-13. This is an attempt at representing the communication between the staff member and the patron population and the advice provided concerning exit usage. Finally, in Scenario 9.433, the worsening environmental conditions are included (after 120 seconds), as well as the biasing of the exits described in Scenario 9.432. This scenario is expected to provide the best representation whilst using the current software release.

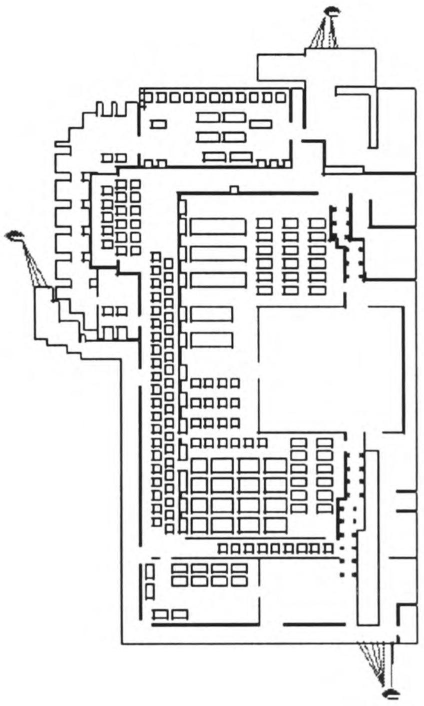


FIGURE 9-13: BUILDINGEXODUS REPRESENTATION OF THE CABARET ROOM

In scenario 9.434 the new behavioural developments are used. All of the behavioural options available are implemented, although it is expected that the majority of them will only have a minor impact over the results. Of most importance during this scenario will be the ability to communicate, the visual access of the evacuees, the evacuee familiarity with the structure and the exhibition of group behaviour. During this scenario, the patron familiarity is modelled, so that they are initially only aware of the entrance to the north-south corridor and are unaware of the potential fire exits to the north and south of the room (exit A and exit B, see Figure 9-13). All of the patrons are attributed with a response time of 1000 seconds, simulating their desire to maintain their position, as in the previous scenarios. A member of staff is positioned on the stage. He is aware of the evacuation, therefore replicating the knowledge levels and location of the busboy in the original incident [49-52]. This is an attempt to *simulate* (rather than *predict*) the conditions of the original event. The member of staff also has a complete awareness of the structure (simulating the knowledge and actions of the busboy [52]) Once the patrons have become aware of the situation, their response and their subsequent actions are examined in detail.

In scenario 9.435, the member of staff is absent, again attempting to demonstrate the importance of the staff presence/absence to the outcome of the evacuation. Instead five patrons are assumed to be present, each of whom have become aware of the incident. This awareness is simulated by their instant response. These then attempt to alert the remaining patrons of the incident, through communication. Due to the relative lack of familiarity and lack of social standing of the information providers (as compared to a member of staff, see Section 5.2, Chapter 5 and Section 8.3, Chapter 8), the communication process will therefore be less efficient and will be largely based on the observations of the patrons themselves. Although this was not the case during the original event, it is artificially generated as a hypothetical scenario to allow analysis of the potential outcome of the changing events and also further examination of the sensitivity of the behavioural developments in representing these factors.

These simulations are intentionally designed to approximate the actual events. Although the process, uses information that might not normally be available to the fire safety engineer, this is to enable a more detailed understanding of the advances made, by the new behavioural algorithms. These examinations can not have been said to be conducted 'blind'. The intention of this analysis was not to predict the outcome of the event without access to the any of the original information. Although a feat in itself, this might only have demonstrated the *comprehensive* nature of the model rather than its sophistication. Indeed this case was originally chosen because a significant level of information that was available. Instead, it is hoped that the new algorithms can be shown to more appropriately represent the decisions and actions of the protagonists involved given the surrounding conditions and that it is more sensitive to these changing conditions. This process enables a degree of forensic analysis, the outline of which is provided. This is intended to demonstrate the capability of the new model to investigate the outcome, given certain actions were not taken. This process should enable a greater degree of confidence to be achieved concerning future predictions made by the new model, due to its increase in sophistication.

Although some additional detail is provided that might not normally be available (such as specific staff actions), significantly *less* information is engineered within the new behavioural model, than in the present model. For instance, the patrons are not expected to respond without reason and have a limited familiarity with the enclosure. An attempt has been made to credit patrons and staff members alike with appropriate information levels and position them in locations and conditions. It is noted that the exact positioning of the staff members is a convenience. This is purely to guarantee the analysis of all of the behavioural features. Given the situations, the new model can then be examined to see if the behavioural outcome arrive at by the simulated evacuees are appropriate for the situation. *The sophistication and accuracy of the behaviour produced is therefore examined whilst simulating the information levels of the patrons and staff members.*

9.4 Results

Case 9.41 the Garden Room

In Scenario 9.411, where the present model is implemented, a relatively simplistic set of results is produced with the outcome of the simulation largely dependent upon the *starting position* of the evacuees. The variation evident in the evacuation results prior to the randomisation of each population is entirely due to the resolution of conflicts. Due to the distribution of response times evident in the population, even this variation is limited. More extensive differences are evident once the patron population has been randomised within their original rooms. This process enables the patrons to fall within different exit catchment areas, therefore affecting the exit usage and producing distributions within the results (see Table 9-3).

Due to the restricted nature of the response times allocated to the patron population, the majority of patrons evacuated prior to the arrival of significant levels of smoke or toxins (see Table 9-4). Despite the eventual environmental deterioration, the limited congestion and the limited distances involved enabled the patrons to successfully evacuate. This reflects the original outcome of the patron movement (see Figure 9-6). The accuracy of this behaviour in relation to the original response is entirely due to the imposition of the appropriate response times rather than any sensitivity of the simulated evacuees to the provision of information.

The present buildingEXODUS model is able to accurately capture the outcome of the patron behaviour given that the initial conditions are supplied in sufficient detail, although still does not reflect the real causes of the patron response. The information provided includes the provision of a latent evacuation response, through the use of the response time mechanism. For engineering purposes, the modelling of the exact cause of individual behaviour may not be considered essential. However, the ability to do so enables a more flexible occupant response as well as aiding the qualitative understanding of the simulation.

Therefore, the outcome of the simulations might be similar to the original event, but the process and the experience of the simulated patrons are different. The evacuation times produced reflect the different levels of exit usage, i.e. fluctuations in the levels of congestion, as well as the resolution of congestion (see Table 9-3).

TABLE 9-3: EXIT USAGE DURING SCENARIO 9.411

Exit	Exit Usage
E	7 [0-16]
F	156 [149-169]
G	94 [87-105]
H	35 [28-46]
north-south corridor	0 [0]

Due to the initial position of the patrons, the present model was able to capture the original exit usage (with exits E, F, G and H being the most popular) without using exit biasing or the imposition of target doors (see Table 9-3 and Chapter 3). This is largely due to the distances between the exits and the shape of the geometry. In essence, an interpretation of these results would need to assume that the patrons have full knowledge of all the exits; or they reacted to the signage (and that sufficient signage was provided) or they were given appropriate information by a staff member.

TABLE 9-4: EVACUATION TIMES DURING SCENARIO 9.411

	Evacuation times(secs)
9.411 (Present model)	137 [130-139 secs]

In contrast to this in Scenario 9.412, where the new behavioural features are used, the patrons are attributed with an extended response time (of 1000 seconds) identifying their normal propensity to stay within the enclosure. They are therefore entirely dependent upon the provision of information by either the member of staff or from the environment.

The staff member initially positioned in the north-south corridor, as he was in the original incident, was responsible for the provision of this information during the actual event. The patrons are also shown to be dependent upon this staff member during the *simulated* event (It should be noted that this is *simulating* rather than *predicting* investigative behaviour). The staff member initially moved south along the corridor, simulating the original investigation of the conditions. This behaviour is extracted directly from the original data-set [52], although his decision once confronted with the smoke is not imposed by the engineer but is instead calculated by the model (see Section 8.4, Chapter 8). Once confronted with the relatively dense smoke, the employee can either continue on through the smoke moving towards the Main Bar area, or return back into the Garden room. In the ten repeat simulations performed, the staff member elected to continue on through the smoke 3 times, thereby not warning the Garden room patrons and on 7 occasions chose to return, enabling communication to occur.

In the 30% of cases where the staff member elects to continue through the smoke, the staff member leaves the simulation (through an exit) and is assumed not to interact with the patrons in the Garden Room again. Although the staff member was subsequently subjected to moderate hazard levels, he was always able to reach the exit (which simulated the North-south corridor). This activity fundamentally determined the eventual actions of the patrons and the results produced. This decision would have been influenced by the relatively close proximity of the external exit, representing access to the main bar area, as well as the identity of the staff member. However, at this early stage, the smoke hazard was relatively light, enabling the staff member the possibility of passage. The member of staff therefore left the simulation without further interaction with other evacuees.

In this scenario, the patrons in the Garden room were only alerted of the incident once the smoke arrived within the Garden room. Once the smoke density exceeded a specified threshold after approximately 90 seconds (of 0.1 l/m, a feature currently available in the buildingEXODUS model [24]) the influx of smoke alerted the patrons to the existence and extent of the incident that they perceived as relatively serious. At this stage, *all* of the patrons responded. These patrons were initially unaware of all but the 'internal' exit leading towards the north-south corridor. Some of the patrons became aware of additional exits through line-of-sight observations (see Section 5.4, Chapter 5). Therefore their location was deemed to afford them the opportunity of receiving information concerning the exit. Given that their familiarity may have expanded through the addition of these exits to their door vector (see Section 7.3, Chapter 7), these exits became potential targets towards which they might evacuate. The environmental conditions and the presence of other patrons impeded the reception of this information. Therefore this process was not guaranteed.

The patron's limited understanding of the enclosure meant that a large number of them moved back into the main enclosure, along the north-south corridor. The remaining patrons, due to the visual access available, moved towards the exits at the north end of the Garden room (see Figure 9-14). This information was communicated to other members of the population, due to the existence of groups or through the simulation of communication between strangers ('emergent' collective behaviour, see Section 8.3, Chapter 8).

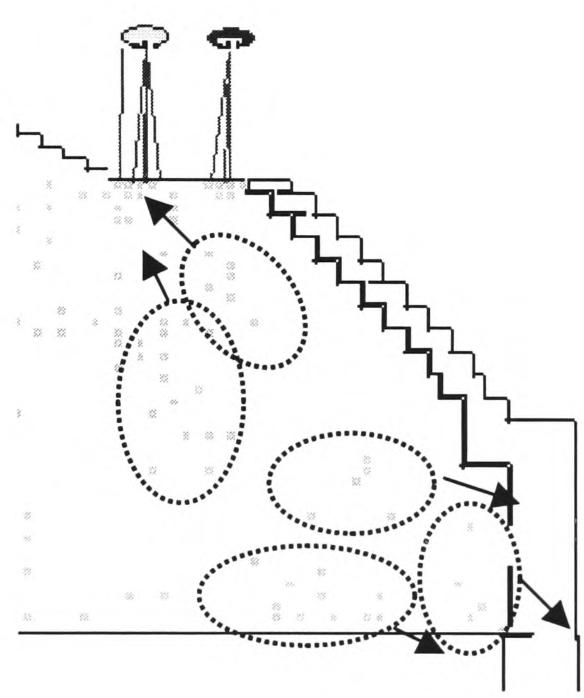


FIGURE 9-14: GROUPS OF PATRONS CAN BE SEEN MOVING IN DIFFERENT DIRECTIONS ACCORDING TO AWARENESS AND LINE-OF-SIGHT CALCULATIONS.

Although some of the patrons were situated relatively closely to the kitchen entrance, many had no idea that there was an exit in that direction (see Table 9-5), therefore reducing its usage drastically. This was due to the initial lack of exit familiarity and the narrowness of the approach to this corridor preventing or limiting the required line-of-sight. In reality, the external exit that was available by moving through the kitchen was some distance from the internal exit leading out of the Garden room to the Kitchen area. This effect was somewhat fortuitously represented due to the nature of the geometry, rather than because of a long-term analysis of the situation by the simulated evacuees.

