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Validation of an Evacuation Model Currently Under Development

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Abstract

Current evacuation models have been found to have limitations either in the scope of their simulation, or the size of the scenario that can be simulated. A model currently under development called EvacuatioNZ was produced to address some of these limitations. EvacuatioNZ is a coarse network model that simulates the occupant movement times as well as the human behaviour before and during the evacuation process. It incorporates the Monte Carlo approach in producing probability distributions of evacuation times. This model is designed to allow the expansion or modification of the program as more knowledge on human behaviour and occupant emergency movement is obtained, without the need to reproduce the entire model.

The main aim of this research was to assist in the development of this evacuation model by carrying out validation processes that tested the model's components. This would allow the model to be used with reasonable confidence by designers and fire engineers.

Individual component testing on the model has shown that the basic components of movement are working satisfactorily, and are producing results that are comparable to values produced by the Nelson and MacLennan flow equations. Tests using a combination of components have also been found to produce representative results, when similar assumptions are being used. However, more components, including the behavioural components, should be tested before this model can be used for design purposes.

The current version of the program still has some limitations that need to be addressed in order to increase its functional value. Further research should also include the model validation using more calculation examples, as well as data from actual trial evacuations to validate the components of human behaviour in the model.

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1.0 Introduction

1.1 Impetus for the Research

Currently there are numerous evacuation models available. Earlier evacuation models did not consider human behaviour in their calculations, and required the user to set their own factor of safety to account for it. Newer models have been produced, incorporating some human behaviour so that they can simulate more realistic evacuations.

However, the study of human behaviour in fires is still relatively new, and latest research keeps revealing new aspects of human behaviour and new evacuation data. Current available models are 'fixed' in their components, making it difficult to modify the components according to the latest research and findings. Moreover, it would not be convenient or economical to reproduce a model each time a new aspect of human behaviour is found.

Furthermore, most of the available models are deterministic models, where the output from the model is a single value that is supposed to represent the entire scenario. There is a need to produce a probabilistic model that can take into account the uncertainties and variation that are present in real situations.

Therefore, the impetus of this research is to produce a probabilistic model that can be expanded or modified as more knowledge on human behaviour and occupant emergency movement is obtained, without the need to reproduce the entire model. This can be achieved using object-oriented programming, which allows program components to be inherited.

1.2 Goals of the Research

The main aim for this research is to be able to assist in the development of an evacuation model that will be able to produce results that are representative of actual evacuations in real fires or trial evacuations. This will allow the model to be used with reasonable confidence by designers and fire engineers to help show that the occupants in their building will have sufficient evacuation time.

This research will test the model's components and actively participate in the improvement of the representation and performance of the model by carrying out qualitative and quantitative validations.

At the same time, the study will also attempt to reveal the limitations and deficiencies in the evacuation model and suggest means of improving the functional features and performance of the model.

1.3 Outline of this Report

This report will endeavour to provide the reader with sufficient information on the subject of evacuation modelling. It will also provide information regarding the new evacuation model called EvacuatioNZ. It must be noted that the report will only consider one version of the model, which is EvacuatioNZ Version 1.0e.

Chapter 1 will explain the reasons and aims for this evacuation study as well as describe the outline of this report. Chapter 2 will provide a summary of earlier studies in evacuation modelling, which consists of the modelling of occupant movement and human behaviour in fires. It will then proceed to introduce the different types of models that are available, as well as outline several examples of evacuation models.

The main sections of the report will be based on the new evacuation model called EvacuatioNZ. Chapter 3 will present the general features incorporated into the model, and also provide information on the format of the input and output files used by the model.

Chapter 4 will provide insights on some of the mechanics of the model. Although there are many technical aspects in the model, only the model mechanics that are relevant to the subsequent sections will be described in this chapter.

Chapter 5 will describe the component testing that was carried out on the model. This is followed by a discussion on the various results obtained from the validation process. A simple scenario is simulated using the evacuation model and its results are discussed in Chapter 6.

Chapter 7 will present some general discussion regarding the model and the component testing, and highlight some of the problems experienced during the validation process. Some conclusions and ideas for future research are then presented in Chapter 8 of this report.

1.4 Limitations of this Study

This study is limited to the features and testing of Version 1.0e of the EvacuatioNZ model. As a result of this study, several improvements have been made to the model since the writing of this report, but will not be discussed here.

Many theories and equations on occupant movement have also not been described in detail in this report. The report just provides a basic review of studies carried out by other researchers. It is therefore recommended that the reader consult the papers by the authors referenced in this report for further information.

2.0 Literature Review

2.1 Occupant Emergency Movement

Occupant movement has been studied extensively for over 30 years. Major contributions have been produced by Fruin (1971), Predtechenski and Milinskii (1978), Pauls (1987) and MacLennan (1995). Most of the studies on occupant movement suggest concepts that are similar to traffic flow models. The efficiency of occupant movement is determined by the occupant flow, or the number of occupants that are able to pass a point per unit time. Studies have shown occupant flows to be influenced by the width of the building component, occupant movement speeds and occupant densities.

The width of the building component affects the number of people that are able to pass at the same time. In addition to that, studies by Pauls (1987) and Fruin (1971) have shown that occupants would usually stay a certain distance from walls and other obstacles while they are walking. This distance, also called the boundary layer, is required for balance and lateral body sway. Therefore, while there is an actual width, the occupants will only be effectively using a smaller width of the building component, which is the actual width subtracted by the boundary layers on both sides.

Occupant movement speeds have been found to be influenced by occupant densities of a certain range. Pauls (1987) has suggested the lower limit to be when the occupant density is below 0.54 persons/m^2. This lower limit is where the occupants can move at their own speed, independent of other occupants. Fruin (1971) has suggested that even when unimpeded, occupants have a wide range of walking speeds. At extremely high occupant densities (4 - 5 persons/m^2), movement will cease until a sufficient number of people have left the crowd. The relationship between movement speed and occupant density is a linear one, with factors to account for the type of building component being traversed, such as a door, corridor, or stairway.

Occupant density is basically how crowded it is along an evacuation route. Occupant density is usually measured in persons per square metre, but Predtechenskii and Milinskii (1978) accounted for it as the inverse of the area of horizontal projection created by an occupant. Occupant density is a very important factor in determining the occupant flow. An occupant density of 1.9 persons/m^2 has been found to be the optimum density, where the occupant flow is at its maximum. On the other hand, higher densities have been found to not only significantly reduce the movement speeds, but also cause discomfort to the occupants. This discomfort varies from person to person, depending on their culture, social setting and relationship to those around them. [Fruin (1971)]

In designing for occupant movement, it is important, especially in tall buildings, to recognise that there can be two types of evacuations. The most common type is the uncontrolled evacuation, where the occupants from every floor are allowed to evacuate at the same time. This form of evacuation will result in high occupant densities on evacuation routes, and will possibly put the occupants at the level of fire origin at a higher risk, as they are unable to evacuate quickly. The occupants queuing to leave the building often face frustration and stress.

The second type of evacuation is termed controlled or staged evacuation, where the occupants who are in immediate danger are evacuated first, followed by the other occupants. This means that the evacuation starts on the level of fire origin, followed by the floors above. The benefits of this system are that the occupants that are in immediate danger can evacuate faster and with less stress. Also, the occupants in greater danger are evacuated first, so the number of casualties may be reduced. On the other hand, controlled evacuation is very demanding on the management system in the building. It not only requires accurate and unambiguous information on the public announcement system, but also requires sufficient trial evacuations to ensure that the occupants and wardens are familiar with the system.

In conclusion, previous studies on occupant movement have produced concepts similar to the traffic flow concepts. It is important, however, that further research be carried out, especially in the field of emergency movement. The designer must not forget that in dealing with total evacuation times, they have to not only consider the movement times, but also human behaviour which may significantly increase the evacuation times.

2.2 Human Behaviour in Fires

Human behaviour in fires is a newer scope of research when compared to the study of occupant movement. Earlier evacuation models did not incorporate any behavioural model, and were thus termed 'ball-bearing' models.

Conventional ball-bearing models have often produced minimum evacuation times, opting to model the occupants as unthinking 'spheres' that roll in the direction of a specified exit, with no interaction between the 'spheres' other than manoeuvring attempts and queuing effects.

However, calculated movement times from ball-bearing models have been found to be significantly less than the obtained times in real evacuations. Although human behaviour has normally been associated with pre-movement activities, studies have indicated that occupants have delays both in starting the evacuation and during the movement phase.

There could be delays in starting evacuation attempts due to any number of reasons. Significant pre-movement times could be due to the ambiguity of the fire cues, such as the presence of smoke or alarm signals, or warnings from other occupants. Occupants may also downplay the fire cues when they are in groups as shown in a study by Latane and Darley (1970). There might also be significant pre-movement times for occupants who are sleeping as concluded by Kahn (1984).

Bryan (1995) in his study realised that people do not respond well to non-voice alarms, such as alarm bells and sounders. Among the reasons for this is that people are uncertain about what the signal indicates. Some might fail to recognise it as an alarm bell, while others might decide that the alarm is merely a system test. In places where false alarms occur frequently, the effectiveness of the alarm would be affected, and occupants might not bother to respond to it. The occupants' uncertainty or failure to recognise the alarm would result in a delayed response or a non-evacuation.

Proulx and Sime (1991) studied the effectiveness of differing levels of emergency information in an underground rail station. Among the types studied were the alarm bells, the presence of staff supervision, and non-directive and directive public announcements. From their study, they concluded that the pre-movement times were significantly reduced by the use of both non-directive and directive public announcements, as well as the supervision of staff members. The most efficient method was by directive public announcements as it gave clear instructions and the staff member could control the evacuation and still have an overview of the situation at hand. The alarm bells were found to be ineffective in starting the evacuation and were found to be more of an inconvenience to the passengers than an indication of an emergency evacuation.

Tong and Canter (1985) also supported the use of voice public announcements. They, however, cautioned that the actual content of the message would need to contain useful information and be easy to understand. Visual alarms may need to be installed for occupants with hearing impairments.

In places where there are no alarm signals, most occupants would only be alerted to a fire if they encounter other fire cues. Typical examples of these are the presence of smoke or flame, strange noises or warnings from other occupants. However, these cues are ambiguous and usually cause the occupants to seek more information instead of evacuating the building. As they spend more time obtaining information, they will potentially have less time to evacuate the building.

Fire cues are important indicators of a fire emergency. However, the perception of cues by occupants depends on the intensity of the cue and the occupants' focus of attention. The latter is very important as occupants may perceive the cues but still be able to redirect their attention back to their focus of attention.

Latane and Darley (1970) researched the effects of group inhibition on cue perception. They realised that the recognition of ambiguous fire cues was inhibited by the presence of other people in the room. Occupants in a group tended to unconsciously reduce the significance of the cues they perceived, most likely because they did not want to over-react and cause embarrassment. In the presence of ambiguous cues, the occupants tended to be influenced by the behavioural response of other occupants. Because of this, the occupants would perceive the fire cues later and have a higher tendency to enter into non-adaptive flight behaviour.

Occupants may also be involved in non-escape actions such as notifying the fire service of the fire, activating manual call points, and saving their property.

Humans are thinking creatures, and are able to decide which route to choose when evacuating the building. Studies by Sime and Kimura (1988) and Sime (1989) have indicated that in emergency evacuations, occupants usually exit through the routes that they are familiar with. Designers should therefore be expecting unbalanced use of stairways and exits according to the familiarity of the occupants to those exits. This is especially true for emergency routes usually fitted with entry alarms that prevent their use in non-emergency situations, as their use during an emergency will be much less than expected.

Furthermore, Frantzich and Benthorn (1996) have proposed that there exists a relationship between the distance of the exit and its familiarity, to the choice of exits by the occupants. From experiments that they have carried out, occupants are usually found to head towards a familiar exit, unless a much closer exit is known. In addition to that, an open exit attracts more occupants than a closed exit. This finding is especially useful in increasing the use of fire exits usually not known by the general public. The occupants would be more likely to use the fire exit if they are able to see that it leads to the outside.

The choice of exits may also be influenced by instructions from staff members or the tendency to follow the crowd.

During the movement phase, there are a number of ways in which delay could occur. Unlike the ball-bearing assumption, real occupants interact with each other and their surroundings. Occupants might be warning other occupants of the fire or helping other occupants who may be mobility-impaired, and societal effects such as staff supervision over the public and family groupings can be seen. Upon encountering the fire source, occupants might also decide to interfere and attempt to extinguish or control the fire.

Fahy and Proulx (1995) found out from the World Trade Centre evacuation that most occupants were willing to walk through smoke although a majority of them did turn back later. Therefore, if there is thick smoke present, the occupants could either reassess their route, or decide to continue along the route. Their movement speed in smoke would definitely be reduced by poor vision. This would result in longer evacuation times.

Wayfinding may take a significant amount of time especially in complex building layouts or for occupants who are not familiar with the building. Occupants may wish to evacuate the building quickly, but may have difficulty finding their way out. Conventional methods of placing signs above doorways and higher on walls so they may be seen may not be effective in fire emergencies once the smoke levels start to drop to that level. Poor lighting may also worsen the occupants' attempts at wayfinding. Therefore, designers should keep the building layout simple as well as provide adequate emergency lighting. Signs also have to be easy to understand and continuous along the escape route to reinforce the idea that it is the correct path. Regular trial evacuations will also help in familiarising the occupants to the fire escape routes.

Mintz (1950) developed the concept of non-adaptive group behaviour, otherwise known as panic, where the different reward structure perceived by some occupants may lead them towards competitive behaviour. Schultx (1968) defined panic as a fear-induced flight behaviour, which is non-rational, non-adaptive, and non-social. This behaviour is infectious throughout the group and results in selective, individual competition to reach the exit. It serves to reduce the escape possibilities of the group as a whole. However, it must be noted that panic rarely occurs and is usually caused by inadequate amount of information available to the occupants. Effects of panic behaviour have been seen in fire incidents such as the Beverly Hills Supper Club fire. [Kentucky State Police (1977)]

Generally, non-adaptive behaviour also implies the disregard of behaviour that might facilitate the evacuation of others or inhibit the propagation of smoke, heat or flame from the room of fire origin. Most of the non-adaptive actions, such as leaving the door open, are not done on purpose, and are usually the result of failed attempts in adaptive behaviour. In short, there are not many cases of irrational or self-destructive behaviour in fires. What is labelled as panic or self-destructive behaviour, are usually rational decisions taken by occupants based on the information available at the time of the incident.

There are still numerous human behavioural aspects in fire situations that influence the evacuation times. Our question, as designers, is how we can allow for human behaviour in our designs of the fire safety systems. And before we account for every minute detail of human behaviour in fires, how much does it influence the evacuation process, and is it really necessary to go into such complexities to account for it?

2.3 Available Evacuation Models

Evacuation models are increasingly used by designers and fire engineers to demonstrate that their buildings are safe and are able to provide sufficient time for the occupants to evacuate in the event of a fire or other emergency.

2.3.1 Type of Evacuation Models

There are several types of evacuation models currently available. Each type differs in the way it approaches the analysis and the different means of representing the space, the occupants and their behaviour.

Gwynne et al (1999) divided the different approaches to the evacuation analysis into three types, namely optimisation, simulation, and risk assessment. The optimisation model assumes that the occupants can evacuate in an efficient manner and therefore ignores the peripheral and non-evacuation activities. The simulation model is an attempt to represent the behaviour and movement observed in evacuations. Its accuracy in predicting evacuations paths and decisions are greatly influenced by the accuracy of the behaviour models used. Risk assessment models provide statistically significant values for hazards and evacuation times by producing probability distributions of values collected from the repeated runs of each simulation.