The patrons who returned into the north-south corridor (having not chosen to due to their location, or not being able to adopt other exits) were assumed overcome by smoke, even if they successfully reached the exit during this simulation. It should be remembered that the simulated exit here actually lead to another part of the building; an area which had become untenable at this time-frame. However, patrons *actually* began to perish in the corridor after 90 seconds, even before they progressed out through the simulated end of the north-south corridor.

No redirection due to the environmental conditions was apparent, as the patrons were largely unaware of alternative routes. If other routes had been available, the patrons would have adopted these exits as their original targets, rather than moving to the more distant main entrance. The progress of the smoke eventually overtook these evacuees removing the option of redirection and making their movement increasingly erratic (see Section 7.1, Chapter 7). Under these conditions the last patron evacuated alive after approximately 65 seconds, with fatality rates ranging from 42-73 patrons.

In 70% of the simulations, the staff member chose to return to warn the patrons in the Garden room. Once the employee redirected back into the Garden room (see Chapter 8), he was able to inform the patron population of the situation and allow them to respond. On entering the Garden room, the staff member had visual access to the patrons situated within it. He was confronted with the patron population that was entirely unaware of the situation. This discrepancy in the information levels caused the staff member to 'communicate' with them. (Again, it should be noted that the member of staff was not attributed with the potential task of collecting the patrons who were situated in the Garden room, but redirected away from the smoke according to the potential risk that it posed to him). The necessity of an evacuation was relayed to the patrons, as well as information concerning the existence and use of their nearest available exits. This awareness was lacking prior to the arrival of the staff member, as until this point the patrons were only aware of the north-south corridor leading to the main entrance. None of the patrons were advised by the staff member to head towards the north-south corridor due to the presence of smoke. Therefore all of the patrons evacuated using the exits available in the Garden room (see Figure 9-11 and Figure 9-15).

The communication process was not optimal. Although the information imparted by the staff member was treated more seriously than might otherwise have been the case, the patrons did not necessarily move off instantaneously. However, the patron response was *relatively* efficient, due to the role of the informer, being established as a member of staff and the visual access that he had to the majority of the structure due to its relatively small size. The communication process was therefore dependent upon *physical* and *social* processes, both of which are represented by the new behavioural model

The existence of group clusters also accelerated the spread of the information (see Figure 9-15 and Section 8.3, Chapter 8). Given this the patron response was relatively rapid, although still spread over a period of time (approximately 0-30 seconds). The entire population eventually evacuated in less than 100 seconds (see Table 9-6).

It is also evident from Figure 9-15 that the evacuees were attempting to maintain the space around themselves during the evacuation; that is an attempt was made to maintain a buffer zone between themselves and other members of the population. This is due to the introduction of the population proximity function outlined in Section 6.2, Chapter 6. Therefore instead of the evacuees rigidly adhering to the potential map, the existence and location of other evacuees affected their short-term navigation.

The necessity of the patrons to adapt their egress route due to congestion was reduced by the even distribution of patrons between the exits, preventing an advantage arising through redirection (see Figure 9-16) and the fact that this could be perceived by the patrons through line-of-sight calculations. The use of redirective behaviour was subsequently restricted, because the adaptive algorithm employed by the evacuees did not estimate that the behaviour provided an advantage to their evacuation.

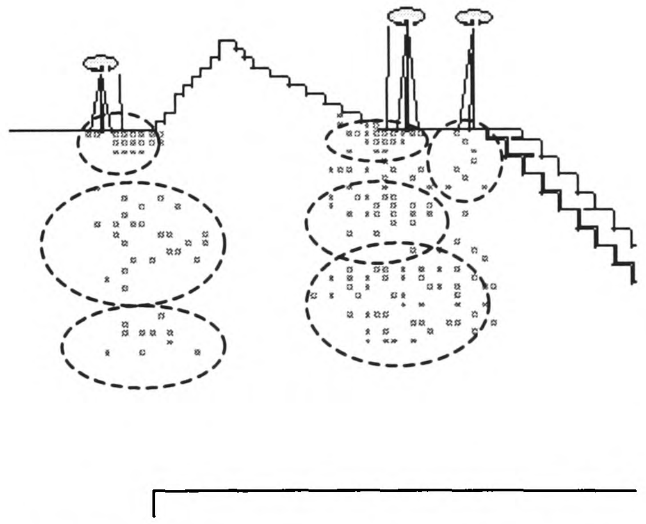


FIGURE 9-15: GROUP CLUSTERS EVIDENT IN SCENARIO 9.412.

Redirective behaviour was also limited by the maintenance of groups within the population (see Figure 9-15 and Figure 9-16). These groups tended to stay together, either redirecting or maintaining their routes accordingly. The more senior members of the social groups reduced their travel speeds in order to maintain their proximity with the slower moving group members; behaviour described in the original events [52]. The staggered arrival of these groups diminished the congestion around the exits. Therefore, the complex behavioural developments interacted with each other, affecting the surrounding conditions and therefore affecting the likelihood and effectiveness of their individual performance. The new behaviours were not enacted irrespective of their surroundings, but were both sensitive to and affected the surrounding environment.

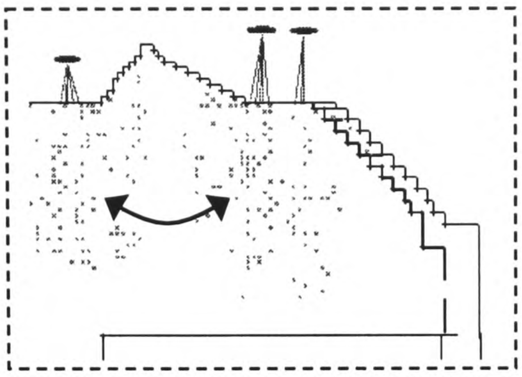


FIGURE 9-16: LIMITED REDIRECTION OF PATRONS BETWEEN MAIN VISIBLE EXITS.

TABLE 9-5: EXIT USAGE DURING SCENARIO 9.412

	Staff Redirection	Staff Continues
Exit	Exit Usage	
E	5 [2-9]	2[1-3]
F	59[54-62]	63[60-65]
G	116[111-118]	36[35-37]
H	34[30-36]	16[14-19]
North-south corridor	0	80[73-85]

The discrepancy between the evacuation times produced between scenarios 9.411 and 9.412 is significantly affected by the time at which the member of staff arrives in the Garden room, as well as the increased fatality rate in scenario 9.412. In a more detailed forensic analysis of the events, this time would be varied to enable a more accurate understanding of its impact upon the evacuation. However, this has identified a potential use of the model; that through analysis the potential impact of the procedural actions of individual members of staff can be assessed.

The fatality levels produced in the patron population during the simulations were also dependent upon the activities of the staff member. If the staff member decided not to return to the Garden room, there were on average of 59 fatalities. This should be compared with the absence of patron fatalities, once the staff member had informed the patron population of the incident. This was due both to the early awareness of the situation, as well as the increased exit awareness provided by the communication process. This further highlights the importance of the staff members during the simulation (as identified in the original report [52]) and the projected increase in fatalities anticipated by the model if the staff members were less vigilant.

Continuing this investigation, some further analysis was performed in Scenario 9.413, where it was assumed that the provider of information was not a member of staff but instead a senior patron. Under these circumstances the reception of the information was less efficient (reflected in the average overall evacuation time of 109 seconds, ranging from 95-131 seconds). This was entirely due to the seniority and communication structures outlined in Chapter 5 and Chapter 8.

TABLE 9-6: RESULTS PRODUCED DURING SCENARIO 9.412 AND 9.413

Scenario	Evacuation times (secs)	Fatalities
9.412 (staff redirection)	95 [90-99]	0
9.412 (no staff redirection)	71 [65-74]	59 [42-73]
9.413	109 [95-131]	29 [20-31]

Due to the informer's lack of familiarity with the structure, the adoption of information and the subsequent exit usage was notably different from when the provider of information was a staff member, with significantly more people moving into the north-south corridor (averaging approximately 31 patrons, see Table 9-7). This also affected the efficiency of the overall evacuation. The advanced, although inefficient, warning provided by the 'informed' patrons enabled more of the remaining patron population to survive than if the patrons relied upon the development of the environmental conditions. Here the fatality rate of patrons ranged from 20-31. It is apparent that these figures fall between the results produced when a member of staff informed the patrons and the patrons being alerted by the environmental conditions, as might be expected (see Table 9-6).

As indicated previously the dependence of the patron population is clearly demonstrated by the fatality rates in Table 9-6. In Scenario 9.411, no fatality rates are recorded. Therefore given that the engineer has made appropriate assumptions concerning the provision of information, then the current buildingEXODUS model is able to accurately reflect the original fatality levels. In Scenario 9.412, the information levels are more accurately represented within the population. The patrons are therefore dependent upon the action taken by the member of staff once confronted by deteriorating environmental conditions. If he returns to the Garden room, then he is able to relay the existence of the incident and the existence of previously unfamiliar exits. This enables the patrons to evacuate without loss of life. If the member of staff does not redirect, then the patrons only become aware of the incident on the arrival of smoke, making their evacuation more hazardous and causing a number of fatalities (averaging 59 fatalities). Finally, in Scenario 9.413, a patron is assumed to be aware of the incident and attempts to alert the other patrons within the Garden room. The patron's relative lack of social standing and lack of familiarity both contribute to the consistent fatalities that occur during this scenario (averaging 29 fatalities). These scenarios demonstrate a number of points. Firstly, the patrons required information as early as possible. Secondly, the more information that was provided the better their chance of survival. Finally, the more respected the provider of this information, the greater the likelihood of the patrons adopting the information. These factors concur with the findings of the original report [52].

TABLE 9-7: EXIT USAGE DURING SCENARIO 9.413

Exit	Usage
E	20 [8-22]
F	54[31-65]
G	59[41-65]
H	35[20-37]
north-south corridor	31[24-45]

The main achievement of the use of the new behavioural model in these scenarios has been a vast increase in the variety of the results produced, whilst more accurately reflecting the potential outcomes of the performance of specific actions by *significant* members of the population. According to the decision of the staff member, the simulated outcome was similar to the original outcome (if a similar decision was made by the main protagonist) or a vastly different outcome was produced (if the staff member had come to a different conclusion). Also the reported conditions of the original incident were replicated in the majority of the scenarios; namely a general lack of congestion, the receipt of instruction from a member of staff and the evacuation of the patrons prior to the extensive arrival of smoke.

CASE 9.42 THE MAIN BAR

To examine the potential of the present model to represent the information available to the evacuees, two separate scenarios are examined. Initially (in Scenario 9.421) a member of staff was assumed to have informed the patrons of the incident. To represent this case, the exits are not biased, reflecting the distribution of the original evacuees between the exits and also that the staff members are assumed to have informed the patrons to react to the incident.

The information levels assumed during this scenario are based around the assumption that communication has taken place. The patrons that were situated in the Main bar responded immediately (avoiding the environmental difficulties altogether), simulated as being able to see the oncoming smoke (as in the original event [52]) or as having been informed by a passing member of staff. The patrons in the Dining hall responded after 30+ seconds generally moving towards the exit through the kitchen. This is entirely due to their initial location and the fact that this exit had not been simulated as being unattractive or unfamiliar. This distribution of the patrons between the exits alleviated the congestion around the main exit and therefore removed the possibility of the patrons encountering the significant environmental difficulties in the Main bar that arrived after approximately 30 seconds. On average the entire evacuation took 2 minutes 6 seconds to complete (see Table 9-8). No fatalities were evident during this scenario.

In scenario 9.422, where the levels of familiarity are equivalent to those that existed prior to the arrival of the member of staff [52], *all* of the patrons moved towards the main exit, causing increased levels of congestion. This was due to the patrons being unaware of the potential egress route through to the kitchen in the absence of staff communication. The patrons only began to evacuate once the environment had encroached into the Dining room area. Under these circumstances a number of the patrons (averaging 18 patrons) were overcome due to the environmental conditions. This occurred around the entrance to the main foyer (see Figure 9-17). The last patron evacuated alive from the area after, on average, 185 seconds. The extended evacuation time is due to the extensive congestion that occurred around the main entrance, as well as the impediment to movement provided by the environment.

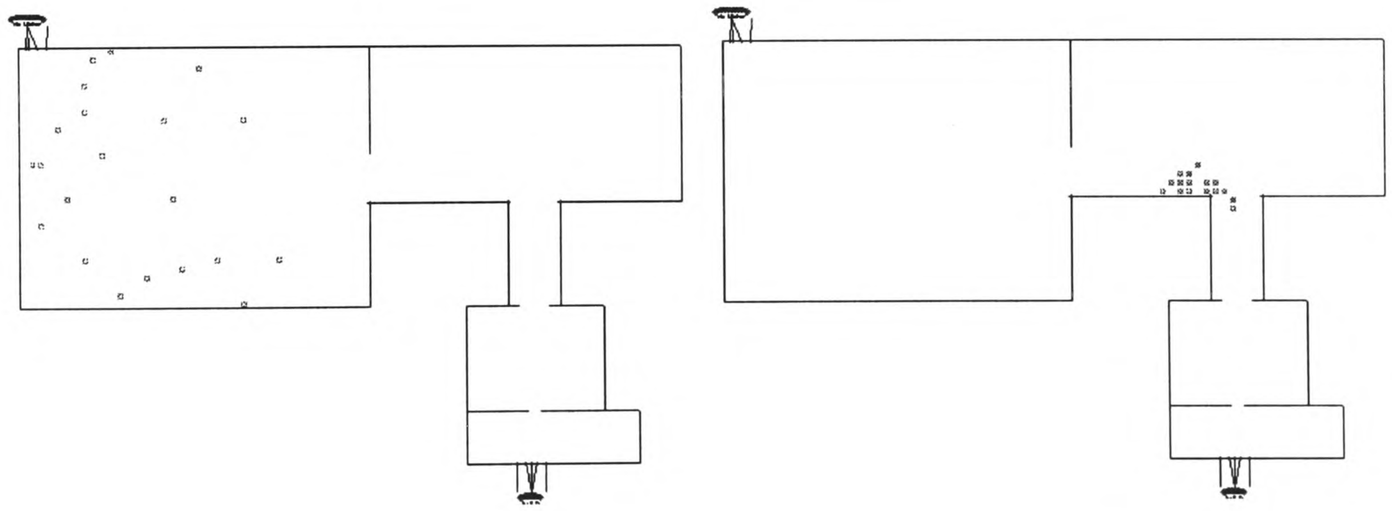


FIGURE 9-17: (LEFT) STARTING POSITIONS OF DECEASED PATRONS. (RIGHT) POSITION OF DEATH

Under these conditions the likelihood of patron survival was largely determined by their starting position (see Figure 9-17), as the limited patron familiarity was uniform throughout the population. This scenario, in conjunction with Scenario 9.421, demonstrates that although the present model is behaviourally less sophisticated, it is still able to analyse the potential impact of information levels upon the evacuation results.

TABLE 9-8: RESULTS FROM CASE 9.42

Scenario	Exit usage		Evac. time(secs)	No. of Fatalities
	Kitchen	Exit D		
9.421	101	101	126 [122-130]	0
9.422	0	183	185 [180-188]	18 [17-20]
9.423 (staff in Main bar redirected)	97 [95-102]	104 [120-105]	81 [74-94]	0
9.423 (no staff redirection in Main bar)	30 [28-35]	143 [138-146]	135 [120-131]	31 [27-34]

Once the new model was implemented in Scenario 9.423, similar levels of evacuee congestion to those in Scenarios 9.421-2 were evident around the main exit. This was due to the early response of the patrons situated in the Main bar area. This response was enabled by the provision of information by the instantly responding member of staff situated at the extreme eastern end of the Main Bar area. The process of communication in this instance was relatively efficient due to the small and simple nature of the Main bar. Although the patron response is identical in Scenario 9.421 and 9.423, the reason for their speedy response is entirely different. The behaviour exhibited during the imposition of the present model (Scenario 9.421) was due to the provision of information by the engineer, while during the implementation of the new behavioural features (in Scenario 9.423), the response was due to the provision of information by a simulated member of staff. This difference does not necessarily affect the validity of the results. Indeed in a practical engineering sense, the difference is largely academic. However, this does increase the ability to generate and analyse a variety of occupant behaviours; a capacity that would be of particular use to the fire safety engineer attempting to understand (or predict) the behaviour of the evacuees.

After these patrons began to evacuate form the Main Bar, the smoke worsened due to its close proximity to the Zebra room. As in the original evacuation, none of the patrons originally situated in the Main bar perished due to their prompt response. (Although the arrival/non-arrival of this staff member is acknowledged as being a significant factor, it is not addressed, as a similar scenario is investigated using the patrons situated in the Dining room).

Smoke worsened around the Main bar area after 30 seconds. Depending on their starting position and the randomisation procedure, several patrons were seen to move from the Dining room into the Main bar. However, these patrons were unable to redirect away from the smoke once it arrived, due to their initial lack of familiarity with the 'kitchen' exit and the deterioration of the environment in the Main bar area.

Infrequently, evacuees were seen to redirect away from the congestion around the entrance to the main foyer (see Figure 9-18). This is entirely due to line-of-sight calculations enabling patrons to become aware of new routes. It must be stressed that this was a rare occurrence, due to this lack of familiarity, group behaviour and the relative distance to the next available exit.

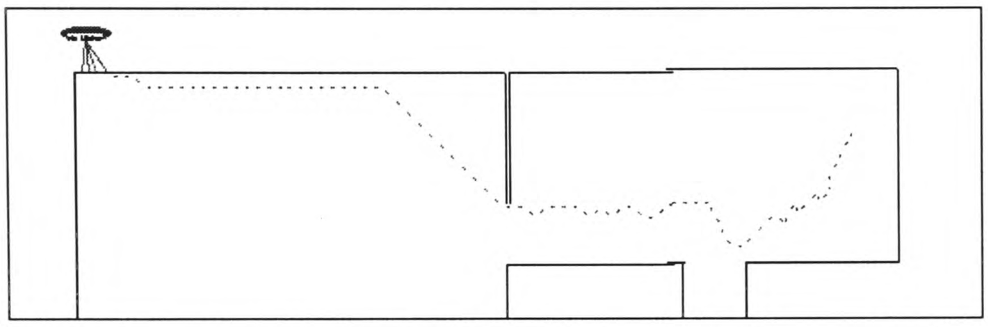


FIGURE 9-18: PATRON REDIRECTION DUE TO CONGESTION

The member of staff in the Dining room reacted after between 30-40 seconds. He initially attempted to move into the bar area, but was faced by the worsening smoke conditions present in that room. Again the outcome of the evacuation of the patrons in the Dining room was largely dependent upon the actions of this single member of staff (this simulated member of staff may represent the influence of a number of staff members, forming a composite of their actions).

If the employee turned away from the smoke back into the Dining room, he was able to inform the patrons of the incident who were then taken out through the kitchen area with which they were previously unfamiliar. Therefore the existence of the incident and an increased familiarity of the building was imparted to the patron population. Under these conditions the patrons evacuated relatively efficiently, after approximately 70 seconds (see Table 9-8). Again, the communication process was completed in a relatively quick time due to the size and nature of the Dining room.

If the staff member does not retreat away from the difficult environmental conditions, the patrons in the Dining room became aware of the incident through the arrival of smoke around them. Due to the delay in their awareness of the incident and the reduced level of exit familiarity, the patrons in the Dining room evacuated towards the Main exit, through the foyer to the south of the geometry. These were eventually overcome by the environment in the Main Bar area, which had had additional time to develop in density and toxicity level. These patrons then perished in the Main bar area (see Table 9-8).

It is apparent that the evacuation times have been reduced in the simulations involving the new behavioural features. This is largely due to the increased number of ways in which information can be transmitted between the simulated patrons (line-of-sight, communication, etc.). An apparent effect of the introduction of the new behavioural developments is that it is able to capture the outcomes produced in Scenarios 9.421 and 9.422, in a single scenario. This is enabled by the increased sophistication of the decision-making process.

The changing conditions of the room provide an excellent means by which to demonstrate the dynamic representation of the evacuee motivation (see Figure 9-19). This is affected by the high-density evacuee congestion and the possible interaction of some of the patrons with smoke. Therefore, as the evacuee experience differed between patrons, so their internal perception differed, affecting their motivation. This motivation may have been communicated between .evacuees, as could the knowledge of the existence of smoke (see Chapter 8). Figure 9-19 also demonstrates both the population density function (see Chapter 6) with the evacuees maintaining their distance from each other where possible, and the wall proximity function (see Chapter 6) where the evacuees can clearly be seen to have occupied the central section of the geometry, again where possible.

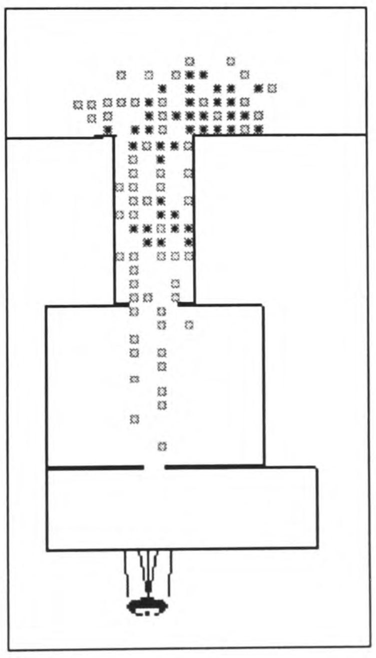


FIGURE 9-19: PATRONS IN DARK ARE HIGHLY MOTIVATED, REACTING TO THE HIGH-DENSITY POPULATION OR TO THEIR CONTACT WITH SMOKE.

If we compare the results produced with the conditions cited in the original report [52], some gratifying conclusions can be made. Firstly, both of the attempts at modelling the incident with appropriate assumptions (Scenario 9.421 and 9.423) produce results that are comparable to the original observations, in terms of exit use and the absence of fatalities; that is the entrance to the kitchen was utilised and no fatalities were recorded. However, during the introduction of the new behavioural features (Scenario 9.423), the variety of results produced increased, again being entirely dependent upon the actions of the members of staff. For this level of variety to be introduced whilst using the model currently available, required the intervention of the engineer (i.e. generating new conditions in Scenario 9.422). Again, this is a perfectly valid engineering practice and one that should be conducted in an attempt to replicate all of the potential outcomes of an incident. The introduction of a more sophisticated behavioural model enabled the simulated evacuees to be sensitive to the changing conditions around them and act accordingly, removing the necessity of the engineer to intervene at such a low level. The production of a greater variety of behavioural actions in itself is not necessarily advantageous. However, in this instance, the new behavioural model reflected the importance of the staff behaviour as a determinant in the outcome of the incident [52].

The impact of the new model during this scenario is dominated by the transfer of information, allowing the closer simulation of the actions of the staff members. By accurately modelling the initial familiarity of those involved, the importance of the communication process was all the more clear. The new model enabled the demonstration of the importance of the staff actions, whilst reflecting the performance of these actions upon the patron population. By forensically examining the consequences of the staff decisions, their loyalty to the patron population was demonstrated as being vital to their safe egress. It was also able to reflect the congestion evident around the main entrance, the gradually encroaching environmental difficulties and the evacuee response to these difficulties.

CASE 9.43 THE CABARET ROOM

The Cabaret room was the scene of the highest levels of congestion and the most extensive environmental problems leading to the highest level of patron fatalities. The different models are examined to determine whether they are able to represent these conditions and for the impact of the simulated conditions upon the behaviour observed.

Initially, in Scenario 9.431, the present model was used with no exit biasing, no evacuee response time and no environmental conditions. This provides a useful benchmark against which the more sophisticated representations may be compared. It also reflects what might be considered the initial step if a complete analysis of this situation was being performed.