Some models do not account for the behavioural effects of the occupants during the evacuation process. These models are often referred to as 'ball-bearing' models. Others take into account the human behaviour that could be involved during the evacuation process. The models that incorporate human behaviour are more realistic because they model the decision-making and actions that the occupants may be involved in.

The occupants can be inputted either globally or individually. The global perspective assumes the occupants as a homogeneous grouping of people, without considering that the occupants might have different identities. On the other hand, the individual perspective allows diversity of the occupants. It assigns personal attributes to the occupants, allowing individual movement and decision-making.

The building space can be represented in two ways; fine network and coarse network. The fine network approach usually uses a network of nodes of equal spacing to represent a space. Therefore, a large room could be made out of many nodes. This approach would allow the accurate representation of the geometry, but the input could be tedious, with many of the programs requiring CAD drawings. The coarse network approach represents each space as a node, and sets each node with properties as entered by the user. The nodes are connected via arcs, which represent the actual connection of the building components. There is some flexibility in the input in that the user can specify more than one node to represent the room when it is relevant, such as in the case of a long room or corridor. This approach increases the speed of computation, but does not take into account overtaking or other local interaction between individuals.

2.3.2 Examples of Evacuation Models

2.3.2.1 EVACNET+ [Kisko, Francis & Noble (1984)]

EVACNET+ is a public domain program that models building evacuations. It requires a coarse network model of the building and the number of occupants at each node. The nodes are connected via arcs, where the user would have to input the traversal time and the flow capacity of each arc. The model produces results that describe an optimal evacuation of the building, which implies that the evacuation times obtained from the program are the minimum evacuation times. EVACNET+ does not incorporate any behavioural aspects during the evacuation and is therefore a ball-bearing model. However, the program produces quite a lot of results that are beneficial in the analysis of building scenarios. It provides details about the evacuation at each time step, and therefore enables the user to identify bottlenecks in the building.

2.3.2.2 EXITT [Levin (1987), Kostreva & Lancaster (1998)]

EXITT is a sub-program in HAZARD I that simulates occupants' escape from a burning building. It requires a coarse network model to describe the building. The occupants are assumed to travel at a speed, which is a function of their normal travel speed, smoke conditions and whether they are helping other occupants. The model uses some decision rules, such as a shortest path algorithm introduced by Dijkstra (1959), to determine the path out of the building for each occupant. The path is then checked at each time step to ensure that the path remains safe; otherwise, a new path will be determined.

EXITT incorporates some human behaviour, such as investigating the fire and assisting other occupants, but during the evacuation, restricts it to finding the shortest path and avoiding paths with extremely high smoke concentrations. The output allows the users to see the movement and decisions of the occupants in the evacuation. The program can use smoke data from other programs as input to observe the effects of smoke toxicity on the occupants. However, the program does not include a queuing model. Therefore, it could produce inaccurate results in situations where occupant densities are high. Because of this, EXITT has limited use on commercial and public buildings.

2.3.2.3 EXIT89 [Fahy (1994)]

EXIT89 is an evacuation program designed to handle the evacuation of large populations in high-rise buildings. The program can handle up to 89 nodes per floor and up to 700 occupants. It uses the same basis as EXITT, but does not include a lot of behavioural aspects in its modelling because it is too demanding to handle that amount of detail, especially in large population scenarios. Pre-movement activities and delays can be incorporated manually by setting a delay at each location in the building. Other activities during the evacuation are not considered significant in larger and more impersonal buildings.

EXIT89 requires a network description of the building, the number of occupants at each location and smoke data if smoke blockages are to be considered. The model allows the occupants to use either the shortest evacuation routes or the more familiar routes out of the building. The walking speed is determined as a function of density as given by Predtechenskii and Milinskii (1978), which uses the projected body areas of occupants as one of their variables.

Evaluations by Persson (1996) have revealed some deficiencies in EXIT89. Persson realised that the method used by EXIT89 to evaluate occupant movement speed would produce evacuation times that were independent of door widths. This assumption can be accepted at low occupant densities. However, at higher occupant densities, the assumption becomes unreasonable as it implies that the evacuation times would be the same for door widths of 1 metre and 5 metres. EXIT89 also has a problem of moving occupants as crowds. This has the effect of preventing all the occupants from passing a node that has become blocked even though some of the occupants may have managed to pass before the blockage occurred.

2.3.2.4 BuildingEXODUS [Gwynne et al. (1999)]

EXODUS is a suite of software tools designed to simulate the evacuation of large numbers of people. It was initially developed for the evacuation of aircraft, but has been modified to allow for the simulation of building evacuations. BuildingEXODUS is made up of five core interactive sub-models, which are Occupant, Movement, Behaviour, Toxicity and Hazard. The model uses the fine network approach, where the building is divided into nodes of equal size. In this case, each node has an area sufficiently large enough for one occupant.

BuildingEXODUS is a behavioural model, with the Behaviour sub-model determining the occupants' response to each situation. The Behavioural model can be defined as Global or Local. The Global behaviour usually involves employing an escape strategy, whereas the Local behaviour might be the choosing of a specific exit for the occupants. If the two behaviours are conflicting, the Local behaviour will always override the Global behaviour.

BuildingEXODUS takes into account factors such as familiarity of the building and conflicts in congested spaces. The occupants are treated as individuals, not crowds, and toxicity data from other programs can be used to observe the toxicity effects on the occupants.

2.3.2.5 Simulex [Thompson et al. (1996)]

SIMULEX is an evacuation program capable of simulating the evacuation of large populations through geometrically complex buildings. The program uses plan layout in DXF format directly from CAD programs as the input for the building. Occupants can be placed graphically on the 2D floor plans.

SIMULEX models the physical presence of each person by using three circles to represent a person. The larger circle in the middle represents the torso, whereas the two smaller circles represent the shoulders. The program models different types of movement such as normal unimpeded walking speed, reduction of walking speed due to the proximity of other occupants, overtaking, sidestepping and body twisting. The occupants assess their evacuation routes using distance maps, which provide the distance to all the exits from any point in the building. The occupants would travel the shortest distance to the exit.

Other human behaviour is not incorporated in the model. SIMULEX is a more sophisticated ball-bearing model that uses the fine network approach. Because of the complexity in the movements being simulated, it takes a significant amount of time to produce results.

The output of the program is not only a text-based document, but also a visual display of the evacuation. The user can view the movement of each individual at any point in the building and at any time during the evacuation. Therefore, the user is able to view the people overtaking, sidestepping, shuffling and queuing during the evacuation. The user can easily observe bottlenecks that may occur in their building system.

3.0 Background to EvacuatioNZ

3.1 General

EvacuatioNZ is an evacuation model that is currently under development at the University of Canterbury. It incorporates the Monte Carlo approach in producing probability distributions of evacuation times. It uses the coarse network approach, which eases the representation of the building space, and represents the occupants in an individual perspective. The later version of the program will also incorporate the latest research findings in human behaviour. The current version, and the one under consideration in this report, is Version 1.0e.

The program is written in C++ language using Microsoft Visual C++ (Version 6.0). This development environment was chosen for several reasons. As desktop PCs become more powerful, there is a trend towards using them as the target platform for modelling programs. Even complex CFD models such as the Fire Dynamics Simulator (FDS) model [McGrattan & Forney (2000)] developed at NIST will execute adequately on a current PC system.

EvacuatioNZ improves on other evacuation models as it does not have a limit on the number of occupants and nodes it can simulate. Users can model as many occupants in as many nodes, and are only limited by the processing capacity of their computer. This is very useful as buildings become larger, higher and more complex.

There is also a desire to make the model as 'future-proof' or as 'durable' as possible. C++ is a current industry standard language and is widely used. Another advantage is that the Microsoft development environment can be used to write and cross-link codes in other languages such as FORTRAN or J++.

C++ is an object-oriented programming language. Its concept of inheritance eases the modification of its components. Therefore, EvacuatioNZ is unlike the older models, where model components are intimately linked to the remainder of the model making the use or modification of the behaviour aspects extremely difficult.

3.2 Input and Output files

3.2.1 Input files

EvacuatioNZ requires the user to input data concerning the building space, occupant behaviour, and scenarios into several input files. There are currently 7 input files. They are called: MAP, PERSON TYPE, EXIT BEHAVIOUR, POPULATE, SIMULATION, SCENARIO, and POSTPROCESS. The input files are categorised into two types: those that describe the physical aspects of the scenario and those that describe the behavioural aspects. In addition to that, there are several input files, which detail the operation of the program. All input files require the user to have some basic knowledge of Extensible Mark-up Language (XML) [Light (1997)].

Physical Aspects

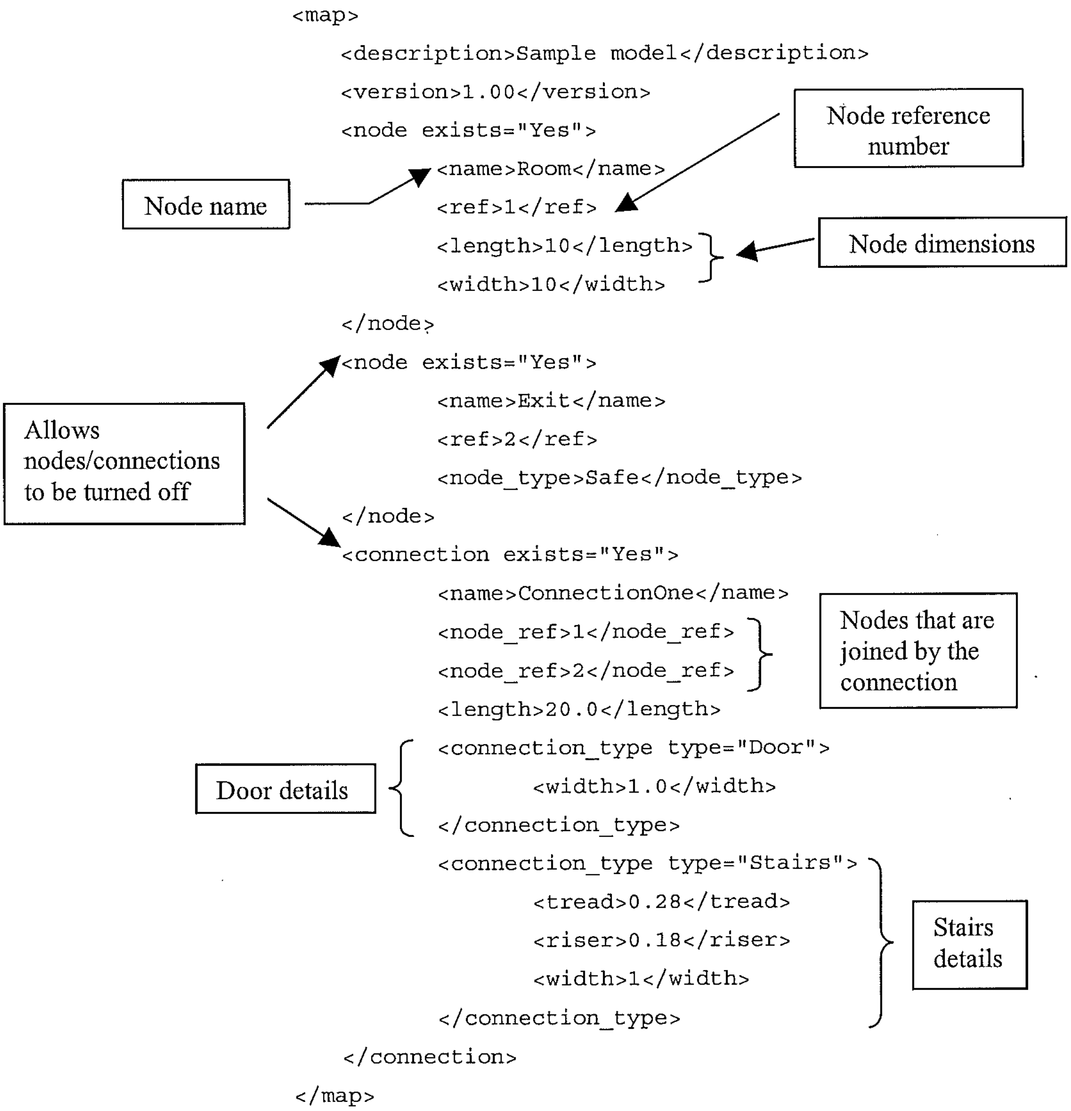
Several input files are used to specify physical aspects of the scenario. They are the:

- MAP file
- POPULATE file
- SIMULATION file
- SCENARIO file

(a) MAP file

The MAP file is essential for the operation of the model. Defined areas of a building, such as rooms or corridors, are represented as nodes. The user would need to specify each node with a name, its dimensions and a reference number. The nodes are connected through paths, also known as connections. Each path that connects the rooms is represented as the distance required to travel between the nodes and the configuration of that path. A path may include a door that constricts the flow; the path might be level, on a slope or could be stairs.

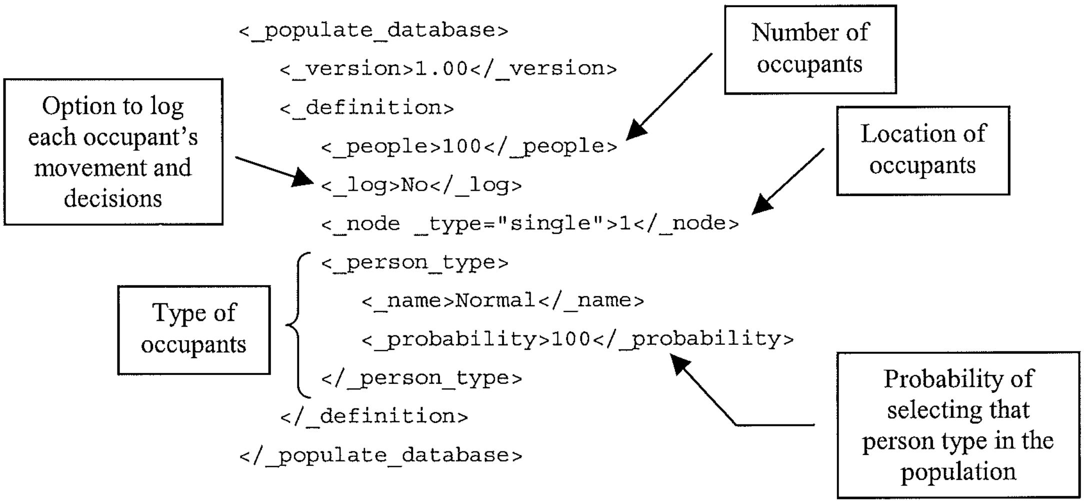
There is flexibility in creating the MAP file. Several paths may lead away or towards a node and more than one path can be used to connect the same two nodes. The paths are given certain characteristics such as their type, length and the nodes to which they connect. A sample of the MAP file is provided below:



```
<map>
   <description>Sample model</description>
   <version>1.00</version>
   <node exists="Yes">
          <name>Room</name>
          <ref>1</ref>
          <length>10</length>
          <width>10</width>
   </node>
   <node exists="Yes">
          <name>Exit</name>
          <ref>2</ref>
          <node_type>Safe</node_type>
   </node>
   <connection exists="Yes">
          <name>ConnectionOne</name>
          <node_ref>1</node_ref>
          <node_ref>2</node_ref>
          <length>20.0</length>
          <connection_type type="Door">
                 <width>1.0</width>
          </connection_type>
          <connection_type type="Stairs">
                 <tread>0.28</tread>
                 <riser>0.18</riser>
                 <width>1</width>
          </connection_type>
   </connection>
</map>
```