As the exits had no biasing attached to them, they appeared equally attractive to the patrons within the geometry. Therefore the adoption of exits was *entirely* dependent upon the patron's starting location. This leads to the inappropriate representation of exit usage demonstrated in Table 9-9, where the exit leading to north-south corridor was particularly overused in comparison with the actual exit usage (where Exit A and Exit B were used by the vast majority of the population [52,226]). The evacuation times produced reflect the balanced use of the exits (see Table 9-9), where the evacuation is completed relatively quickly, averaging 251.9 seconds.

This situation was partially remedied in scenario 9.432, where the exit leading to the north-south corridor was biased to make it less attractive to the patrons. This more realistically represents the perceived attractiveness of the exit A and exit B, due to their identification by a member of staff during the actual event. The patrons also now had a distribution of response times, more realistically representing their response to the provision of information. These changes in the exit usage (see Table 9-9) and patron response are reflected in the extended evacuation times generated (see Table 9-10), which averaged approximately six minutes. (It should be noted that the introduction of a distribution of response times does not necessarily increase the evacuation times, as it might alleviate some of the exit congestion)

In Scenario 9.433, the decreasing tenability of the environment was introduced in addition to the conditions of Scenario 9.432. As a result, a number of fatalities are produced, which are reflected in the reduced evacuation times evident in Table 9-10. The evacuation times were reduced as the evacuation times generated by the buildingEXODUS model (present and new) reflect the last recorded time for an evacuee to leave a structure rather than representing the last evacuee alive. Scenario 9.433 predicted that, on average, 141 fatalities would occur during the simulations (ranging from 136-143 fatalities, see Table 9-10). These patrons died prior to exiting and were therefore not recorded as having evacuated, consequently reducing the overall evacuation time. The simulated level of fatalities compares favourably with the actual results. These fatalities also tended to occur around exit A and exit B, as was the case in the original event (see Figure 9-20). This was due to the biasing applied to the exits in an attempt to generate appropriate results. It should be remembered that the definition of the hazard is relatively arbitrary. More important than the level of the fatalities (and in this case the perceived accuracy of the fatality level) is the existence of fatalities and their location (i.e. around the exits).

However, the present model is not able to replicate the transfer of information between the evacuees; the cause behind their response. Instead the response is imposed upon the patron population through the use of the response times. These response times represent the *'what if'* scenarios defined by the engineer [7]. In this case, the engineer has asked *"what if the patrons move off in x seconds?"*. This would then *implicitly* represent the communication process. The model is therefore able to represent the outcome of the evacuation rather than accurately representing the causes behind it or processes involved in it.

TABLE 9-9: EXIT USAGE IN CASE 9.43

Exit	Scenario 9.431	Scenario 9.432	Scenario 9.433
north-south corridor	282 [260-293]	13 [8-16]	17 [15-19]
Northern exit (Exit A)	471 [461-496]	631 [619-637]	568 [561-573]
Southern exit (Exit B)	449 [421-461]	558 [541-563]	473 [461-482]

Given the quality of the data available the results generated in Scenario 9.433 are expected to be some of the most accurate produced given the limitations of the present model.

TABLE 9-10: EVACUATION TIMES AND FATALITY LEVELS ACCORDING TO DIFFERENT SCENARIOS IN CASE 9.43

Exit	Evacuation times (secs)	Fatalities
Scenario 9.431	252[250-254]	0
Scenario 9.432	363[360-364]	0
Scenario 9.433	247[242-248*]	141 [136-143]

*this time is reduced due to the fatalities of the patrons

During Scenario 9.434, the new behavioural developments are used. Initially, a member of staff was positioned on the stage located towards the centre of the room, simulating the position of the busboy during the original event [49-52,226]. Again this is information to which we would not normally have access. However, given that it does exist, it can now be represented within the new behavioural model, enabling the model to cope with a wider variety of situations and simulate the variety of information levels that existed within the population. This was therefore an attempt at generating both appropriate quantitative and qualitative results given the accurate representation of the initial conditions of those involved. The sensitivity of the evacuee to the provision of information and their subsequent behavioural response is of particular interest.

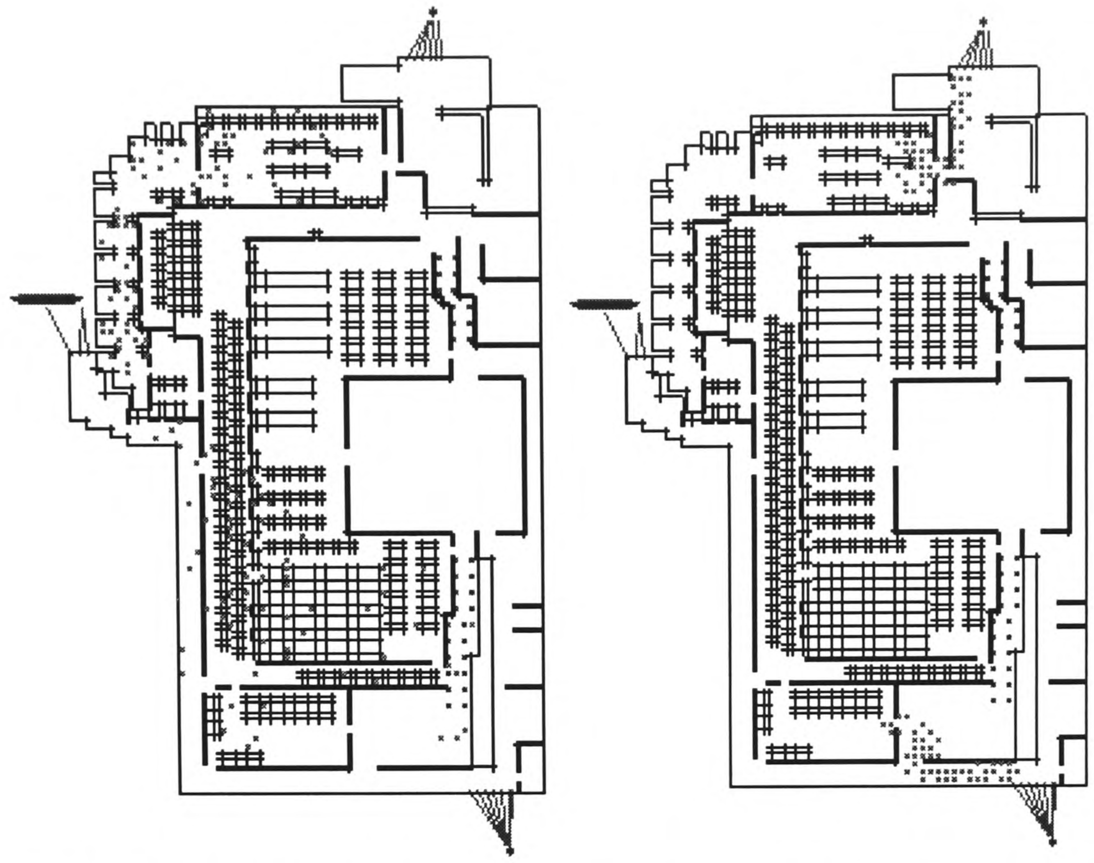


FIGURE 9-20: THE START LOCATIONS (LEFT) AND THE FINAL LOCATIONS OF THE FATALITIES OF OCCUPANTS DURING A SCENARIO 9.433 SIMULATION.

Once the member of staff began to evacuate, he attempted to communicate with the surrounding patrons. This started with those immediately around him, who fell within his *zone of influence*, therefore allowing the transfer of information (see Chapter 8). These patrons responded relatively quickly due to the imposition of social structures upon the population. These then became aware of the incident and moved towards their nearest exit according to the instruction of the staff member. This was because the existence of exit A and exit B had also been communicated to them by the member of staff, making the patrons aware of these exits and also making the exits relatively attractive.

TABLE 9-11: EXIT USAGE DURING SCENARIO 9.43.

Exit	Scenario 9.434	Scenario 9.435
north-south corridor	3[0-6]	229[220-235]
North exit (Exit A)	741[722-767]	99[94-102]
South exit (Exit B)	445[415-461]	69[60-74]

Due to the visibility afforded to him from his stage position, the staff member was able to communicate further into the room alerting the majority of the patrons therein, through line-of-sight calculation (see Section 5.4, Chapter 5). Therefore an increased number of patrons may have information supplied, due to their location being deemed visible from the stage position. Due to the existence of small groups within the population, the information was steadily propagated throughout the population (see Figure 9-21). The communication process was, however, hampered by the size of the room, the existence of areas to which the member of staff did not have 'visible' access, and the simulated imperfection of the communication process (see Section 8.3, Chapter 8).

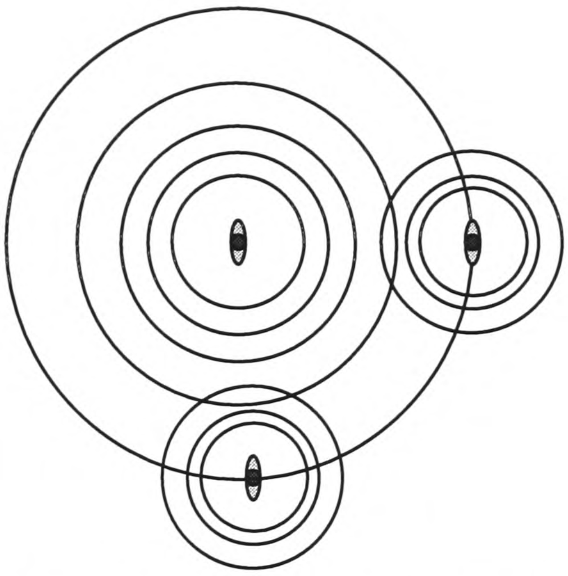


FIGURE 9-21: RIPPLE EFFECT, AS INITIALLY WELL PERCEIVED INFORMATION (FROM MEMBER)IS FURTHER TRANSMITTED INTO SMALL GROUPS

However, once the transfer of information had begun, those newly informed patrons themselves became providers of information, all the more motivated as a member of staff had originally informed them. Outside of the staff member's immediate area of influence, the information was largely propagated through small social groups (see Figure 9-21).

Eventually the entire patron population responded to his information and started moving toward their *nearest* exit of which they had been made aware. On some occasions the patrons moved back towards the north-south corridor (see Table 9-11). Although recorded as occurring during the actual event, this movement was not anticipated to occur during the simulation. This simulated movement was simply due to these patrons being located close to this exit rather than through the selection of this exit as being more attractive.

The majority of the patrons moved towards the northernmost exit (Exit A), as was the case during the actual event. This was due to the size and shape of the structure as well as the seating arrangement. The fluctuations in the exit usage were due to the randomisation procedure (affecting the evacuee's initial position and subsequent exit adoption) and the information provided to them by the member of staff. On a number of occasions, patrons also became aware of exits through line-of-sight calculations (bolstered by the number of patrons using the exits) and altered their egress routes accordingly. The exact nature of the social clusters also had an impact upon the exit adoption, with social groups tending to stay together, maintaining similar travel velocities. Therefore, the exit selection of single senior patrons may have affected a number of the other members of their group. The population that used Exit A consistently fell between 60-65% of the entire population, whereas exit B was generally used between 34-38%.

TABLE 9-12: EVACUATION TIMES AND FATALITY LEVELS GENERATED

	Evacuation times (secs)	Predicted Fatalities	Actual Fatalities
Scenario 9.434	371 [366-380*]	150 [80-279]	162#
Scenario 9.435	221 [216-225]*	443 [396-597]	162#

*this time is reduced due to the fatalities of the patrons
#fatality level in the Cabaret room

After the initial waves of evacuees, the congestion began to build due to the load of evacuees using the limited number of exits. This was especially the case around exit A, simply due to its weight of usage. These patrons queued until the arrival of smoke, at which stage their movement became more erratic, demonstrating their difficulty in maintaining their egress route through the difficult conditions. The immediate effect of the arrival of smoke upon path adoption can be seen in Figure 9-22. Here the worsening conditions evident in the environment makes the evacuee movement less and less efficient, as predicted by Jin [9,11] and as simulated by the behaviour described in Section 7.1, Chapter 7. In this particular example (as depicted in Figure 9-22), the patron was still able to successfully evacuate despite his inefficient movement.

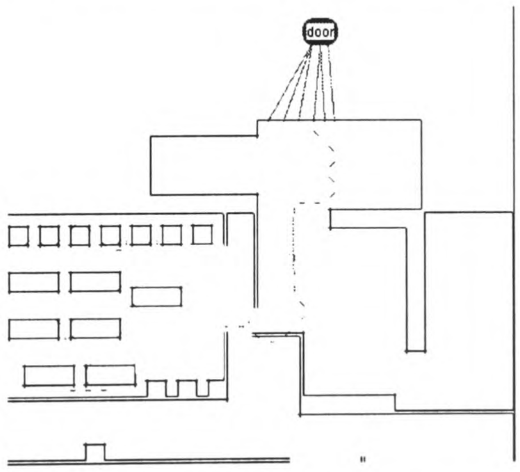


FIGURE 9-22: EXAMPLE OF EVACUEE DIFFICULTY MOVING THROUGH SMOKE ACROSS A DIFFICULT TERRAIN. THE DASHED LINE INDICATES THE PATH OF A SINGLE PATRON MOVING THROUGH DENSE SMOKE

This form of behaviour closely reflects that reported in the actual event. Indeed, after the patron cited as an example in Figure 9-22 had staggered through the dense smoke conditions and had exited, the majority of the patrons remaining in the room became fatalities. This form of inefficient movement was referred to in the original report [52]. As noted by one patron,

"..the smoke was right on us. I got up to the double door...and I jumped down in the crowd and ...we surged backwards and forwards."[52]

or as reported by the authors of the original report,

"Where exiting difficulties occurred, they related principally to the crowded conditions aggravated by the heavy smoke" [52]

Therefore the chain of events originally reported-namely *congestion*, *erratic movement* and *fatalities*-is closely reproduced.

The number of fatalities in the Cabaret Room during Scenario 9.434 ranged from 80-279, averaging approximately 150 patrons (see Table 9-12). This was again significantly affected by the exit usage. Once a disproportionate number of patrons moved toward exit B, large-scale congestion formed, delaying the patron evacuation and therefore making them more susceptible to the environmental conditions. Once the load was more evenly spread between the northern (Exit A) and southern (Exit B) exits, the prevailing conditions allowed a closer representation of the fatalities in comparison with the original event (see Figure 9-23). Again it should be noted that the relatively accurate replication of the fatality levels are somewhat fortuitous as the toxicity levels imposed involved simplifications and extrapolations. The existence and location of the fatalities is more important than their extent, in this instance.

The randomisation procedure was also vital during these simulations, as the exact starting position of the patrons was unknown. This procedure is not only used in concert with the new behavioural features, but one that should be universally applied to any modelling process.

No long-term adaptation of egress routes between the exits occurred in the Cabaret room during scenario 9.434. This was due to the complexity of the room, the extensive congestion around the exits and the large distance between the available exits reducing the attractiveness of redirection. In the actual event, a limited amount of redirection occurred in the Cabaret room, due to existence of congestion delaying further progress [52]. During these instances, patrons were redirecting towards what may have been an unfamiliar area of the structure-a behaviour that is not represented in the new developments. The absence of this behaviour during the simulation may point to the necessity for the increased sophistication of the algorithm to account for complexity.

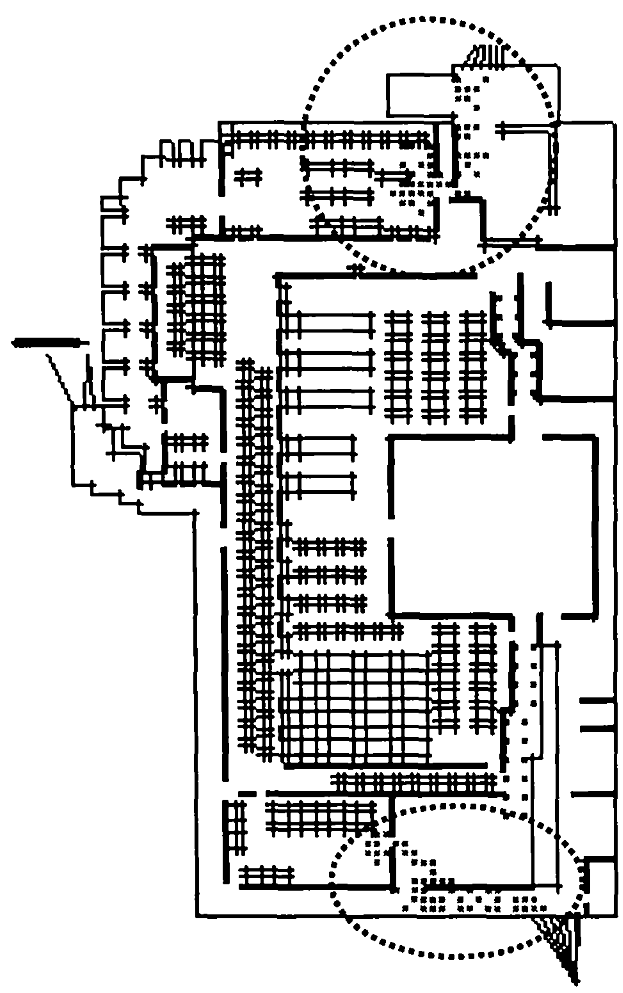


FIGURE 9-23: EXAMPLE FATALITY LOCATIONS IN SCENARIO IN 9.434, DENOTED BY DASHED CIRCLE. HERE 43 PATRONS DIED AROUND EXIT A AND 47 DIED AROUND EXIT B.

However, *short-term* adaptation was evident around the Main bar area, due to the implementation of the population density function, as well as, to a lesser degree, the wall proximity function (see Section 6.1 and 6.2, Chapter 6). Due to the highly motivated nature of the patrons, they were also able to move away from the exit of their choice (see Chapter 3). Once implemented, the extensive congestion evident in the bar area was dissipated so that both sides of the bar were used, as in the actual event [52]. Therefore the simulated evacuees were effectively making short-term adaptation by avoiding localised congestion (see Figure 9-24).

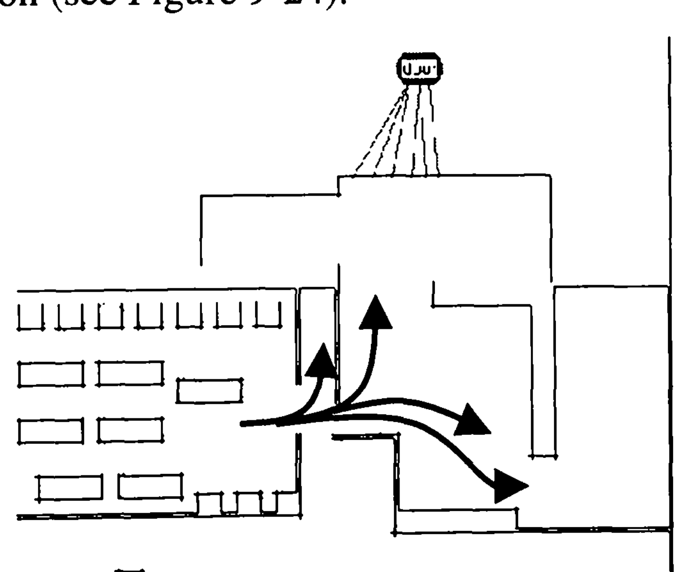


FIGURE 9-24: POTENTIAL PATRONS REDIRECTING AROUND THE BAR AREA

To investigate the sensitivity of the patrons to the seniority structure and its effect upon the communication process, a hypothetical situation was also examined. In scenario 9.435, instead of a staff member communicating the information to the patrons, several patrons were assumed to have become aware of the incident and to have then passed on the information. These five patrons were positioned throughout the geometry to maximise the communication potential, in an attempt to limit the differences between this scenario and scenario 9.434.

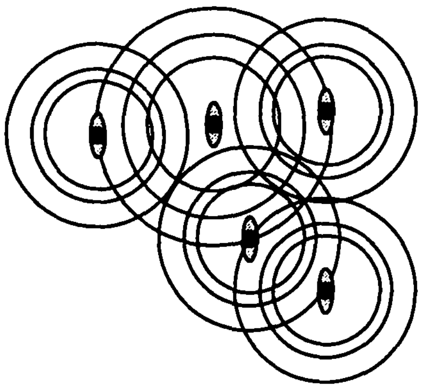


FIGURE 9-25: MORE LOCALISED RIPPLE EFFECT, DUE TO LESS SUCCESSFUL TRANSMISSION OF INFORMATION.

More fundamental than their reduced social standing was the limited familiarity that these patrons had with the structure. Once these 'informed' patrons responded (which, given the time-frame, they were assumed to do instantly) a 'ripple' effect was evident throughout the population, as those patrons that were located adjacent to the providers of the information slowly responded (see Figure 9-25). This was an inefficient process, taking between 60-90 seconds to spread throughout the population. This time may have been significantly increased if social groups were not included or if the initial providers of information were less senior than they were (see Section 5.2, Chapter 5 and Section 8.3, Chapter 8).

In comparison to the effect noticed in Scenario 9.434, the rippling effect of the evacuee response was far more dependent on the newly informed patrons subsequently propagating the information throughout the rest of the population. This was entirely due to the fact that the initial provision of information was not made by a member of staff, who would have affected more people and would have been taken more seriously.

Once the population had responded, they generally moved towards the exit leading to the north-south corridor. This was due to the reduced levels of familiarity that existed in the providers of the information. Therefore, no additional exits were communicated to the patron population. This effect was slightly reduced, through the performance of line-of-sight calculations upon the other available exits, allowing the evacuees to become aware of new exits during the evacuation. The line-of-sight was hindered by the high-density population and the differing levels of visibility afforded by the geometry. Although unintentional, the probabilistic methods used to simulate line-of-sight calculations closely reflected the difficulties reported in perceiving the existence of the alternative exits caused by the nature of the structure and the ineffectual signage [52].

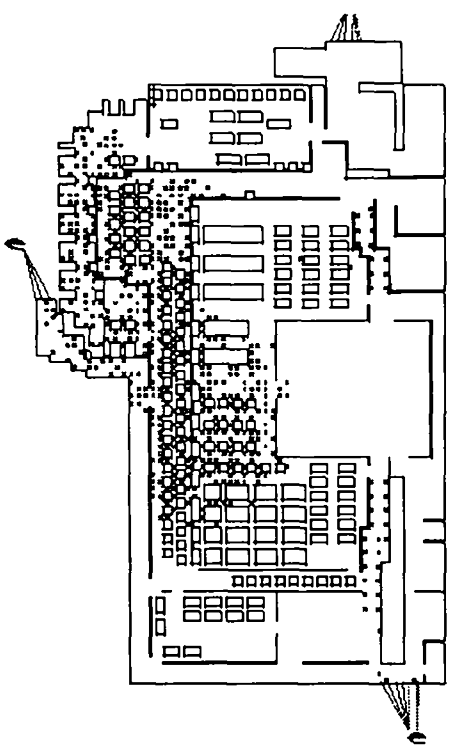


FIGURE 9-26: POSITION OF FATALITIES (APPROXIMATELY 315) DURING THE SCENARIOS WITHOUT STAFF MEMBERS

It should be noted that the provision of information, concerning the existence of the incident, although vital in instigating the response of the patrons, was a fundamental cause of the congestion around the internal exit to the North-south corridor. If not accompanied by the additional information concerning the existence of alternative means of exit (as in Scenario 9.434), then the benefits of communication in this instance are tempered. This further supports the findings of the report authors pointing to the importance of the informers being staff members [52].