(b) POPULATE file

To execute an evacuation model, the POPULATE file must be specified. The POPULATE file allows the user to specify the number and type of occupants in each node. The type of occupant used in this file will be defined in the PERSON TYPE file. The user can also specify more than one person type for the population. In this case, the user can set a probability for each person type, which determines the probability of it being selected. The POPULATE file also allows the logging of each individual's movements and decision-making processes. A sample of the POPULATE file is shown below:



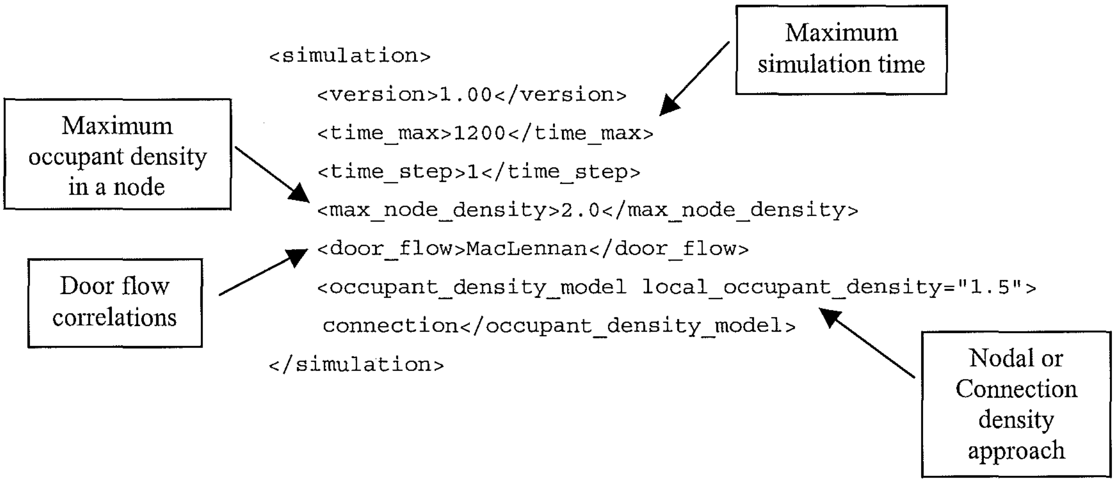
```
<_populate_database>
   <_version>1.00</_version>
   <_definition>
      <_people>100</_people>
      <_log>No</_log>
      <_node _type="single">1</_node>
      <_person_type>
         <_name>Normal</_name>
         <_probability>100</_probability>
      </_person_type>
   </_definition>
</_populate_database>
```

(c) SIMULATION file

The SIMULATION file allows the user to specify some of the parameters for the simulations, such as the maximum time for each simulation and the time step in which the program does the iterations. The maximum occupant density can also be specified by the user, and is used to determine the maximum number of occupants that are able to enter a node.

In the simulation file, there is also the option of selecting one of two door queuing correlations; the MacLennan door queuing correlation and the Holmberg door queuing correlation. The difference between the two correlations will be discussed later in Section 5.

In addition to that, there is also another option of using either the nodal density approach or the connection density approach. These different approaches will be discussed in the next section. Below is a sample of the SIMULATION file:



```
<simulation>
    <version>1.00</version>
    <time_max>1200</time_max>
    <time_step>1</time_step>
    <max_node_density>2.0</max_node_density>
    <door_flow>MacLennan</door_flow>
    <occupant_density_model local_occupant_density="1.5">
     connection</occupant_density_model>
</simulation>
```

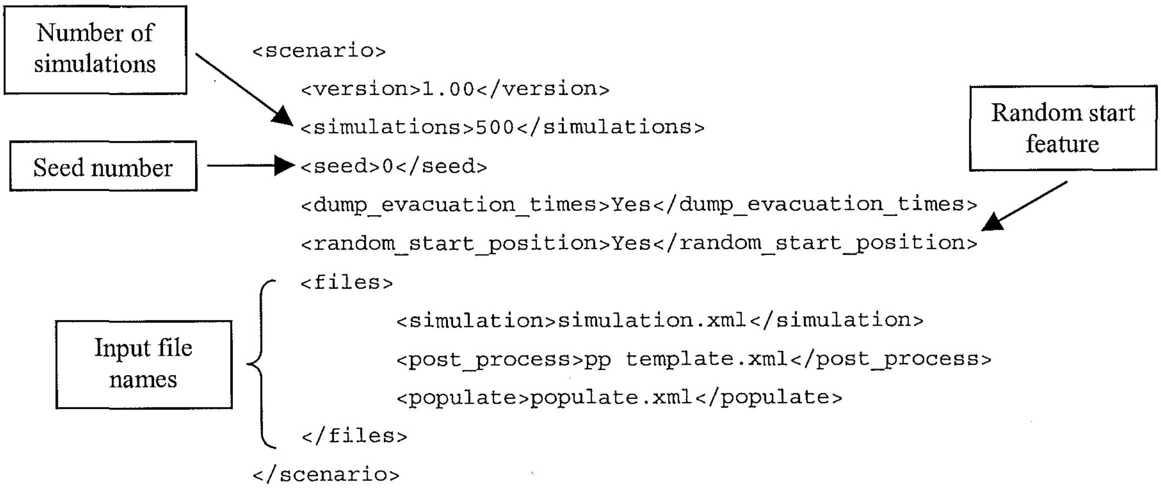
(d) SCENARIO file

The SCENARIO file allows the user to set the number of simulations for each scenario and use a seed number. To understand the function of the seed number, it is necessary to understand its mechanics.

A computer program can usually produce pseudo-random numbers using a table of random numbers built into the program. A seed defines the location of the starting position in the table. When the same seed number is used, the program will read the same random numbers from the table. Therefore, a seed allows the reproduction of simulation results for runs using the same seed number. The only exception is seed number zero, where the starting position in the table is determined from the date and time of the simulation, and is therefore very difficult to reproduce.

The user can also specify whether the occupants should be randomly distributed throughout the node. This feature is called the random start feature, and can be specified in the SCENARIO file. Further information about the random start feature will be provided in the Section 4.3.

In the SCENARIO file, the user can also specify so that the evacuation times from all the simulations are collected into an output file. A sample of the SCENARIO file is seen below:



```
<scenario>
    <version>1.00</version>
    <simulations>500</simulations>
    <seed>0</seed>
    <dump_evacuation_times>Yes</dump_evacuation_times>
    <random_start_position>Yes</random_start_position>
    <files>
          <simulation>simulation.xml</simulation>
          <post_process>pp template.xml</post_process>
          <populate>populate.xml</populate>
    </files>
</scenario>
```

Behavioural Aspects

The input files that are used to determine the behavioural aspects are those that specify the state variables, types of people (the PERSON TYPE file), exit behaviours (the EXIT BEHAVIOUR file) and event behaviours. If these files are omitted, the model can be executed as a ball-bearing model.

There are only two input files on behavioural aspects in the current version of EvacuatioNZ. They are the PERSON TYPE file and the EXIT BEHAVIOUR file. These files are described below:

(a) PERSON TYPE file

The PERSON TYPE file determines the maximum potential speed and exit behaviour of the occupants. The maximum potential speed is the maximum limit to the Nelson and MacLennan equations, and is specified by the user. If left unspecified, the occupant speeds will be calculated using Nelson and MacLennan's equations. The exit behaviour specified here will be defined in the EXIT BEHAVIOUR file. A sample of the PERSON TYPE file is shown below:

```
<_person_type_database>
   <_version>1.00</_version>
   <Normal _person_type="">
      <_speed>1.20</_speed>
      <_exit_behaviour>Default</_exit_behaviour>
   </Normal>
</_person_type_database>
```

Description of
person type
"Normal"

Maximum potential speed
(if not specified, it will revert
to Nelson and MacLennan's
movement speed equations)

"Default" exit behaviour,
will be specified in the
EXIT BEHAVIOUR file

(b) EXIT BEHAVIOUR file

The EXIT BEHAVIOUR file allows the user to specify the type and probability of exit behaviours that are exhibited by the occupants in their scenarios. Exit behaviour deals with the choice of exit paths that the occupants would use during the evacuation. The user can specify several exit behaviours, each with their own probability of occurring. There are several types of exit behaviours currently incorporated into the model. These are:

- First route

This exit behaviour allows the occupants to use the first exit path that is available to them. In a scenario where there are multiple exit paths, the occupant will choose the first exit path that they 'see'. The order of paths that the occupants will see is determined by the order of connections listed in the MAP file for that particular node. This type of behaviour is common for occupants who are not familiar with the building. However, because of the method in which the order of paths is specified, care must be taken when entering the connection details in the MAP file.

- Shortest route

The shortest route is defined as the path with the shortest path length to the next node. This exit behaviour implies that the occupants would choose the shortest path to the neighbouring node. This is a more local behaviour and should not be mistaken with the nearest safe node behaviour, which suggests that the occupants know the shortest route out of the building.

- Preferred route

Studies have shown that even during emergency evacuations, most people prefer to use familiar exits in comparison to the less-used fire exits. This is usually true in buildings where trial evacuations are seldom carried out. To account for this, the preferred route behaviour causes the occupants to choose the paths that they prefer to use. This could be a path that is familiar to them, or the path that they had used to enter the building. While this behaviour has not been fully incorporated into the model, it is intended that in the next version of the program, the user will be able to specify the familiar paths in the MAP file.

- Nearest safe route

The nearest safe route is the path that leads to the nearest safe node. This behaviour is usually observed in occupants who are very familiar with the building and know all the paths that are available to them. This behaviour is currently set as the default behaviour for validation purposes, as most calculation examples use this assumption.

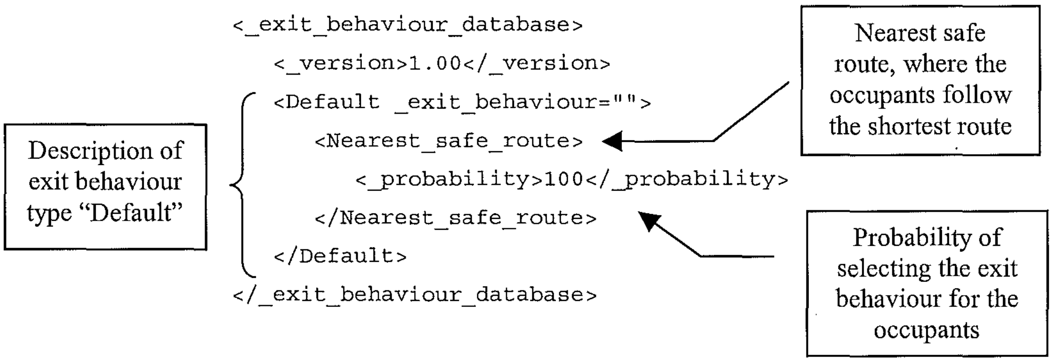
- Random route

This behaviour implies that the occupants randomly chooses a path from all the paths that are available to them.

- None

When the 'None' behaviour is chosen, the occupant does not choose any of the available paths. This means that they remain in their current node.

A sample of the EXIT BEHAVIOUR file is provided below:



```
<_exit_behaviour_database>
   <_version>1.00</_version>
   <Default _exit_behaviour="">
      <Nearest_safe_route>
         <_probability>100</_probability>
      </Nearest_safe_route>
   </Default>
</_exit_behaviour_database>
```

Other Files

The POSTPROCESS file is the file that specifies the properties and data of the output files. There are 3 typical output files, which are the COMPLETION, CONNECTION UTILISATION and NODE OCCUPATION files. These files will be explained in greater detail in the next sub-section. Below is a sample of a POSTPROCESS file.

```
<_EvacuatioNZ_PostprocessorTemplate>
   <_completion>
      <_file>completion.csv</_file>
      <_evacuation_time/>
   </_completion>
   <_connection_utilisation>
      <_file>connection utilisation.csv</_file>
      <_time>
         <_minimum>0</_minimum>
         <_maximum>12000</_maximum>
      </_time>
      <_node>
         <_ref>1</_ref>
      </_node>
      <_node>
         <_ref>2</_ref>
      </_node>
   </_connection_utilisation>
   <_node_occupant>
      <_file>node occupation.csv</_file>
      <_time>
         <_minimum>0</_minimum>
         <_maximum>12000</_maximum>
      </_time>
      <_node>
         <_ref>1</_ref>
      </_node>
      <_node>
         <_ref>2</_ref>
      </_node>
   </_node_occupant>
</_EvacuatioNZ_PostprocessorTemplate>
```

There is also an OUTPUT file, which gives detailed instructions on how the program will arrange the output data in a comma-delimited document. It is automatically generated by the program, but can be modified by the user. As it is typically a very large document, it will not be shown here.

3.2.2 Output files

The output of each scenario is presented in 3 files, which can be easily imported into Microsoft Excel. These files are called: COMPLETION, NODE OCCUPATION, and CONNECTION UTILISATION.

The COMPLETION file records the total evacuation times of each simulation that was carried out. For example, if 250 simulations were executed, there would be 250 individual evacuation times in this file. This file is useful in obtaining probability distributions of evacuation times.

The NODE OCCUPATION file records the number of occupants in each node at each time step. This is especially useful in identifying potential bottlenecks in the building and determining the nodes that are used more frequently.

The CONNECTION UTILISATION file shows the number of occupants using each connection. From this file, the under-utilisation or unbalanced use of the exit paths can be determined.

There is also an optional output file called the LOG file. This file will only be created if the user has specified for it in the POPULATE file. The LOG file shows a record of the movements and actions of each individual occupant.

3.3 Validation Procedure

The validation of the model will be carried out systematically. According to Gwynne et al (1998), model validation involves a range of activities encompassing component and functional testing, and qualitative and quantitative validations.

Component testing is carried out to verify that each component of the model is working and can produce satisfactory results. Functional testing checks that the model can produce relevant results to reach the objectives of the modelling.

Quantitative validation involves the comparison of the predictions produced by the model with values from other reliable sources, such as data from real evacuation trials. Results from other evacuation programs or calculation methods can also be used to validate the 'ball-bearing' component of the EvacuatioNZ program. Qualitative validation also needs to be carried out to compare the nature of predicted human behaviour with the educated expectations of human behaviour in that situation. This validation can be quite subjective but is required to ensure that the program can model realistic human behaviour.

As the evacuation model is still in the early developmental stage, the first and most important process would be to check its individual components to ensure that they are working satisfactorily. When that has been completed successfully, qualitative and quantitative validations should be carried out by comparing the results from the model with actual data or results from other models. During this time, functional testing should be performed and modifications can be made to the program to ensure that the program is producing and presenting relevant results.

4.0 Mechanics of the Model

Before the results from the validation process are discussed, it is vital that the reader understands the basic mechanics of this evacuation model. This section will explain some of the workings of the model and some of the features available in the model.

4.1 Safe Node

A safe node is a node in which the occupants are considered safe from the effects of fire. It is the destination of all the occupants evacuating the building. In a scenario with more than one safe node, the occupants can choose the safe nodes that they will travel to, according to the exit behaviour specified by the user.

The EvacuatioNZ program does not require the user to specify the dimensions of the safe node. Ordinary nodes require dimensions to enable the calculation of the maximum number of occupants in the node, i.e. how many people can fit inside a node. This feature would enable the calculation of delays experienced by occupants who are trying to enter a node, but are unable to due to the node being fully utilised. For the safe node, the model assumes that it is a final exit with a sufficiently large area, or an exit that leads out to the open. Therefore, its dimensions are not required.

4.2 Movement Speeds

In EvacuatioNZ, there are 3 types of movement speeds. The first is the maximum walking speed, also called the maximum potential speed, which is specified by the user. This value is the maximum speed that the occupant can travel, and is only determined from their physical ability. Occupants would be able to travel at their maximum potential speed if they are moving in their normal posture and there are no restrictions to their movement. The restrictions to their movement may include other occupants and building components. Buchanan (1995) reported that the maximum movement speed on a level surface in uncongested conditions is about 73 m/min or 1.22 m/s.

The second is termed as the travel speed in the model. The travel speed is dependent on the occupants' posture. A crawling occupant would be moving at a travel speed, which is significantly less than their maximum speed. Alternatively, a standing occupant could move at their maximum speed. In this case, their travel speed would be equivalent to the maximum speed.

The third type is called the path speed. The path speed takes into account the occupant densities and connection types. When the occupant density exceeds 0.5 ppl/m^2, the occupants will start to encounter restrictions to their movement because of the proximity of other occupants. This will consequently reduce their movement speeds. The path speed will also be influenced by changes in the path width or the presence of a staircase or slope.

4.3 Random Start Feature

The random start feature is a facility to randomise the start positions of the occupants. When this feature is activated, the occupants are randomly spread throughout their starting node. This feature helps to make the model more realistic because in real situations, occupants are distributed within the space, and they do not usually have the same travel distance to the room exit. The result of this is that the occupants arrive at the door at different times. Therefore, by using the random start feature, we allow the occupants closer to the door to leave the room before the majority of the other occupants arrive to queue.

Figure 4.1 shows the effects of using the random start feature in a stair example. When the random start feature is activated, the occupants are randomly distributed in the stair node as shown in Figure 4.1(a). The occupants now have different travel distances to the end of the node. When the random start feature is turned off as shown in Figure 4.1(b), the occupants are all situated at the same distance away from the node exit.

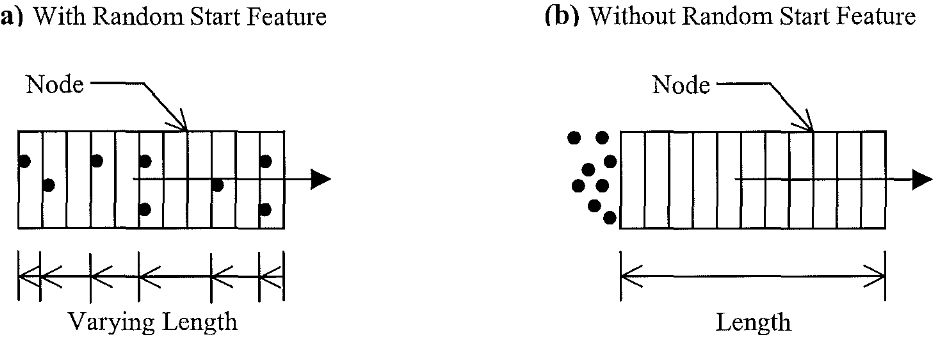


Figure 4.1: The random start feature

For simple buildings with a single exit path, the random start feature will produce a approximately bell-shaped distribution for the evacuation times. If the random start feature is turned off, the evacuation model will only produce a single evacuation time for that scenario. A simple single-exit path building was simulated both with and without the random start feature. The results are shown in Figure 4.2.

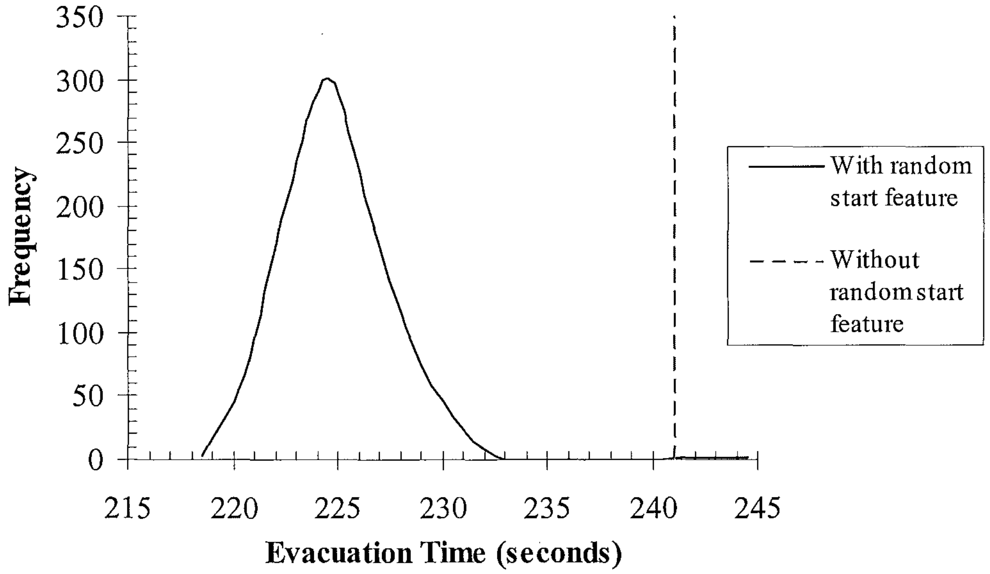


Figure 4.2: Results for a simple single-exit path example

Figure 4.2 reveals that the scenario without using the random start feature produces an evacuation time that is higher than the scenario using the random start feature. The reason for the longer evacuation time is that all the occupants are starting at the same position, and therefore they are travelling at the furthest distance away from the node exit. On the other hand, the random start feature allows some occupants to exit the node earlier, thereby reducing the node occupant density and allowing the rest of the occupants to travel at a faster speed. Thus, it produces lower evacuation times.

The distributions above are only valid for simple single-exit path examples. In complex, multi-exit path buildings, the occupants can choose their evacuation paths, and this creates a variation to the evacuation times based on their choice of exit. Because of this, EvacuatioNZ will produce a distribution for the evacuation times even when the random start feature is turned off. To explain this further, a multi-exit path building was modelled in EvacuatioNZ. The following figure displays the results of the simulation run.

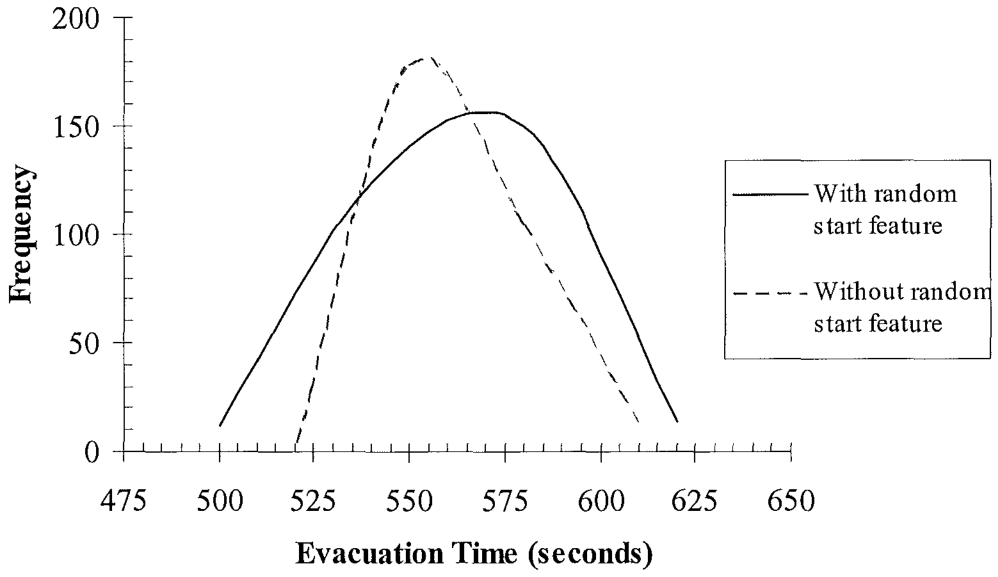


Figure 4.3: Results for a multi-exit path example

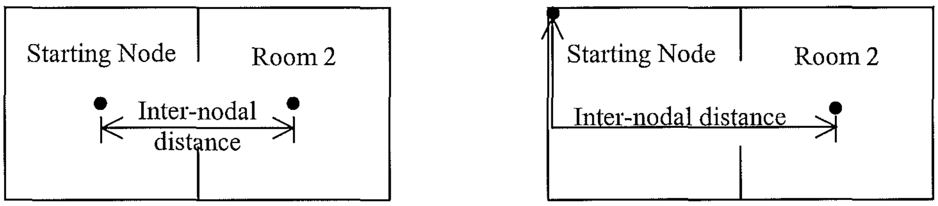
Figure 4.3 shows the results for the simulation of the multi-exit path building. It illustrates that when the random start feature is used, the distribution of the evacuation times is more widely spread. However, even when the random start feature is not used, the program still produces a distribution because of the variation caused by the occupants choosing different evacuation routes in each simulation. The distribution is, not surprisingly, less spread out compared to the scenario using the random start feature, as the random start feature increases the variation of the evacuation times.

4.4 Inter-Nodal Path Distances

Coarse network models have the advantage of requiring fewer details on the building layout and decreasing computational times. However, there are some drawbacks on using coarse network models. When defining the MAP file for the building, there is an uncertainty on how to specify the distance between the nodes. What is the appropriate path length between two nodes that will represent the actual travel distance?

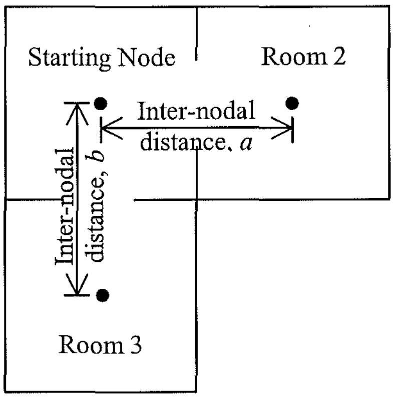
In general, we could represent this length as the distance from the centre of one room to the centre of the other room, as shown in Figure 4.4(a). However, this may not always be the case, particularly when we consider the initial node that an occupant starts in. An occupant could start anywhere in the room and therefore, their travel distance to the exit door could be anything from zero to some maximum distance which is a function of the room dimensions. For small rooms, this would not present a problem but for large spaces, the travel distance to the exit becomes significant.

The problem becomes even more significant if the initial node has more than one escape route. This scenario is shown in Figure 4.4(c). If the occupant were to choose the nearest safe route or the closest route, it would have to depend entirely on their distance to each of the exits. That means that the exit choice would be affected by how we represent the inter-nodal path distances.



(a) Using the distance between the centre of each node

(b) Using the maximum distance for the starting node



(c) Suggested definition of inter-nodal distance for multi-exit scenarios

Figure 4.4: Inter-nodal path distance

The method currently used in the program for specifying the inter-nodal path distance in single-exit scenarios is to measure the distance from the corner of the starting node to the centre of the next node. The distance used should account for possible obstructions that may be present in the room, by summing up vertical and horizontal distances, as shown in Figure 4.4(b). This makes the simulation results a bit more conservative than if compared to using the average distance. However, this definition of the inter-nodal path distance may need to be checked especially in multi-exit scenarios.

4.5 Nodal Density vs Connection Density

EvacuatioNZ calculates the movement speeds and occupant flow rates from Nelson and MacLennan's flow equations. These equations relate the movement speeds and flow rates to the occupant densities. However, while developing the model, it was recognised that there are two ways to define occupant densities. We might call these the nodal occupant density and the path occupant density.

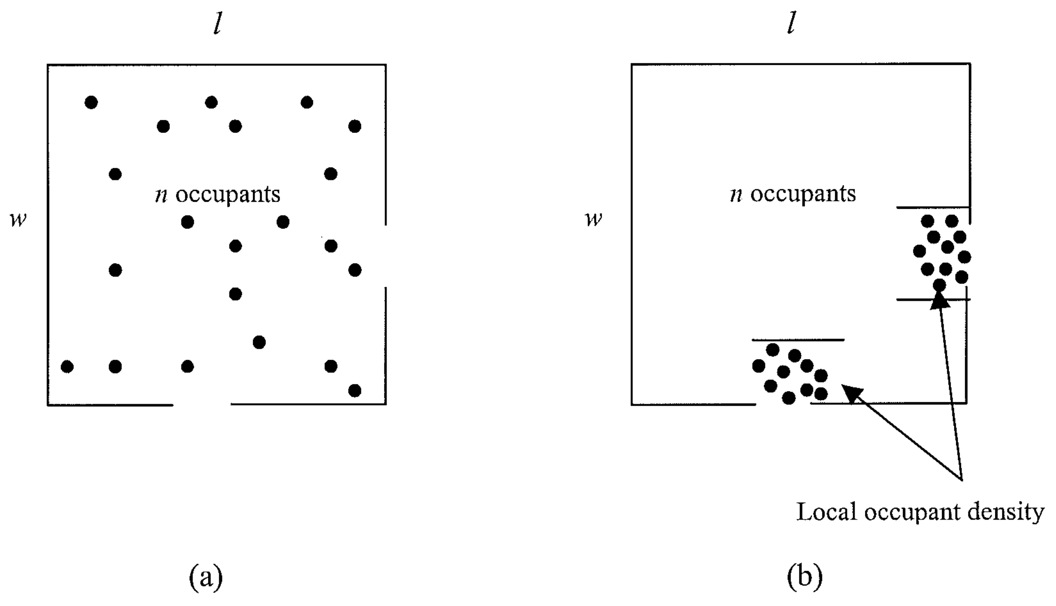


Figure 4.5: Difference between (a) Nodal occupant density approach and (b) Connection occupant density approach

The nodal occupant density is the average occupant density in a node, and can be determined from the number of people in a room and the floor area in the room ($D_o = n / w.l$). Figure 4.5(a) shows the nodal occupant density approach, which is a reasonable approach to use at the start of an evacuation. However, as people proceed towards an exit, the local occupant density around the occupants, also known as the path occupant density, increases even though the nodal occupant density does not change (Figure 4.5(b)). People will crowd around the exit at some characteristic occupant density that is usually higher than the nodal occupant density. Therefore, their movement speed is less than that calculated using the nodal approach.

This characteristic occupant density might vary between groups of people and their current circumstances. Social or racial groups may have different personal space requirements. The crowding density of occupants in an emergency situation may be higher than in a non-emergency situation.

However, there is some difficulty in trying to determine the occupant density from the path of travel. The number of people using the path can be determined, but how can the 'area' of the path be determined? A path does not have an actual area. For example, consider a path between two nodes through a door. Using the path length and width of the door does not provide a meaningful area.

Therefore, two approaches for determining the occupant density were considered for the model developed in this study. The first approach assumes that the nodal occupant density is sufficient for the calculation of the movement speeds. The second approach assumes that the people would crowd around an exit at some characteristic maximum occupant density. Any value can be specified by the user but practically, the occupant density has a maximum value of 3.5 ppl/m^2 as suggested by Nelson and MacLennan (1995). Pauls (1995) has noted that the occupant density of 3.5 ppl/m^2 is rarely achieved and has suggested a maximum value of 2.0 ppl/m^2.

5.0 Component Testing

Component testing is a fundamental approach to validating a model. In this section, some model components will be tested to ensure that they are working and producing representative results.

5.1 Door Queuing

An attempt is made to verify that the door queuing component in the model is working. This is done by comparing different correlations of flow rates through doors, and comparing the results of hand calculations with the output from EvacuatioNZ .