Some redirective behaviour was evident between the exit leading to the north-south corridor and the southern exit (Exit B). This included both short-term and long-term adaptation to congestion. This was due to the evacuees becoming aware of the existence of the southern exit, but initially still being more attracted towards the exit leading towards the north-south corridor. Patrons therefore queued at the entrance to the north-south corridor, whilst being aware of the existence of exit B. This provided an alternative egress route once the conditions became appropriate. This behaviour was limited by the substantial distance between the exits, the significant levels of congestion at all of the exits and the existence of social groups.

The extensive use of the exit leading to the north-south corridor caused massive amounts of congestion. Once the environmental conditions began to decline, further reducing the evacuation efficiency, an increased number of patrons were susceptible to the conditions, leading to a notable increase in the fatality levels (ranging from 396-597 fatalities). This is demonstrated in Figure 9-26 where the extent and location of the patron fatalities is evident around the exit leading to the north-south corridor.

Again the evacuation times for Scenario 9.435 are foreshortened simply because a large number of the patrons were overcome by the conditions and therefore were not recorded as having evacuated.

The importance of the arrival of the employees and their ability to relay detailed information to the patrons is evident in the increased number of fatalities and the location of these fatalities in Scenario 9.435. Even if the simulated patrons exited the simulation into the north-south corridor, they would have in reality been situated in even worse conditions, reducing the likelihood of their survival. The importance of this action was also noted in the original report [52]. Therefore through designing appropriate scenarios and implementing the behavioural developments, the same conclusions are reached concerning the importance of specific behavioural actions as those identified in the actual report. This demonstrates adequately the sensitivity of the new model to the communication process and its potential in assisting in the design of evacuation procedures, as well as perhaps indicating its usefulness as a means to interrogate the outcome of an historical event.

The new behavioural developments were also able to represent the difficulties provided by the environment and the consequent behavioural response. This was reflected in their motivation, their incompetent movement and the number of fatalities (especially in Scenario 9.434). The patrons were also seen to experience significant levels of congestion, due to the occupant load and the lack of exit capacity, as was noted in the original report [52].

It would be incorrect to say that the present version of buildingEXODUS was unable to model the occupant behaviour exhibited in the Cabaret room. Indeed from Scenario 9.433, it is apparent that the fatality level and the general exit selection appears similar to that exhibited during the original event [52]. The present model requires the engineer to pose the correct question, and design the simulation to correctly reflect these questions, in order for the results to be of use. This is a reasonable expectation. Admittedly engineering decisions were required to a limited degree in the new behavioural model as well, e.g. location of the staff member. However, once the initial conditions had been determined whilst using the new behavioural developments, the model enabled the patrons to react appropriately rather than restrict their behaviour through the imposition of a deterministic or limited set of behavioural actions. Through limiting the level of engineering required on the scenario, the impact of individual factors, such as the provision and use of information become more apparent.

9.5 CONCLUSION

A number of points should be noted when examining the results generated in the previous sections. Firstly, information, especially concerning the precise actions and locations of the members of staff, was available that would not normally have been. This was used to better illustrate any potential differences between the two models, as well as providing a better basis for analysis of the results produced. It also enabled the demonstration of the sensitivity of the models to the provision of this new information. The validation process, especially when interested in the qualitative aspects of the results, should take advantage of as much of the available information as possible, increasing the rigour and transparency of the analysis. Despite the differences that were evident in the results produced, the present model generated acceptable quantitative results given the data available and the limited areas for comparison (namely the exit usage, the location and extent of the fatalities and the overall evacuation times). The scenarios used to generate these results were slightly more contrived, relying upon artificial levels of patron awareness and understanding.

Once the new model was implemented, the occupants were credited with information levels that were as close to the original events as possible. That is, their familiarity with the structure and their awareness of the event closely mimicked that of the original patrons. Therefore, unlike the present model, extraneous information was not *generally* necessary to enable the accurate simulation of the incident (such as the imposition of response times).

It may be argued that certain pieces of information such as the location of staff members at particular time-frames would not have normally been available. Of course this is true. However, given that a detailed data-set was available it provided a useful means of comparison for the behavioural development of the model. Given the time-frames in which the scenarios are set, they represent the reported actions of the members of staff rather than compromises necessitated through shortfalls in the model. Also, given that the occupants are appropriately positioned and are attributed with accurate levels of information, the introduction of the new model afforded them with a more sophisticated means by which to structure their egress behaviour. It is fair to say that the similarity between the results produced and the original results are slightly artificial due to the provision of this additional information. However, irrespective of this, the new model was able to better utilise the information provided and better reflect the actions of the original evacuees once the information was supplied. In effect, the new model implemented more sophisticated means for the patrons to decide upon their actions and consequently more accurately simulated the events of May 1975. It was not necessary for the user to engineer the scenarios to the same extent, as was required during the use of the present model.

The absence of a detailed understanding of exit usage and the overall (or exit-based) evacuation times prevents us from making the claim that the introduction of the behavioural developments was responsible for quantitative improvements in the results. Indeed a number of the results produced by the models examined are quantitatively similar.

The new developments were shown to increase the sensitivity of the buildingEXODUS model to the conditions that arose during the simulation. As events changed and the patrons were forced to take behavioural decisions in response, different actions were adopted affecting the overall outcome of the evacuation. These decisions not only had implications for the outcome of the immediate decision-maker, but also had implications for the surrounding occupants who perceived this decision. This was especially the case if the occupant was perceived as having specialist knowledge or was a senior member of the patron community. The provision of information allowed the simulated evacuees to react in a more rational and sophisticated manner, taking decisions based on local conditions as well as on prior knowledge. For instance, the arrival of difficult environmental conditions might have forced an occupant to redirect. However, the capacity of the occupant to do so was dependent upon their prior familiarity with the structure.

The present model is able to analyse changes in the conditions during a simulation. This is largely achieved through parametric analysis. This analysis is improved through the behavioural developments, allowing the forensic analysis of evacuation behaviour and the design and implementation of specific procedures. This is of particular benefit when analysing the impact of individual evacuees or the performance of specific actions upon the overall outcome of the incident. In this instance, this might be how important the diligence of staff members was to the safe evacuation of the patron population, or, more specifically, the importance of Walter Bailey's actions in the context of the safety of the occupants of the Cabaret room. From even these calculations, the actions of the staff members can certainly be said to have been very important. The new model can not only therefore better predict occupant actions but can also assist in understanding the reasoning behind the decisions, aiding forensic analysis.

The new model was demonstrated as being sensitive to the non-uniform and evolving nature of the conditions. Therefore the capacity of the simulated evacuee to receive and process information was dependent upon their location and perception of the surrounding events. Instead of either a global representation or the manipulation of the scenario by the engineer, the model automatically reacted and accounted for the developing information landscape.

What was known and recorded about the original event-namely the fatalities and the areas of congestion-was represented during the use of the new behavioural developments. More accurately, these findings fell within the *distribution* of the results produced. It would not have been satisfactory for the model to generate a 'stock' response to a particular event. This would give the impression that only one rational or appropriate response existed to a particular situation. Obviously this is not the case, as any decision will be largely dependent upon the information available, the exact surrounding conditions and the individual that is making the decision. An example of this could be seen during Scenario 9.412. Here, a staff member made a decision concerning their path of egress, according to the surrounding environment and the exits available. This in turn affected the decisions of the patrons who were previously not aware of the incident.

These are the main variables that influenced the distribution of results produced. The behavioural distributions produced were not wide enough to invalidate them, but were still varied enough to represent the impact that behavioural actions can have upon the overall results.

Obviously it should be emphasised that a large number of the behavioural actions evident in the original incident were not and could not be represented by the behavioural developments. Indeed, a number of the developments have been shown to require further work to increase their sophistication. In several circumstances they were shown to be insensitive to the complications of the conditions, while in others they did not have the scope of representation. However, the new model was able to generate appropriate evacuee responses, without necessarily requiring extensive engineering of the data available or the scenario.

The original purpose for this examination should also be borne in mind; to demonstrate the ability of the behavioural developments to function simultaneously and to generate appropriate outcomes. Part of this process must also implicitly be aimed at demonstrating that the developments are not enabled irrespective of the environment, but are instead responsive to the surrounding conditions. The simultaneity of their inclusion should not interfere with this process. During the cases examined the behavioural developments were seen to interact appropriately and by doing so generated results that better reflected the original results. *No anomalous results were produced*, although the combination of the behavioural features did occasionally produce unforeseen outcomes due to the complexity of the algorithms and the cases examined. These were generally for the better. Indeed if the outcome of a simulation is entirely predictable, it denotes an innate simplicity in the underlying model. Obviously, this unpredictability should be bounded, so that totally unprecedented and potentially irrational behaviour is limited.

Although areas for further development have been highlighted the comparison against the Beverly Hills Supper Club incident has demonstrated the robustness of the new developments, as well as better outlining the behavioural sophistication of which it is capable. The results produced have been satisfactory and have increased our confidence in the overall usefulness of the behavioural developments. Obviously more validation involving the simultaneous analysis all of the behavioural algorithms is required. However, these cases have provided a useful initial step in this process.

CHAPTER 10 CONCLUSION

10.1 CONCLUSION: THE IMPLICATIONS OF THE WORK

Of all of the factors that influence the outcome of an evacuation, that of occupant behaviour is the most difficult to predict, the most easily misinterpreted and the least understood. The approach taken by the majority of methods used to simulate the outcome of an evacuation is to ***ignore the influence of occupant behaviour****.* This dissertation has assumed as its primary task the analysis, composition and eventual distillation of evacuation behaviour into a form that enables the development of a comprehensive model.

Previous attempts at representing occupant behaviour have tended to be *top-down* implementations (see Chapter 3), i.e. the behavioural systems are globally defined and are uniform throughout the geometry (e.g. the release version of the buildingEXODUS model [5-7,21-28]). Instead of this simplistic viewpoint, the representation of occupant behaviour during this dissertation has been based around viewing behavioural activities from the *bottom-up*; the occupant behaviour being affected by local considerations, rather than having them imposed by system-wide considerations. Occupant attributes and awareness of the surrounding situation determine the decisions made rather than an external, global rule-base. *Therefore the simulated evacuee is credited with approximately the same relationship to the environment as an actual evacuee.*

This dissertation has demonstrated that it is possible to implement a variety of behavioural developments, taken from numerous fields of study and distil them into a functioning behavioural model. The rigour and candour with which this has been treated is an attempt at following as empirical a methodology as possible. This has been both to demonstrate the depth of understanding of the author as well as to establish a level of confidence in the methods developed. A criticism often levelled against the evacuation modelling community is that the modelling of human behaviour is too difficult to attempt and too contentious to include in any complete evacuation model that might then be used in establishing the 'egressibility' [13,80,106,118,160,221] of an enclosure. To ignore what is effectively the most significant variable of a calculation due to its difficulty diminishes the use and accuracy of an otherwise valuable evacuation model. As already noted, the inconsistency with which the factors influencing the outcome of an evacuation are dealt with is a significant problem. It is accepted that human modelling is difficult and that the process requires close scrutiny. In an attempt to scrutinise the problem this dissertation has been included a detailed analysis not only of the results produced by the introduction of behavioural algorithms but the *mechanisms* used to generate these results.

Until now, several evacuation models have demonstrated a capacity to replicate the *physical* aspects of evacuation behaviour (see Chapter 3). This has been mainly due to the availability of data concerning occupant movement rates in a variety of circumstances and a general bias of the modelling community towards the physical sciences. In situations where this influence dominates, these models may prove to be sufficient, although these situations would be rare and may fluctuate preventing confidence in the eventual results. As the complexity of modern multi-use structure's increase, so the likelihood of influential factors being limited to physical concerns alone diminishes. *The old lie that an increase in the size of the population reduces the impact of any individual act has been repeatedly refuted through real-life events, especially from the perspective of the individuals involved.*

For modelling to prove a significant advantage over alternative means of determining the performance of a structure (e.g. by conducting a controlled drill or by using a formulaic method), it must be of use in numerous scenarios and cope with *configurational*, *procedural* and *behavioural* aspects of an evacuation, in appropriate detail and to an equal level of expertise. By not doing so they yield the greatest advantage that they possess over more formulaic methods; namely the ability to simulate variability in the outcome of an evacuation due to the occupant decision-making process and yet still be able to make realistic predictions. Through the work in this dissertation, these areas have all been addressed more thoroughly.