Holmberg (1997) carried out experiments to study flow rates through different building components, including doors. From his experimental work, he was able to derive a relationship that gives the maximum flow rate through a door of specified width. The relationship is given as:

$$F_a = 2.6W - 0.59 \qquad (1)$$

Nelson & MacLennan's correlation relates the flow rates to both the door width and the occupant density. By manipulating their equations, relationships similar to Holmberg's can be obtained for different occupant densities and door widths. Nelson & MacLennan stated that the actual flow through a door is:

$$F_a = F_s \cdot W_e \qquad (2)$$

The effective width is the useful width of the building component, where active movement occurs. It is calculated by subtracting the boundary layer from the actual width of the building component. The boundary layer is a clearance space essential for lateral body sway and balance. Nelson and MacLennan (1995) have given values for the boundary layer of different building components in their paper. From there, the equation for effective width is written as:

$$W_e = W - B \tag{3}$$

Specific flow rate is the flow rate per unit width of the building component and is given as the function of movement speed and occupant density, as shown below:

$$F_s = S \cdot D_o \tag{4}$$

Thus from combining Equations (2), (3) and (4), we get:

$$F_a = S \cdot D_o (W - B) \tag{5}$$

The movement speed is a function of the occupant densities and the properties of the building component, and is given by:

$$S = k_t (1 - 0.266\ D_o) \tag{6}$$

Thus from substituting Equation (5) into (6), we obtain:

$$F_a = k_t (1 - 0.266\ D_o) \cdot D_o (W - B) \tag{7}$$

For doors, k_t is given as 84 and the boundary layer width, B, is taken to be 0.15 m for each side of a door. Equation (7) can now be used to obtain the actual flow rates through doors of actual width W and occupant density D_o.

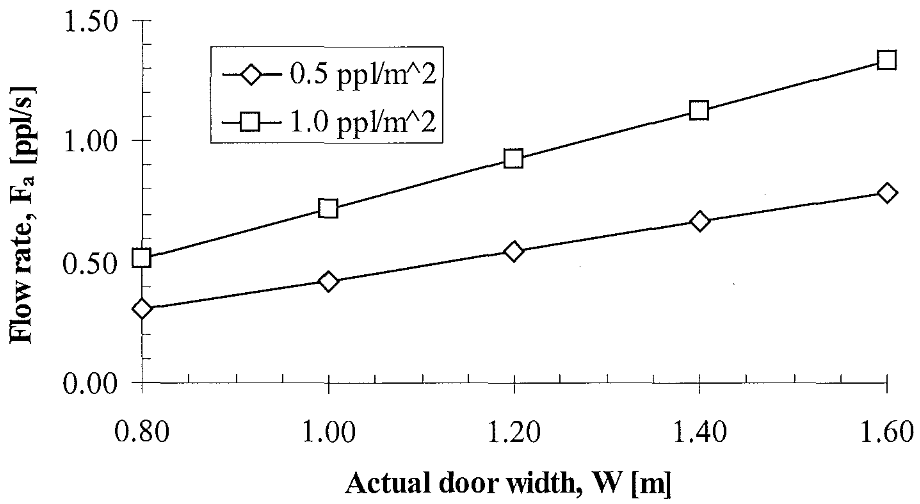


Figure 5.1: Door flow rate for specified door widths and occupant densities using Nelson & MacLennan's door flow correlations.

Figure 5.1 shows two such lines showing different flow rates for door widths between 0.8 and 1.6 m with occupant densities of 0.5 and 1.0 ppl/m^2. The lines are linear; therefore, for each value of density, the actual flow rate is linearly related to the actual door width. In other words:

$$F_a = m \cdot W + c \tag{8}$$

By plotting the gradient and intercepts of each of these lines (Figure 5.2), a pair of relationships can be obtained such that

$$m = -0.37D_o^2 + 1.40D_o, \tag{9}$$

$$c = \quad 0.11D_o^2 - 0.42D_o. \tag{10}$$

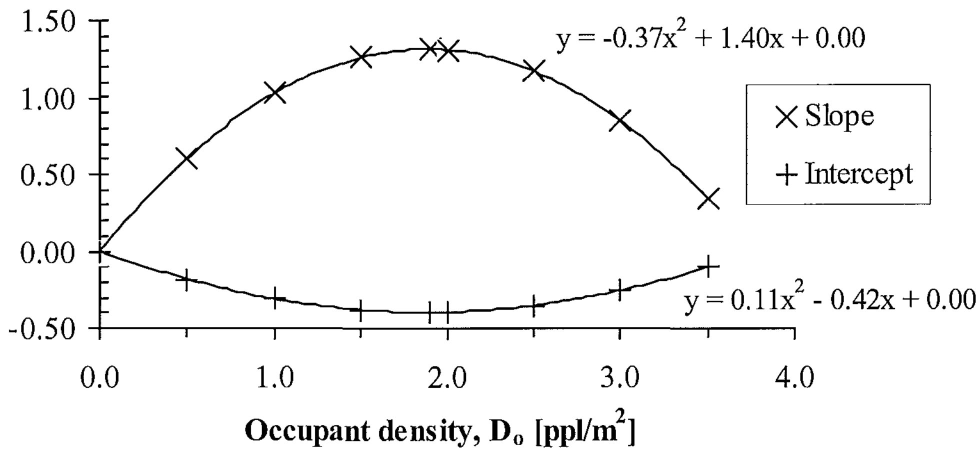


Figure 5.2: Gradient and intercept relationships for Nelson & MacLennan's door flow equations.

From Equation (9), we can find the occupant density at which we get the maximum flow through the door, by finding the density when the slope of the line is zero.

$$\frac{dm}{dD_o} = -0.37x2D_o + 1.40 = 0 \tag{11}$$

From Equation (11), the maximum flow occurs when D_o is 1.9 ppl/m². At this density value, m_{max} and c_{max} are found to be 1.32 and –0.40 respectively. Hence

$$F_{a,\max} = 1.32W - 0.40 \tag{12}$$

Figure 5.3 compares the Nelson & MacLennan and Holmberg equations for the maximum door flow and it is clear that Holmberg's correlation gives a significantly higher flow rate for a specified door width. This could be due to details of the experiments carried out by Holmberg. Holmberg's experimental subjects were all between the ages of 20 and 30 years, and were all fit, young and healthy adults. Moreover, all the test subjects were engineering students, and therefore, it was probable that they were all acquainted and would not mind packing and manoeuvring closer to each other. Therefore, it would be expected that they would flow faster through the door.

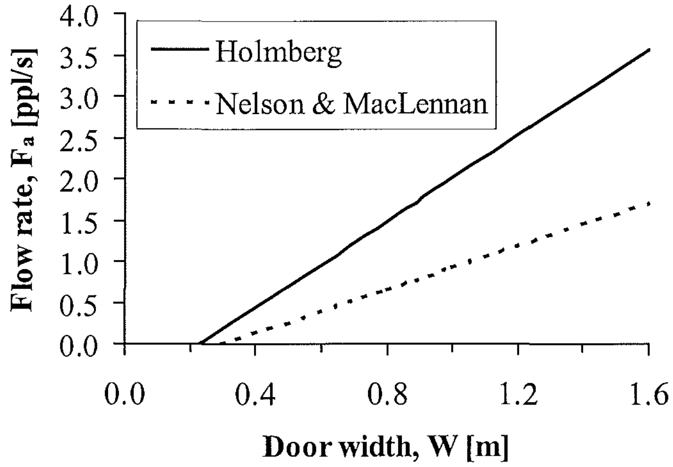


Figure 5.3: Maximum door flow rates from Nelson & MacLennan and Holmberg.

Door queuing is simulated in EvacuatioNZ's coarse network model by calculating the time required to pass through a door and adding an equivalent travel length to the person's movement distance to account for this delay. This equivalent distance is obtained from the current movement speed of the person, which is in turn obtained from the characteristics of the person and the current occupant density in the node that the person is in. The idea is that an occupant moving at his or her original velocity through this equivalent distance would take a similar amount of time as an occupant delayed by the queue to get through the door. The time delay for passing through a door is obtained from the correlations developed by either Holmberg or Nelson & MacLennan (see above).

The door queuing and flow rate algorithm used in EvacuatioNZ was verified by considering a simple two-node map with a door linking the two nodes, as shown in Figure 5.4 and Figure 5.5. The door width was varied and the flow rate for the evacuation of 1000 people was calculated. Two scenarios were considered for the verification process. The first scenario is where the starting node contains the maximum occupant density allowed, and the second scenario is where the occupant density is sufficiently low as to allow the people to move at their maximum potential speed. The essential input files are included in Appendix A.

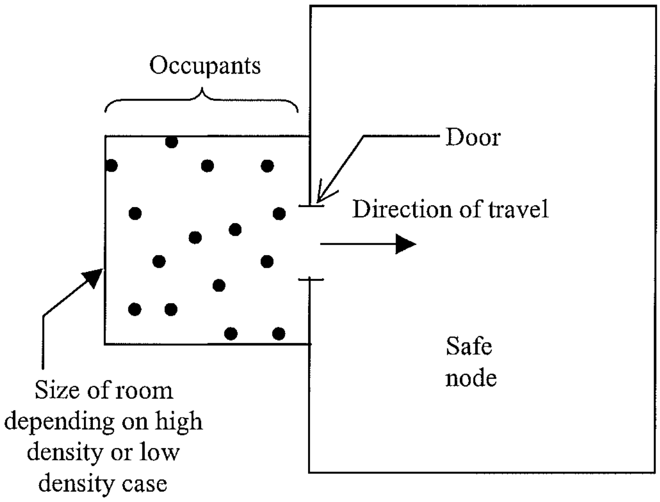


Figure 5.4: Layout of the building for the testing of the door queuing component

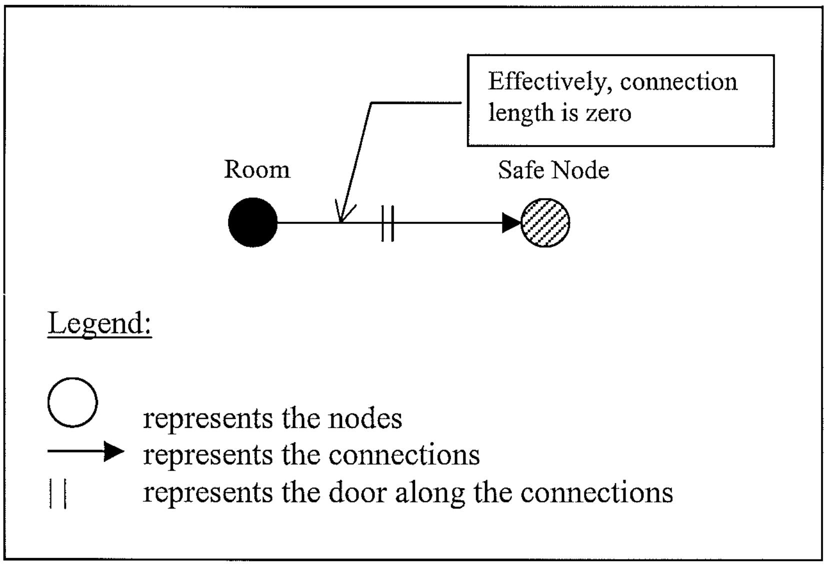


Figure 5.5: Nodal representation of the building in the door queuing example

For the verification procedure, it was assumed that the maximum occupant density was 2 persons/m^2 [Pauls (1995)] and the maximum potential travel speed was 1.2 m/s when the occupant density was below 0.5 persons/m^2. To set the occupant density in the starting node, the area of the starting node was modified for the two scenarios. For

1000 occupants in a node at a density of 2.0 persons/m^2, the node area needs to be set to 500 m^2, which is equivalent to a square room with dimensions of 22.36 m. When the occupant density is 0.5 persons/m^2, the required node area is 2000 m^2, which gives a room dimension of 44.72 m.

The random start feature was used in the analysis because the variation in travel time caused by the random start feature is not considered significant in comparison to the queuing time, especially for situations with large numbers of people. The advantage of having the random start feature is that a more realistic scenario is modelled.

As discussed previously, there are two methods in which we might model the occupant density in a scenario; the "nodal density" approach and the "connection density" approach. EvacuatioNZ was programmed to allow either method to be used and a comparison was made for a simple door flow scenario. For the "connection density" approach, it was initially assumed that the local queuing density around doors was 2.0 ppl/m^2.

The two door queuing models were investigated in detail for a door of width of 1.0 m. The expected evacuation time for the two occupant density scenarios was calculated using the Nelson & MacLennan equations.

For the first scenario with an occupant density of 2.0 ppl/m^2, the actual flow rate through the door from Equation (7) is 55 ppl/min. Thus, the expected evacuation time for 1000 people is 18.17 minutes (1090 seconds). Similarly, for the second scenario with an occupant density of 0.5 ppl/m^2, the actual flow rate is 25.5 ppl/min, which gives an expected evacuation time of 39.22 minutes (2350 seconds) for 1000 people. The calculations using the Nelson and MacLennan flow equations can be found in Appendix A.

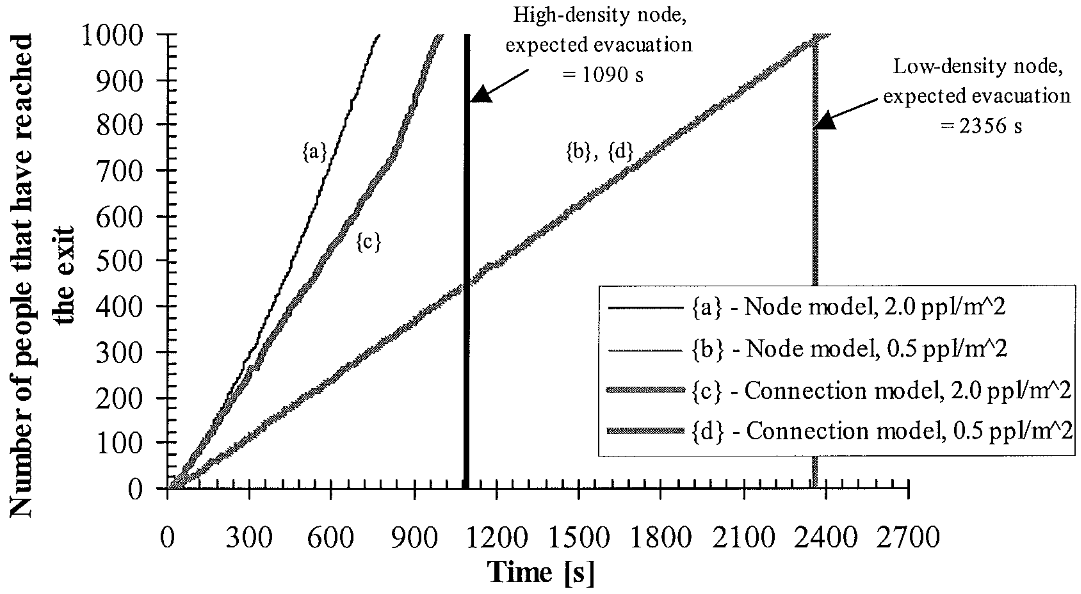


Figure 5.6: Comparison of expected evacuation times using Nelson & MacLennan's equations with EvacuatioNZ simulated times for a 1.0 m wide door.

Figure 5.6 shows the typical results from the EvacuatioNZ simulations compared with the expected evacuation times from the hand calculation. Because of the way in which people are in effect randomly distributed in their starting node, each individual simulation of a scenario yields slightly different results. The variation in the final evacuation time in this particular analysis is about ±15 seconds. Both the node and connection models give almost equivalent evacuation times for the low node density scenario. However, for the high occupancy scenario, the connection model gives a result closer to the expected evacuation time.

The "dog-leg" shown by the high node density connection simulation appears to occur when the occupant density decreases to a value of 0.5 ppl/m^2. At this occupant density, the method by which the movement speed is calculated changes to one that is only a function of the person's physical ability and posture. As it is assumed that the occupants are in the standing position, their travel speed would be similar to their maximum potential speed.

Depending on what value is chosen for the maximum potential speed, the final evacuation time for the simulation will be greater or less than the calculated value shown in Figure 5.6. For example, reducing the maximum potential movement speed from 1.2 m/s to 1.0 m/s increases the evacuation time from 997 seconds to 1029 seconds, i.e. an increase of approximately 30 seconds (~3.2%).

The above analysis was repeated for door widths of 0.8, 1.4 and 1.6 metres using a maximum potential speed of 1.2 m/s and a local door queuing occupant density of 2.0 ppl/m^2.

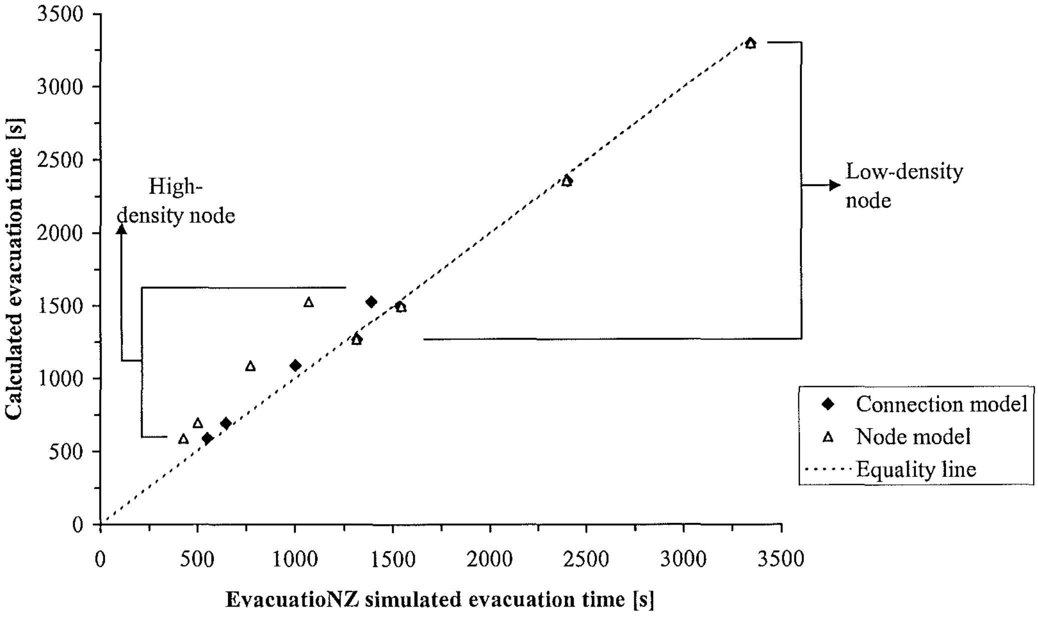
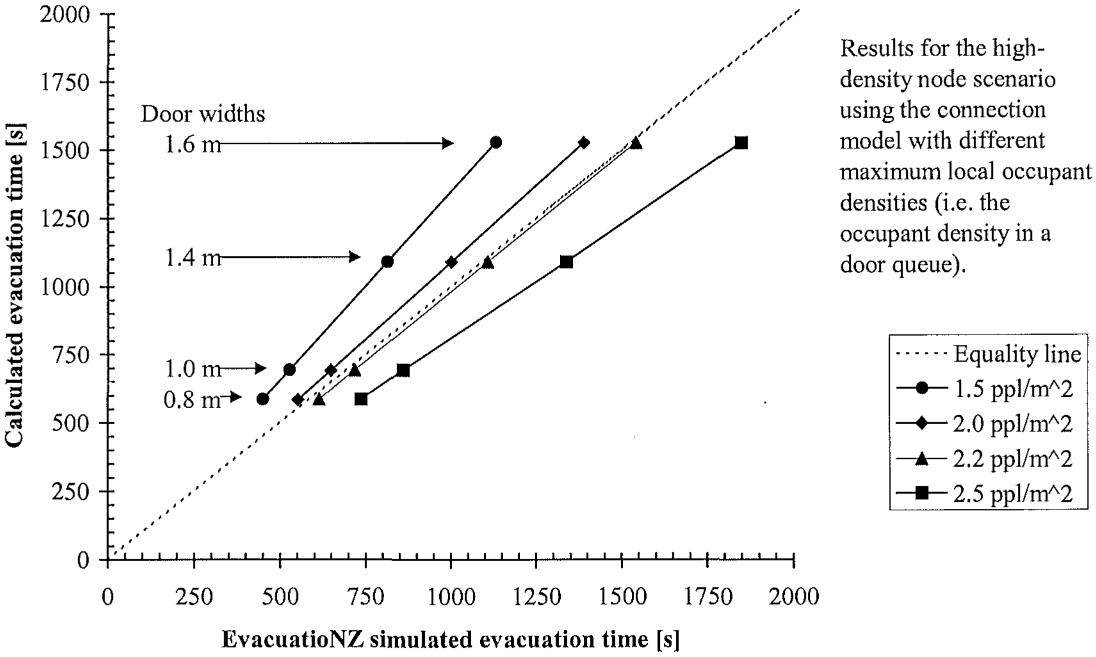


Figure 5.7: Comparison of "nodal density" and "connection density" models.

Figure 5.7 compares the expected evacuation times from hand calculations and the simulated evacuation times obtained from EvacuatioNZ. It can be seen that for the low-density node scenario, the connection and node models give the same results. However, for the high-density node scenario, the connection model gives evacuation times closer to the expected values.

From the results of the analysis, it would seem that for door flows, the connection model produces results that are more representative of the results obtained from Nelson and MacLennan's flow equations.

The next step was to find out what connection density values were producing reasonable results. The value of connection density used in the above analysis was 2.0 ppl/m^2, but that value was just an initial approximation of the density that the occupants might queue in. The above analysis was repeated for different connection densities and the results were compared to the calculated values from Nelson and MacLennan's equations.



Results for the high-density node scenario using the connection model with different maximum local occupant densities (i.e. the occupant density in a door queue).

Figure 5.8: Effects of using different connection densities on the evacuation times

Figure 5.8 shows the effects of using different connection densities at the door. As the connection density is increased, the movement speeds become slower and hence the evacuation times become longer. The connection density of 2.0 ppl/m^2 was initially used. However, from the above figure, it might seem that a connection density of 2.2 ppl/m^2 may be more appropriate.

Therefore, from the analysis of the door queuing model, it is concluded that the connection density approach is more suitable in both high node density and low node density scenarios. The connection density of 2.2 ppl/m^2 was found to produce the most similar results to the Nelson and MacLennan flow correlations for this scenario.

5.2 Movement on Stairs

This section describes the attempt to verify that the occupant movement on stairs in the program is producing reasonable results. This is carried out by comparing the output from EvacuatioNZ simulations with results from hand calculations using Nelson and MacLennan's equations.

The actual flow rate on stairs is obtained from Equation (7) derived in the previous section. For ease of reference, the equation will be shown here:

$$F_a = k_t(1 - 0.266\ D_o) \cdot D_o(W - B) \tag{7}$$

The speed constant, k_t is a function of the stair tread widths and riser heights. The equation used to calculate k_t is given below:

$$k_t = 51.8(G / R)^{0.5} \tag{13}$$

The boundary layer width, B, is taken to be 0.15 m for each side of the staircase. If the staircase had handrails, then the effective width would be the lesser of either 0.09 m of the side of the staircase or the clear width between the edge of the handrails. In this scenario, the staircase was assumed to be without handrails.

The stair movement algorithm used in EvacuatioNZ was verified using a simple two-node example, with the first node as the stairs and the second node as the safe node. The layout and nodal representation of the structure in question is shown in Figure 5.9 and Figure 5.10.

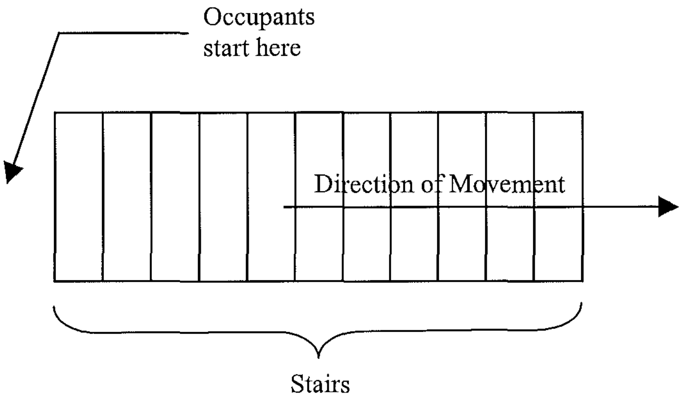


Figure 5.9: Layout of the structure used in the stairs movement test

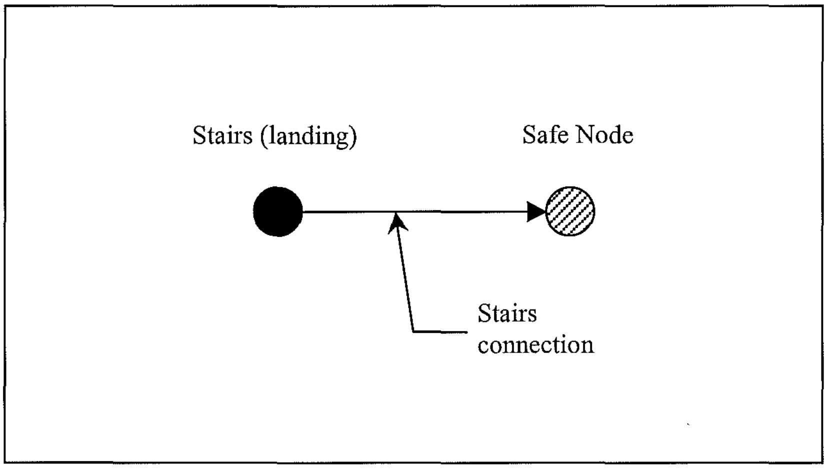


Figure 5.10: Nodal representation of the structure used in the stairs movement test

The stair dimensions were varied and the time required for evacuation was obtained for two different scenarios. The first scenario involved the starting node having the maximum occupant density allowed, and the second scenario involved the starting node having a sufficiently low occupant density as to enable the occupants to travel at their maximum potential speed.

Similar to the assumptions in the Section 5.1, the maximum occupant density was assumed to be 2.0 persons/m^2, as suggested by Pauls (1995), and the maximum potential speed was 1.2 m/s when the occupant density was under 0.5 persons/m^2. To set the occupant density in the starting node, the number of people in the node was changed for each scenario. Thus, for a staircase with a width of 1.0 metre and a length of 100 metres, the number of occupants was set to 200 people for the high node density scenario. For the low node density scenario, the number of occupants was set to 50 people. The essential input files have been included in Appendix B.

In this analysis, the random start feature was disabled to ensure that all the occupants would start travelling from the top of the stairs, as assumed by Nelson and MacLennan in their calculations. However, in the later part of the analysis, the random start feature was used to observe its effects on the evacuation times. The "nodal density" approach and the "connection density" approach were also tested to compare the differences it made to the flow rates.

The expected evacuation time for the two occupant density scenarios was calculated using the Nelson & MacLennan equations, which related the movement speed and flow rates to the occupant densities and stair dimensions. For the first scenario with an occupant density of 2.0 ppl/m^2, the actual flow rate through the door is 61 ppl/min. Thus, the expected evacuation time for 200 people is 198 seconds. Similarly, the second scenario has an actual flow rate of 28 ppl/min, which gives an expected evacuation time of 107 seconds for 50 people. The calculations to obtain these values can be found in Appendix B.

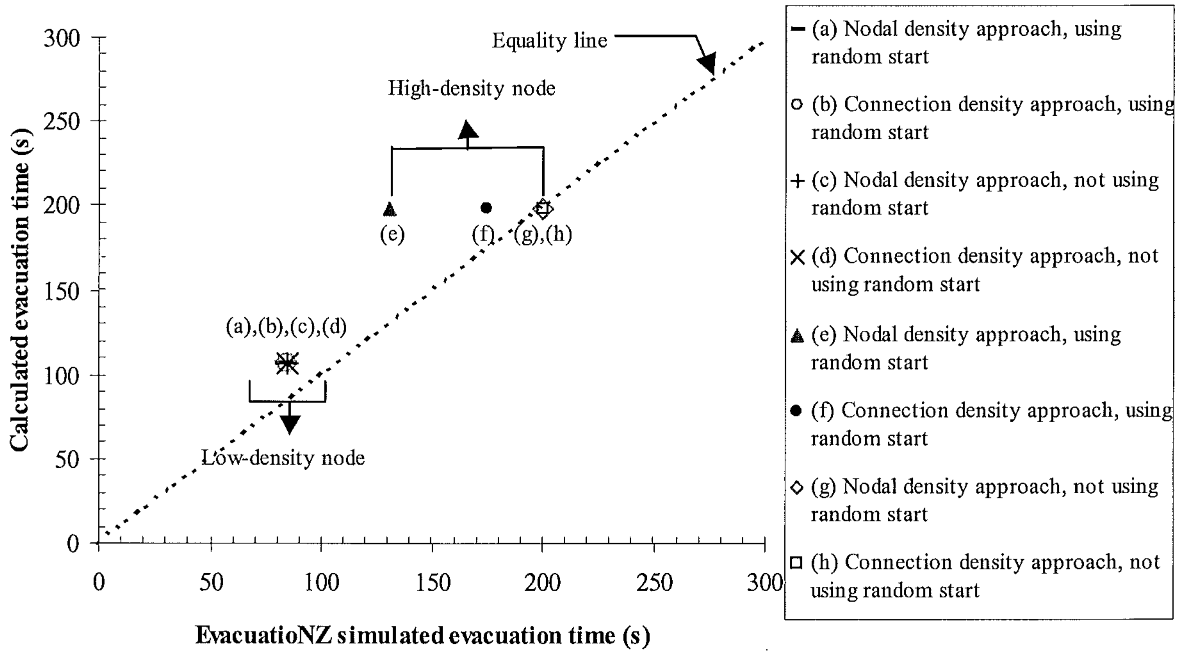


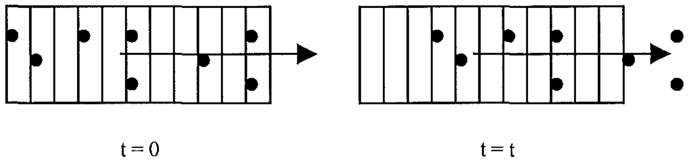
Figure 5.11: Comparison of expected evacuation times using Nelson & MacLennan's equations with EvacuatioNZ simulated times for a staircase.

Figure 5.11 shows the results from the EvacuatioNZ simulations compared with the expected evacuation times calculated from Nelson and MacLennan's flow equations. All the simulations seem to produce results that are comparable to the expected evacuation times.

All the simulations for the low node density scenario produced approximately similar flow rates and evacuation times. This is because when the occupant density is below 0.5 ppl/m^2, the occupants are travelling at their maximum potential speed, which is independent of the occupant density. Therefore, the nodal density approach and the connection density approach both yield the same results. Similarly, the random start feature does not affect the evacuation times as all the occupants are travelling in their maximum potential speed.