Evacuation models must simulate both the factors that influence occupant behaviour ***and*** the potential consequences of the behaviour that would be expected in an actual emergency. These considerations not only include the physical aspects of the event, such as the restrictions produced by the enclosure and the abilities of the population, but should also consider *the sociological and psychological influences of the population involved*. It is undoubtedly the case that these factors have not, until recently, been represented in sufficient detail by the majority of evacuation models. This dissertation has been an attempt at highlighting this problem through the more detailed understanding of the social significance of occupants and the mechanisms that they use to arrive at decisions.

For these advances to be attempted a rigorous analysis of the problem had to be conducted. ***Modelling is a complex task that by its nature requires an interdisciplinary approach.*** To develop and test the behavioural model thoroughly it was essential to understand the limitations of the modelling process and therefore the sensitivity of the model to the inclusion of new developments. An already complex task therefore requires the most efficient means of representation possible, whilst not sacrificing the flexibility and accuracy required.

Three separate and distinct subjects have been examined prior to the development of the behavioural model in an attempt to broaden the sophistication and potential accuracy of the model. Firstly, the *subject matter* being modelled had to be analysed (see Chapter 2). This was essential to determine the factors that might influence occupant behaviour, the processes that the occupants used to arrive at a decision, and finally the decision eventually taken by the occupant. A conceptual framework was therefore developed according to which a model might be developed. A finite list was produced of the most significant environmental influences, occupant attributes and behavioural responses that would be evident during an evacuation. These included the occupant's location, evacuation experience, identity, the social significance of the surrounding population, the occupant's previous actions, the ability to estimate the effect of actions, knowledge of the surroundings, the physical condition of the occupant, the ability to perceive information and the occupant's social position. Most importantly, these factors could develop according to the localised events of the evacuation and to occupant's perception of these events. In effect, the decision-making process linked all of these factors together.

Once the expected occupant behaviour had been examined, the *manner* in which it might be represented within an evacuation model was established (see Chapters 3 and 4). Through investigating the limitations of the existing models, an understanding was developed concerning the ability of the available modelling techniques to represent occupant behaviour. The existing models were found to be lacking in both detail and in scope in their representation of occupant behaviour. These omissions existed in the physical aspects of occupant behaviour (tending largely to be static representations), but more evidently in psychological and sociological aspects of evacuation modelling. Here, very little attempt was made to represent the process by which occupants made decisions, their sensitivity to their surroundings, their identity and the social significance of those around them.

This analysis highlighted the developments required and the technical shortfalls that might be encountered. Novel approaches were required to resolve the deficiencies identified in the existing evacuation models. The developments can be broadly categorised into physical factors (the proximity of other occupants and the structure, the more sophisticated representation of the impact of the environment, line of sight calculations and occupant delays), psychological and knowledge-based factors (including the dynamic representation of occupant motivation according to experience, the occupant familiarity with the structure and the ability of occupants to adapt their behaviour to their surroundings) and sociological factors (including group behaviour, the ability to communicate and the existence of social hierarchies). It also highlighted the need to avoid imposing rigid, deterministic behavioural structures upon the occupant population, but instead develop more flexible localised analytical tools, allowing the simulated occupants the capacity to make decisions according to their own experiences and levels of information. By implementing a decision-making *process,* sensitive to the occupant and the occupant's surroundings, rather than strictly adhering to a deterministic rule-base, the occupant is afforded with the capacity to determine the events of the evacuation rather than having his evacuation determined externally.

Finally, the algorithms representing occupant behaviour had to be *implemented* into the existing buildingEXODUS model (see Chapters 5-8). *Therefore, the representation of occupant behaviour and the subsequent evacuation results outlined in this dissertation are based upon behavioural analysis, modelling design and computational implementation.*

All of the proposed behavioural developments represent an attempt to increase the behavioural representation of the model. This was engineered through the introduction of a more *localised and individualised means of decision-making, based around the simulated occupant rather than the user.* This had to be achieved in conjunction with the occupant's ability to *interpret* and *store* these factors. These developments were moving towards seeing the occupant as an *information-processing* system [206]. This created more variation in the results produced, through considering an increased number of behavioural factors.

The development of the algorithms alone is not sufficient to claim an advance in evacuation modelling. For this claim to be appropriate the new features had to be tested and verified (see Chapter 9). This was achieved through the comparison of the results produced introduced through the developments against the data-sets available. Where these did not exist, hypothetical cases were designed specifically to scrutinise the effectiveness of the developments. For thoroughness, the developments were initially examined individually and then in unison (see Chapters 5-9). This process not only more convincingly demonstrated the integration of the developments, but provided evidence essential for the acceptance of any claimed advances.

Each of the new behavioural features provided new occupant capabilities and affected the outcome of the buildingEXODUS simulations. The differences may have been centred on qualitative and/or quantitative aspects of the evacuation, depending on the proposed behaviour in question. ***However, all of the behavioural features examined produced notable results that enhanced the performance of the model in some manner.*** The differences produced were consistent with the expectations of the proposed behaviour, as well as interacting with the existing behaviour in an appropriate way.

The inclusion of advanced behavioural features such as the ability of the occupant to adapt to the surroundings and the existence of communication and other collective behaviour cannot be introduced at the expense of the quantitative accuracy of the model. On the contrary, these features should ***only*** be included if the sensitivity of the model is receptive to them and an improvement is detected in the overall quantitative and qualitative aspects of the results produced. The existence of computational overheads precludes such an unnecessary luxury. ***However, it is contended that the inclusion of appropriately (and transparently) tested behavioural features increases the flexibility and functionality of the model through the more accurate modelling of occupant behaviour.*** This allows the model to simulate a greater variety of occupant behaviour, which are sensitive to the context in which the occupant is found. Not only do the occupants have a richer behavioural repertoire but also the performance of these actions is more sensitive to the events around them.

As noted earlier, the development of a more comprehensive and detailed evacuation model does not provide an overarching solution to the determination of enclosure safety. It does provide a computational tool that, if used expertly and appropriately, will assist the user (who might be a fire safety engineer, a regulator or a member of the fire service) in the analysis of safety. It is intended to be sensitive to the information provided to it, in the form of data-sets and scenario specific information. The algorithms may then react and interpret the data provided. However, the provision and analysis of the results is not a task that could or should be left to an inexperienced user.

The evacuation process is significantly affected by the nature of the occupant population, the information available to them, the manner in which they perceive this information and the manner in which the occupants adapt their behaviour in response to these conditions. For the user to understand and simulate the evacuation process, it would be a fundamental error to view ***egress as an optimal response***, with evacuations unfolding deterministically, according to expectation. Instead the evacuation process should be seen as the culmination of a number of factors, the most important of which does not respond deterministically to events, but weighs up the situation according to the occupant's understanding of the situation, preferences and abilities. It is therefore more fruitful to view ***egress as a result of reflective analysis***. This dissertation has therefore been an attempt at implementing behavioural developments according to this principle.

10.2 FUTURE WORK: EGRESS AS REFLECTIVE ANALYSIS

The modelling process does not provide a natural conclusion to a piece of research. Instead, it produces a model or development that receives continual scrutiny through its use, extending the verification/validation of the model. This highlights the need for constant revisions of the model to take place. Indeed, every new set of results produced by the model should add to the verification process. Given that the model must be continually updated, a suggestion is now made for future work involving the development of a more *coherent* model. This was achieved through the analysis of the psychological, sociological and mathematical fields to provide a method that was consistent and supportable. Only a brief reference to this analysis is made.

It was necessary for the model to be able to reproduce the proposed behavioural features previously outlined, as well as enabling the simulated occupant the capability of *creatively* responding to the environment around him. Indeed, in a number of respects the results eventually produced by the model suggested should be very similar to those seen in Chapters 5-8, given the success of some of the developments outlined. The system extends the idea that behaviour is governed by *local considerations* and that the occupant is not a passive actor within the incident but rather an intelligent *problem-solving* entity that attempts to control the outcome of the unfolding events.

The most significant advance of this system over the behavioural advancements described previously is the fact that it is a *single* system rather than a *composite* of a number of smaller systems. The proposed unified system describes the occupant as a problem-solving entity, who is able to analyse the system in a complete and consistent fashion, rather than in the piecemeal manner highlighted in the previous chapters (although this method was justified due to the requirements of verification). Having identified that occupants should be considered as being individual entities, it is then equally important to represent the interaction and coalition of these individuals into group formations, through the occurrence of collective behaviour. The mechanism derived should be (and is) able to represent the internal processes implemented by the individual to adjudicate and perform actions, but must also represent the pooling of occupant resources in a coherent fashion. This must be capable of representing the emergent and imposed social structure identified in Chapter 2.

Developments in the fields of psychology and sociology have influenced the design of the proposed model. These include perception control theory [206] and socio-cybernetics [227]. These provide the adaptive mechanisms required to model the distributed learning processes identified in evacuation behaviour.

Perception Control Theory [206] sees the individual as processing information to achieve purposive actions. It connects the goals of purposive occupants with their experiences prior to the evacuation, their perceptions of their surroundings during the evacuation and the performance of specific actions. These are then stored internally and can be retrieved to form criteria against which subsequent experiences and actions can be compared. *Given that there are external influences out of the occupant's control, the individual must adjust their actions according to the perceived success of their performance.*

Socio-cybernetics is the logical social extension of Perception Control Theory that allows the collaboration of independent adaptive units to share resources and to affect distant and independent individuals. It sees the relationship between the individual and society as a *bottom-up* relationship. For a collection of individuals to perform these purposive actions in a unified manner *the occupants must have a similar goal with which to compare the surroundings to allow them to arrive at a joint decision.* The alignment of these goals between the population members is achieved through various forms of communication. *Collective behaviour is therefore formed from a common purpose. In effect, the first theory sees the individual as retrieving information from and affecting their environment, while the second sees significant others as being part of that environment, with whom interaction can occur.*

Once the theoretical requirements have been defined, their application to evacuation modelling and specifically buildingEXODUS was investigated. To represent the occupant, given the theoretical framework outlined, individuals are represented as Learning Automata, [208-209]. This representation implies that the occupant is involved in a *constant interaction with their environment* (that might include other occupants). Here, the occupant receives information from the environment in the form of a *feedback loop*. This information received directly affects the likelihood of performing a finite number of actions available to the occupant. Once selected, the success or failure of the action can be determined through any alteration in the external conditions. The occupant ('automaton') is then seen as learning as it passes through an environment, according to the outcome of its previous activities [208-209].

These automata are then able to interact with each other and analyse future actions through the use of Game Theory [228], which examines the resolution of conflicts and the possible development of co-operation within a population. It describes the interaction between *players* in a *game* situation and provides a mathematical means of codifying these interactions. Each player involved makes decisions in relation to the other players (including the environment). The outcome of this decision is known to the players, or at least can eventually be estimated by them. The uncertainty faced by a player is assumed to be due to the unknown actions of the other players (e.g. environmental uncertainties). *These decisions are formed on the rational basis that the success of an outcome is to be maximised.* These decisions are made and analysed on the assumption that the differences in the outcome *matter* to the individuals concerned. In evacuation modelling the survival of the individual occupants (and possibly other members of the occupant population) provides an ideal index of in determining the success of the performance of an action.

It is not claimed that the proposed model strictly adheres to either the sociological, psychological or mathematical principles briefly discussed above. It is, however, an attempt to apply the principles not simply in an analogous fashion, but in as coherent and consistent a manner as possible. *Developments are made not only through the inclusion of the concepts of reinforcement learning, information-processing and collaborative activities, but to extend them through the use of creative and novel responses to the problems encountered.* The model is based on the occupant being an *information-processing* agent within a *dynamic* environment. The agent is capable of both receiving and emitting information, the perception of which is dependent upon the context in which it is relayed and the identity of the agents involved.