For the high node density scenario, the simulations without the random start feature seem to produce results that are closer to the expected values. Simulations with the random start feature assume that the occupants are randomly distributed along the length of the stairs as shown in Figure 5.12(a). Therefore, at the start of the simulation, some occupants have already effectively traversed the length of the stairs and are about to exit the node. However, Nelson and MacLennan's flow equations assume that all the occupants start from the top of the stairs, which is similar to a scenario with its random start feature disabled (Figure 5.12(b)). Therefore, the time required to evacuate is shorter for the simulations using the random start feature.

(a) With Random Start Feature



(b) Without Random Start Feature

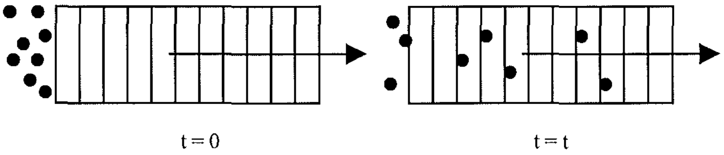


Figure 5.12: The difference of using the random start feature in the stairs example

There are some differences between the results from the nodal density approach and the connection density approach, as shown by the differences in points (e) and (f) of Figure 5.11. The occupant density for the nodal density approach is calculated at every time step. As more people leave the node, the occupant density decreases, thereby increasing the occupants' path speed. The connection density approach fixes the occupant density as a constant, which in this case is 2.0 ppl/m^2. Because of this, the flow rates are not affected by the changes in the node occupant densities. Therefore, the evacuation times are longer for the connection density approach than for the nodal density approach.

From Figure 5.11, it can be concluded that the random start feature should be disabled for the stair movement analysis, even though the situation may be physically unrealistic. Both nodal density and connection density approaches produces results that are representative of the values calculated by Nelson and MacLennan.

The above analysis was repeated for different stair dimensions, and the results were compared to the expected results.

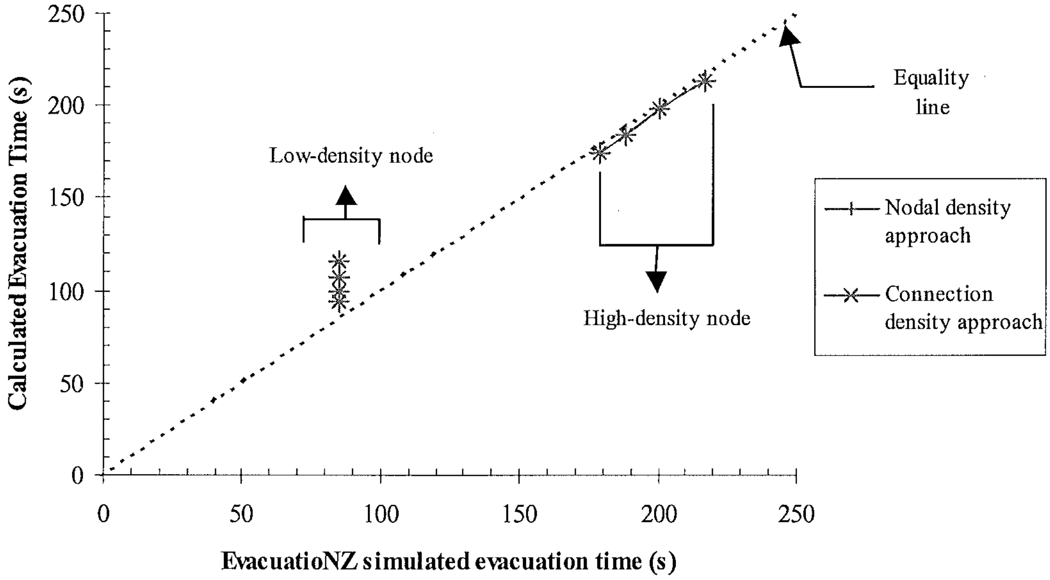


Figure 5.13: Comparison of "nodal density" and "connection density" models.

Figure 5.13 compares the calculated expected evacuation time and the simulated evacuation time using EvacuatioNZ for different stair dimensions. The EvacuatioNZ model is found to produce similar evacuation times for different stair dimensions in the low node density scenario. This is because the model does not account for the decrease in speed on different stairs when the occupant density is below 0.5 ppl/m^2. The program currently sets the occupants' path speed to 1.2 m/s when the density is below 0.5 ppl/m^2, irrespective of whether the occupants are on level ground or on stairs. This feature is not very realistic as we expect the occupants to travel at a slower speed when the stairs are steeper. Therefore, it is suggested that the program be modified to allow for different maximum speeds on different walking surfaces.

From the component testing that was carried out on the door queuing model and the stair movement model, it is found that generally, the results are more representative to the Nelson and MacLennan calculations when the connection density is used for the connection components. Assuming this is so, the results of the simulations would depend on the value of connection density used in the model. The above analysis was carried out using different values of connection density to study its effects on the flow rates and evacuation times of the stairs component.

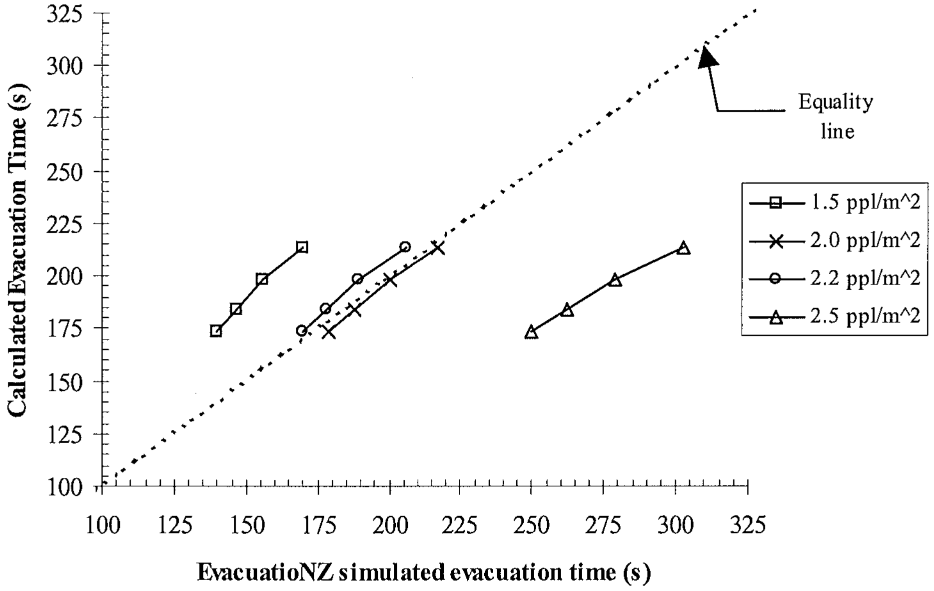


Figure 5.14: Effects of using different connection densities on the evacuation times

Figure 5.14 shows the effects of using different connection densities. As the connection density is increased, the occupants travel at a slower speed, depending on the occupant density. Thus, occupant evacuation times increases. At a connection density of 2.0 ppl/m^2, the simulated evacuation times are the nearest to the calculated evacuation times.

5.3 Conclusions

There are more components that should be tested before this model can be used for design purposes. The behavioural components in the model should also be verified with the latest research findings. However, from the testing of two components that are essential in the modelling of occupant movement, it can be seen that the components are producing reasonable results.

The results are not exactly similar to the values calculated by Nelson and MacLennan, but this is expected of a probabilistic model. There is inevitably some variability introduced by the user when using the random start feature. Moreover, the operation of the program may differ slightly, giving differing results. Therefore, it can be concluded that the tested components are working properly.

This section has only dealt with the testing of individual components. When all the program components have been tested individually, there should also be some testing done on different combinations of components to see whether the model produces reasonable results. In short, the component testing is vital to the validation of the model and is a tedious ongoing process. It should be part of the continuous improvement of the evacuation model.

6.0 Simple Scenario Testing

The program also underwent simple scenario testing as part of the combined component validation. For this purpose, a well-known calculation example was used. It is the simple evacuation example taken from the Fire Engineering Design Guide (FEDG) by Buchanan (1994). It must be noted here that no pre-movement times and delays caused by human behaviour has been accounted for in this analysis.

6.1 The FEDG Evacuation Example Problem

The FEDG evacuation example is a simple ball-bearing calculation example that only consists of one room, a staircase and the exit. It is a single exit path scenario, which means that it only provides the occupants with one escape route out of the building.

The room has dimensions shown in Figure 6.1 and an occupant load of 90 people.

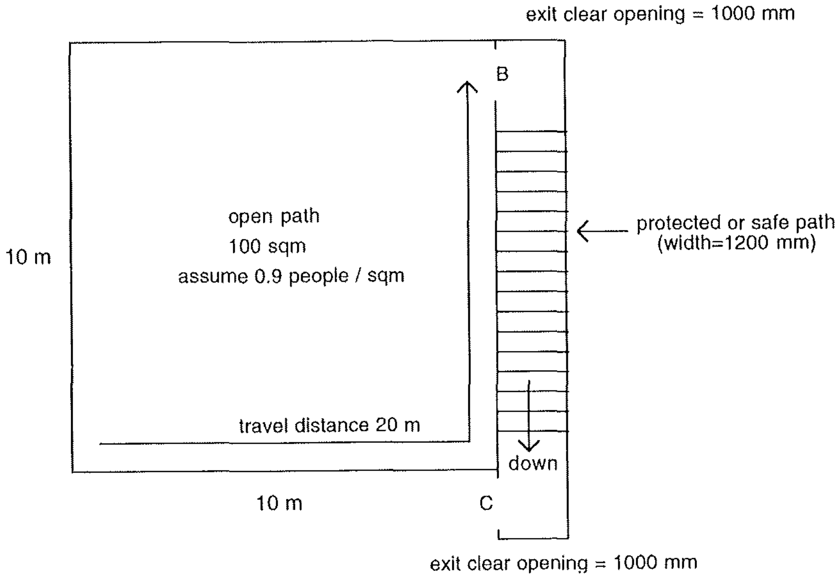


Figure 6.1: Layout of the building in the FEDG evacuation example

The building in question needs to be represented in the form of a network to be entered as input into EvacuatioNZ. Figure 6.2 below shows how it is represented in the model. The input files required to run the simulations are provided in Appendix C.

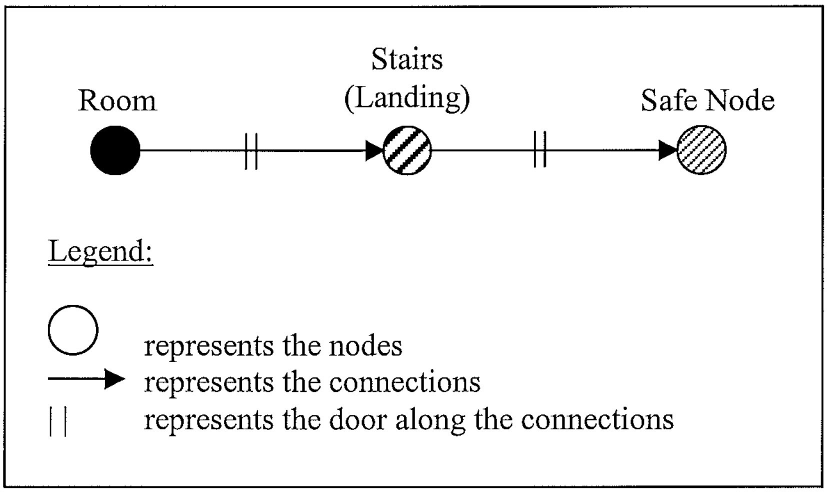


Figure 6.2: Nodal representation of the building in the FEDG evacuation example

Using MacLennan and Nelson's relationship for movement speed and flow rate, the FEDG evacuation example calculates a ball-bearing movement time of 3.15 minutes.

For more detailed calculations, refer to Buchanan (1994).

6.2 Results and Discussion

6.2.1 FEDG Evacuation Example

The FEDG evacuation example was simulated in EvacuatioNZ and its results were compared with the calculated value from the example. Figure 6.3 compares the simulation results for two different door queuing correlations and the value calculated from the FEDG evacuation example.

As it can be seen, the Holmberg correlation produces faster evacuation times when compared to the Nelson and MacLennan correlation. This is expected, as the flow rates for the Holmberg correlation are higher than the Nelson and MacLennan correlation for the same door width.

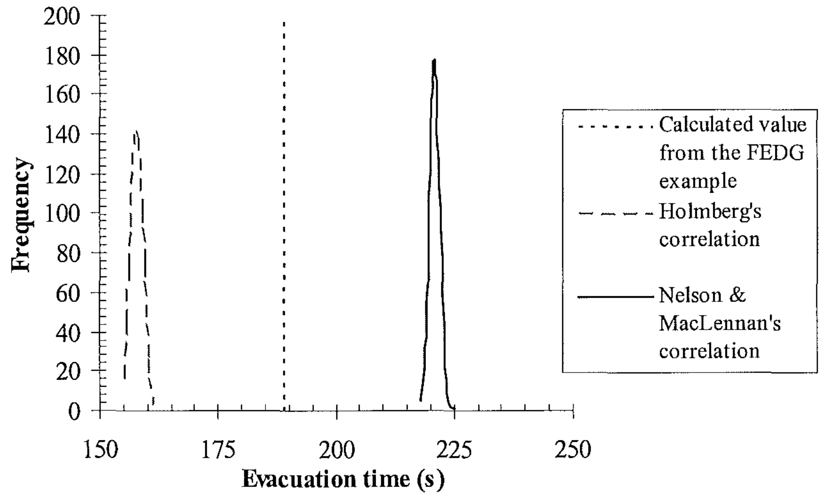


Figure 6.3: Evacuation times simulated using Nelson and MacLennan's correlation and Holmberg's correlation

The results from the Nelson and MacLennan correlation show that EvacuatioNZ produces evacuation times that are approximately 40 seconds longer than the calculated value. This difference is not very significant, and could be due to differences in the way the program approaches the problem.

Simulations were carried out to investigate the effects of using nodal and connection densities. Their results are shown in Figure 6.4.

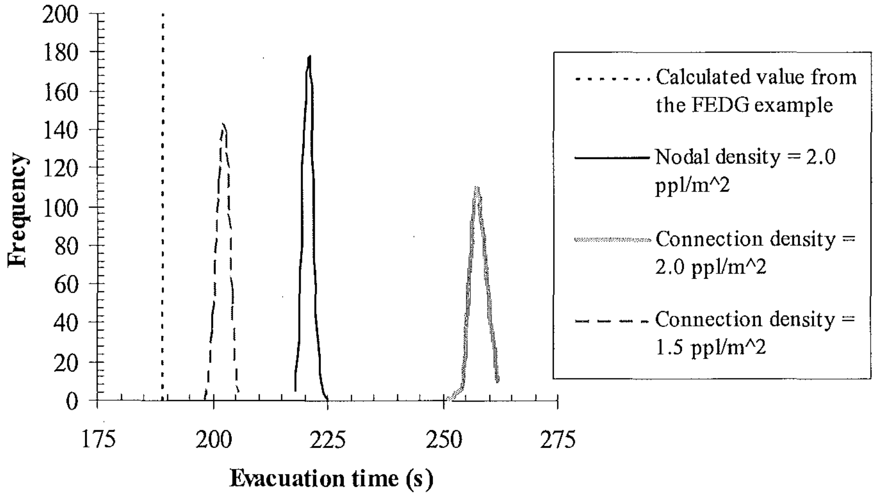


Figure 6.4: Results for the FEDG evacuation example for different nodal and connection densities

Figure 6.4 above shows the differences in using different connection densities. The evacuation times is found to be lower for the connection density of 1.5 ppl/m^2 when compared with connection density of 2.0 ppl/m^2. This is true as the movement speed is a function of the occupant density; it decreases with increasing occupant density. Therefore, for the connection density of 2.0 ppl/m^2, we expect the flow rate and total evacuation time to decrease and increase respectively.