In Chapters 5-8, occupant behaviour was selected from a finite set of options. These options were derived *directly* form the research literature. Therefore the behavioural response was limited to the few that are represented within the model. This would then represent the occupant's *entire* response to an event. A restriction upon occupant choice is still maintained in the model suggested, except at a much more *basic* behavioural level. Occupant behaviour will be formed from the reconstitution of a number of behavioural sub-components. These smaller behaviours will form the building blocks of the occupant's overall behaviour.

The model is based on the assumption that only a small of number of sub-components is initially required, which may then be reconstituted to form a large number of more complex long-term behaviours. Each of the sub-components identified exists in the form of the proposed behaviours described in Chapters 5-8. Therefore the model proposed requires the developments of a means of reconstitution, rather than the complete generation of new behavioural actions. As an initial attempt at identifying these sub-components, four basic behaviours are identified: the *movement* to a new location, *delaying* making a decision, the *redirection* to a new goal and the *transferral* of new information. (This is not a definitive list, but a provisional description that requires a great deal of development).

The form of reconstitution applied will be dependent upon the experiences of the occupant. The overall behaviour is formed from a chain of sub-behaviours, in response to *sub-goals,* which provide the occupant with distinctive decision points. These might include avoiding a high-density population, navigating around a complex geometry, reaching an internal exit, etc. *The completion of these sub-tasks contribute to the overall accomplishment of a long-term goal* [229].

This modular format provides a large degree of flexibility in the adaptivity of the decision-maker, far more than could be achieved through the provision of complete behavioural responses. Instead of the long-term behaviour being internally defined, the behaviour of the occupant is constructed according to his needs. This allows the simulated occupant to *creatively* solve the problems faced, at a relatively low level of representation.

An important part of this system is the ability of the occupant to *communicate with themselves*, as well as others [218]. This would allow the occupant to *estimate* the effect of performing several of the available options, upon him and upon other members of the population. This may include the calculation of egress routes, as examined in Chapter 8 or the interaction with other occupants, which might be addressed through utilising the mechanisms of game theory to weigh up the consequences of potential actions. The behavioural actions will not be taken in isolation. Instead, they will occur simultaneously with a number of other environmental considerations, the most important of which will be the surrounding occupant population. Their actions and identities will act as environmental responses that will have a variety of influences over the subject occupant.

Adjacent occupants may communicate and align their actions, according to the influence that they exert over each others actions through their social position (see Chapters 2 and 8). This may be achieved through accidental alignment, interactive communication or instruction [227]. *Communication, be it environmental, procedural or individual, will be judged according to its origin, its perceived trustworthiness and severity of the imparted information.* This judgement will occur prior to any action performance or behavioural decision. The perception involved in the communication process will again involve prediction and estimation. This analysis will be biased according to pre-existing social relationships, as examined in Chapter 8. *Therefore through the analysis or the maintenance of social expectation, collective behaviour can arise.*

The population does not arrive at the evacuation without previously engaging in some form of social growth and emergence. *Therefore occupant goals and reference structures will exist prior to the evacuation according to occupant experience.* This type of system has already been examined in Chapters 8 and is well suited to the implementation within the buildingEXODUS model.

The system outlined is incomplete and its development is left for future work. However, it does describe the culmination of an extensive development in the modelling process. Given these provisions, the system should be capable of generating the types of behaviour discussed in Chapter 3. It does this through maintaining the influence of external conditions upon the occupant whilst allowing the occupant to decide upon his actions according to analysis, estimation and social responsibility. *In effect it moves from the imposition of expected occupant behaviour, to the generation of novel, adaptive occupant response that has been refined according to expectation. Through a consistent and coherent mechanism, the occupant will determine their response according to their ability to reflect upon the circumstances, analyse the consequences of their actions and adapt their behaviour accordingly.*

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APPENDIX 1: PUBLICATIONS

The front pages of each of the refereed publications are included. These publications are

Gwynne, S., Galea, E., R., Owen, M. Lawrence, P. J. and Filippidis, L.," "Review of modelling methodologies used in the simulation of evacuation", *Journal of Building and the Environment, 34, pp441-749, 1999.*

Gwynne, S., Galea, E., R., Lawrence, P. J., Owen, M. and Filippidis, L "A Systematic comparison of model predictions produced by the buildingEXODUS evacuation model and the Tsukuba Pavilion Evacuation Data", *Applied Fire Science, Vol. 7, No. 3, pp235-266, 1998.*

Gwynne, S., Galea, E., R., Lawrence, P.J. and Owen, M.," An Investigation Of The Aspects Of Occupant Behaviour Required For Evacuation Modelling", *Journal of Applied Fire Science, Vol 8(1), pp 19-59, 1998-1999.*

Gwynne,S. Galea, E., R., Lawrence, P.J.,Owen, M. and Filippidis, L.," Adaptive Decision-Making in buildingEXODUS", *Journal of Applied Fire Science, 8 (4), pp265-289, 1999.*

Gwynne,S., Galea, E.R., Owen, M., Lawrence, P.J. and Filippidis, L., "A Review of the Methodologies Used in the Computer Simulation of Evacuation from the Built Environment",*pp681-691, Human Behaviour in Fire: Proceedings of the 1st International Symposium, Ed: Shields,J., University of Ulster, ISBN 1859231039, TextFlow Ltd,.31/8/98-2/9/98.*

Gwynne,S., Galea, E.R., Owen, M., Lawrence, P.J. and Filippidis, L., "A Comparison of Predictions from the buildingEXODUS Evacuation Model with Experimental Data", *pp711-721, Human Behaviour in Fire: Proceedings of the 1st International Symposium, Ed: Shields,J., University of Ulster, ISBN 1859231039, TextFlow Ltd,.31/8/98-2/9/98.*

Gwynne,S. Galea, E., R., Lawrence, P.J., Owen, M. and Filippidis, L.," Adaptive Decision-Making in buildingEXODUS in Response to Exit Congestion", *Submitted to 6th IAFSS Symposium.*

Gwynne, S. , Galea, E.R., Owen, M. and Lawrence, P.J., "Escape As A Social Response", *Published by the Society of Fire Protection Engineers, 1999.*

Gwynne,S. and Galea, E.R.,"A Review of the Methodologies Used in the Computer Simulation of Evacuation from the Built Environment", *Published by the Society of Fire Protection Engineers, 1998.*

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

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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

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

JOURNAL OF

APPLIED FIRE SCIENCE

Executive Editor: **Paul R. DeCicco**

Volume 8, Number 1—1998-99

An Investigation of the Aspects of Occupant Behavior Required for Evacuation Modeling

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Baywood Publishing Company, Inc.
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ADAPTIVE DECISION-MAKING IN RESPONSE TO CROWD FORMATIONS IN buildingEXODUS*

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ABSTRACT

Given the importance of occupant behavior on evacuation efficiency, a new behavioral feature has been developed and implemented into buildingEXODUS. This feature concerns the response of occupants to exit selection and re-direction. This behavior is not simply pre-determined by the user as part of the initialization process, but involves the occupant taking decisions based on their previous experiences and the information available to them. This information concerns the occupants prior knowledge of the enclosure and line-of-sight information concerning queues at neighboring exits. This new feature is demonstrated and reviewed through several examples.

INTRODUCTION

Computer-based evacuation models offer the potential of overcoming the shortfalls inherent in determining the safety of individual premises [1]. In doing so, they not only address the needs of the designer but also of the legislator in the emerging era of performance-based building codes.

In order to fully assess the potential evacuation efficiency of an enclosure, it is essential to address the following factors;

*Mr. Gwynne would like to thank the University of Greenwich for their financial support through the Ph.D. Bursary Programme. Prof. Galea is indebted to the UK CAA for their financial support of his chair in Mathematical Modelling.

A REVIEW OF THE METHODOLOGIES USED IN THE COMPUTER SIMULATION OF EVACUATION FROM THE BUILT ENVIRONMENT.

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1.0 ABSTRACT.

Computer based analysis of evacuation can be performed using one of three different approaches, namely optimisation, 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 which 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.

2.0 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. Increasingly, computer based evacuation models [1-31] 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 [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 "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

A COMPARISON OF PREDICTIONS FROM THE buildingEXODUS EVACUATION MODEL WITH EXPERIMENTAL DATA.

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1.0 ABSTRACT

In this paper, the buildingEXODUS (V1.1) evacuation model is briefly described and an attempt at quantitative model validation presented. The data set used for validation is the Stapelfeldt evacuation data. An important consideration highlighted by this work is that any validation exercise must be scrutinised to identify both the results generated and the considerations and assumptions on which they are based. During the course of the validation exercise, the data set was found to be less than ideal for the purpose of validating complex evacuation models. However, the buildingEXODUS evacuation model was found to be able to produce good quantitative agreement with the experimental data.

2.0 INTRODUCTION

Validation is an essential step in the continual development and acceptance of evacuation modelling. While no degree of successful validation will prove an evacuation model correct, confidence in the technique is established the more frequently it is shown to be successful in as wide a range of applications as possible.

While the term "validation" is often used its meaning is often misinterpreted. In this paper we will take validation to mean the systematic comparison of model predictions with ***reliable*** information. The information used for validation purposes may comprise experimental data, numerical data, or experiential insight or a combination of these sources. Depending on the nature of the data, the validation may comprise, (i) **component testing** – routine checking of major software sub-components, (ii) **functional validation** – check model capabilities and inherent assumptions are compatible with intended use, (iii) **qualitative verification** – compare predicted human behaviour with informed expectations and (iv) **quantitative verification** – detailed comparison of model predictions with reliable experimental data [1].

In a recently produced report, some 22 evacuation models were identified and reviewed [2]. One of the features common to all the models identified was a lack of convincing validation data. As the number and variety of evacuation models increase it becomes essential to provide a discriminating basis of comparison. Success at a wide range of standard 'validation' exercises provides one means to this end. However, to date, little effort has been invested in the systematic comparison of various evacuation models with common experimental data.

The lack of a convincing quantitative validation history is due for the most part to the scarcity of suitable experimental benchmark evacuation data. The majority of evacuation trials are not conducted for model validation purposes but to demonstrate the suitability of a building design/staff

HUMAN BEHAVIOUR IN FIRE—PROCEEDINGS OF THE FIRST INTERNATIONAL SYMPOSIUM, pp. 711–720

ADAPTIVE DECISION-MAKING IN BUILDINGEXODUS IN RESPONSE TO EXIT CONGESTION

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ABSTRACT

Given the importance of occupant behaviour on evacuation efficiency, a new behavioural feature has been implemented into buildingEXODUS. This feature concerns the response of occupants to exit selection and re-direction, given that the occupant is queuing at an external exit. This behaviour is not simply pre-determined by the user as part of the initialisation process, but involves the occupant taking decisions based on their previous experiences with the enclosure and the information available to them. This information concerns the occupant's prior knowledge of the enclosure and line-of-sight information concerning queues at neighbouring exits. This new feature is demonstrated and reviewed through several examples.

KEYWORDS: evacuation, fire safety, queuing, adaptive behaviour, familiarity, line-of-sight.

INTRODUCTION

Computer based evacuation models *[1]* offer the potential of overcoming the shortfalls inherent in determining the safety of individual premises. In doing so, they not only address the needs of the designer but also of the legislator in the emerging era of performance based building codes. In order to fully assess the potential evacuation efficiency of an enclosure, it is essential to address the following factors:

- the configuration of the enclosure, which encompasses the impact of the geography of the structure,
- the procedures implemented within the structure, which would entail the configuration knowledge of the occupants and the training and activities of the staff,
- the atmospheric environment within the structure through which the evacuation takes place, describing the effect of heat, toxins and smoke upon the occupant's ability to navigate and make decisions,

Submitted and presented at the 6th IAFSS Symposium, Poitiers, 1999 and to appear in the subsequent Proceedings.

Research Report

Escape as a Social Response

by

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RESEARCH REPORT

A Review of the Methodologies and Critical Appraisal of Computer Models Used in the Simulation of Evacuation from the Built Environment

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