The simulations using the connection density of 1.5 ppl/m^2 appear to be the closest to the calculated value of 189 seconds. However, it would seem imprudent to assume that this is the correct value of connection density to be used, and that EvacuatioNZ was therefore, producing representative results for the FEDG evacuation example. Rather, we can only conclude that the evacuation model can be made to produce results that are reasonable.

From this simple scenario, we can observe some problems with the use of the connection density approach. What value of connection density do we use when the building consists of various stairs and doors? Furthermore, is the use of the connection density in general scenarios justified? The use of nodal densities might be justified here, as it is easily determined and not just an educated guess made by the user.

The simulations using the nodal density approach produce evacuation times of around 222 seconds. This is about 40 seconds or 20% more than the calculated value. Although there is a substantial difference, there are some discrepancies in the calculation method used in the FEDG example, which might explain the differences.

The evacuation example in the Fire Engineering Design Guide does the movement calculations individually for the room and the stairs. The first calculation in the example deals with the time it takes for the occupants to exit the room. The second calculation determines the time for traversing the stairs and then uses the two values to obtain the total evacuation time. The problem is that the example does not seem to account for the additional delay incurred by the occupants who, even after queuing at the door, are unable to exit the room because of congestion on the stairs. EvacuatioNZ takes this into account by using the maximum node density value. This can be seen graphically in Figure 6.5.

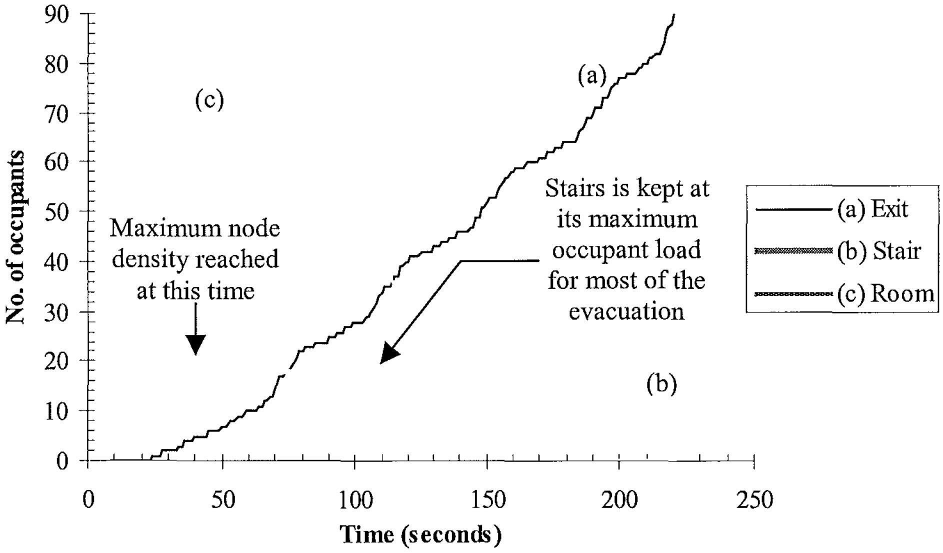


Figure 6.5: The occupation of the nodes during the evacuation

Figure 6.5 shows how the nodes are occupied during the evacuation. The first person exits the room and enters the stairs almost immediately after the start of the evacuation (~ 6 seconds). The number of occupants in the stairs gradually increases as more and more people exit the room, until a maximum number of people are in the stairs. This number corresponds to the maximum node density that the user has specified. In this case, the maximum node density specified was 2.0 ppl/m^2. As a result of this, when the maximum node density is reached in the stairs, the program prevents any other occupant from entering the node until there is sufficient space for the occupant to enter. This additional delay was not accounted for in the FEDG example calculation and could be one of the causes of the discrepancy.

There is also uncertainty in the way the evacuation example obtained the occupant density at the stairs. Solving a quadratic equation, the example obtained two values of occupant density; 0.92 ppl/m^2 and 2.84 ppl/m^2. The subsequent calculations use the density of 0.92 ppl/m^2, as it was considered a more sensible choice. However, the occupant density of 2.84 ppl/m^2 is also possible, especially in emergency situations, and should not be excluded as it produces significantly different results.

Using the occupant density of 2.84 ppl/m^2, the occupants' speed decreases to 15.7 m/min, giving a traversal time of 0.64 minutes, instead of 0.24 minutes for the occupant density of 0.92 ppl/m^2. This increases the total evacuation time to 3.51 minutes or 211 seconds. This value is within 5% of the values simulated by EvacuatioNZ for the nodal density approach scenario. Therefore, by using the other occupant density value, the FEDG calculation produces results that are closer to the simulated values.

6.2.2 FEDG Evacuation Example Using Only One Occupant

The above analysis was repeated for a scenario with only one occupant to further study the example. Using similar calculation methods as the FEDG evacuation example, the times to evacuate the room and the stairs for the one-occupant scenario are found to be 102 seconds and 141 seconds respectively. From EvacuatioNZ, the times to evacuate the room and the stairs are 111 seconds and 130 seconds respectively. Therefore, the simulated values are within 8.5% of the calculated values.

The results from the above analysis implies that the evacuation model is functioning reasonably well. However, from the analysis, we find that the Nelson and MacLennan equations still give queuing delays for the one-occupant scenario. This is not very reasonable, as we would expect the sole occupant to be able to travel without encountering any queuing. Assuming the occupant travels at an unimpeded speed of 1.2 m/s, the occupant would only require approximately 30 seconds to complete the evacuation of the building. The Nelson and MacLennan equations calculate the evacuation time to be 141 seconds, which is significantly higher. Therefore, it can be concluded that the Nelson and MacLennan equations are not suitable in the calculation of evacuation times for low occupant scenarios. Another queuing correlation may have to be obtained for simulating low occupant scenarios.

From these two analyses, it is found that the evacuation model is working reasonably well for the FEDG evacuation example. There are some discrepancies in the simulated results and the calculated results, but they could be due to a number of reasons. Among those is the variation of the simulated results due to the evacuation model being a probabilistic model. The discrepancies are also likely to be caused by the different assumptions made by the evacuation model and the FEDG evacuation calculations.

7.0 Discussion

The component testing that was carried out on the evacuation model produced results that were satisfactory. Both the door queuing component and the stair movement component are found to be working properly.

Although there is still more component testing to be done, the testing of basic components such as the door queuing model and stair movement model is essential as a first step in validating the program. The simple scenario testing of the FEDG evacuation example reveals some differing assumptions that has caused discrepancies in the comparison between the results from the evacuation model and the hand calculation. This example helps to emphasise the need to understand the EvacuatioNZ model fully, as well as to understand the basis of the calculations or other evacuation models used in the validation of the program. There is also a need to do more testing on the combination of components to ensure that the model will work correctly in combination.

During the component testing, several problems with the program were encountered. Most of the problems were corrected during the validation process, resulting in the development of EvacuatioNZ Version 1.0e.

The first problems encountered were that the occupants were found to move back and forth between nodes, resulting in longer evacuation times. This problem was only realised upon inspecting the NODE OCCUPATION file. After some minor adjustments to the model, the occupants stopped moving back and forth, and this resulted in shorter evacuation times.

A simulation of a 10-metre long staircase also found some problems with the stair movement component. From the NODE OCCUPATION file, it was found that the occupants could traverse the stairs in 3 seconds, which was unreasonably quick. This problem has been corrected in EvacuatioNZ Version 1.0e.

An additional problem with the stair movement component is that the model does not differentiate the path speeds along horizontal corridors or stairs. In the program version studied, the occupants are still able to move at their maximum movement speeds even while on the stairs. This problem should be resolved in later versions of the program.

Earlier versions of the program also had problems with the door queuing model. The program would calculate the amount of delay according to the number of occupants and the flow capacity of different building components. However, problems arose as the amount of delay was then imposed on all the occupants. This implies that even the first occupant to reach the door does not get through the door, but instead waits at the door for that amount of time before going through it. This was very unrealistic and caused significantly higher evacuation times, especially as the miscalculation was magnified by each door the occupants have to travel through. After correcting the algorithm, the queuing delay is no longer imposed on all the occupants.

The current version of the program still has some limitations. It does not support the use of smoke data to determine when the node may be impassable, and does not consider the reduction in speed caused by low visibility through smoke.

The program can only carry out simulations for uncontrolled evacuation. There is currently no facility to set a delay for the occupants so that a staged evacuation can be simulated.

It is recommended that some of the limitations and problems in the current program be resolved to improve its functional value and accuracy in its simulation of building evacuations.

8.0 Conclusions

- EvacuatioNZ is a coarse network, probabilistic evacuation model currently under development in the University of Canterbury. It is written in C++ language.

- EvacuatioNZ has facilities that allow easy modification and the addition of new components as more knowledge about occupant movement and human behaviour in fires is found.

- This evacuation model has attempted to resolve some of the problems with earlier models, such as allowing infinite number of nodes and people, subject to the limitations of the computer being used.

- Component testing on the model has shown that the basic components of movement are working satisfactorily, and producing results that are comparable to calculated values.

- Results from the simple scenario testing shows that the components of the model are working adequately well, but there are discrepancies between the results due to different assumptions made.

- The current version of the evacuation model should not be used for design purposes, as it still requires further work. Some of the future work is proposed in the next subsection.

8.1 Further research

- The evacuation model still requires more validation. More of the components need to be tested and checked to ensure that they are working sufficiently well.

- EvacuatioNZ currently does not support smoke input in its simulation, and does not have the features to simulate staged or controlled evacuation. These features should be incorporated in later versions to increase the functional value of the product.

- The evacuation model should also be validated using more calculation examples, as well as data from actual evacuations to validate the components of human behaviour in the model. Actual data from evacuations such as the study from Olsson & Regan (1998) can be compared with simulation results from EvacuatioNZ, if sufficient information regarding the buildings is provided.

9.0 Nomenclature

Abbreviations

FEDG	Fire Engineering Design Guide
ppl	People or Persons
SFPE	Society of Fire Protection Engineering

Symbols

B	Boundary layer width [m]
c	y-intercept of the curve
D_o	Occupant density [ppl/m^2]
F_a	Actual flow rate [ppl/min or ppl/s]
F_s	Specific flow rate [ppl/m/min or ppl/m/s]
G	Stair tread widths [m]
k_t	Speed constant, a function of the building component
l	Length of node [m]
m	Gradient of the curve
n	Number of occupants [ppl]
R	Stair riser heights [m]
S	Movement speed [m/min or m/s]
t_{ev}	Time to evacuate [s]
W	Actual door width [m]
w	Width of node [m]
W_e	Effective width of door [m]

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Appendix A: Door Queuing Component Testing

Input files

(1a) MAP file used in the high-density node situation:

```
<map>
   <description>Single door test</description>
   <version>1.00</version>
   <node exists="Yes">
      <name>Room</name>
      <ref>1</ref>
      <length>22.36</length>
      <width>22.36</width>
   </node>
   <!-- The exit node -->
   <node exists="Yes">
      <name>Exit</name>
      <ref>2</ref>
      <node_type>Safe</node_type>
      <!-- dimensions are not required for a safe node -->
   </node>
   <connection exists="Yes">
      <name>TheLink</name>
      <node_ref>1</node_ref>
      <node_ref>2</node_ref>
      <length>0.0</length>
      <connection_type type="Door">
         <width>1.0</width>
      </connection_type>
   </connection>
</map>
```

(1b) MAP file used in the low-density node situation:

```
<map>
   <description>Single door test</description>
   <version>1.00</version>
   <node exists="Yes">
      <name>Room</name>
      <ref>1</ref>
      <length>44.72</length>
      <width>44.72</width>
   </node>
   <!-- The exit node -->
   <node exists="Yes">
      <name>Exit</name>
      <ref>2</ref>
      <node_type>Safe</node_type>
      <!-- dimensions are not required for a safe node -->
   </node>
   <connection exists="Yes">
      <name>TheLink</name>
      <node_ref>1</node_ref>
      <node_ref>2</node_ref>
      <length>0.0</length>
      <connection_type type="Door">
         <width>1.0</width>
      </connection_type>
   </connection>
</map>
```

(2) POPULATE file:

```
<_populate_database>
   <_version>1.00</_version>
   <_definition>
      <_people>1000</_people>
      <_log>No</_log>
      <_node _type="range">1</_node>
      <_person_type>
         <_name>Normal</_name>
         <_probability>100</_probability>
      </_person_type>
   </_definition>
</_populate_database>
```

(3) SIMULATION file:

```
<simulation>
   <version>1.00</version>
   <time_max>12000</time_max>
   <time_step>1</time_step>
   <max_node_density>2.0</max_node_density>
   <door_flow>MacLennan</door_flow>
   <occupant_density_model local_occupant_density="2.0">
    connection</occupant_density_model>
</simulation>
```

(4) SCENARIO file:

```
<scenario>
   <version>1.00</version>
   <simulations>1</simulations>
   <seed>0</seed>
   <dump_evacuation_times>Yes</dump_evacuation_times>
   <random_start_position>Yes</random_start_position>
   <files>
         <simulation>simulation.xml</simulation>
         <post_process>pp template.xml</post_process>
         <populate>populate.xml</populate>
   </files>
</scenario>
```

Evacuation time calculations from Nelson and MacLennan:

The calculations below are from Nelson & MacLennan (1995). The door used 1 m wide.

(a) For the high-density scenario,

Density = 2.0 ppl/m^2

k_t = 84.0 for level corridors or doorways

$$\begin{aligned} F_a &= k_t D_0(1-0.266D_0)(W-B) \\ &= 84.0(2)(1-0.266(2))(1-0.3) \\ &= 55 \ \text{ppl/min} \end{aligned}$$

$$\begin{aligned} t_{ev} &= \frac{n}{F_a} \\ &= \frac{1000}{55} \\ &= 18.18 \ \text{min} \\ &= 1090 \ \text{seconds} \end{aligned}$$

(b) For the low-density scenario,

Density = 0.5 ppl/m^2

$$\begin{aligned} k_t &= 51.8(G/R_s)^{0.5} \\ &= 51.8(0.28/0.18)^{0.5} \\ &= 64.6 \end{aligned}$$

$$\begin{aligned} F_a &= k_t D_0(1-0.266D_{0)}(W-B) \\ &= 84(0.5)(1-0.266(0.5))(1-0.3) \\ &= 25.5 \ \text{ppl/min} \end{aligned}$$

$$\begin{aligned} t_{ev} &= \frac{n}{F_a} \\ &= \frac{50}{25.5} \\ &= 39.23 \ \text{min} \\ &= 2356 \ \text{seconds} \end{aligned}$$

Appendix B: Stair Movement Component Testing

Input files:

(1) MAP file:

```
<map>
   <description>Single stair test</description>
   <version>1.00</version>
   <node exists="Yes">
          <name>Stair</name>
          <ref>1</ref>
          <length>100</length>
          <width>1.0</width>
   </node>
   <!-- The exit node -->
   <node exists="Yes">
          <name>Exit</name>
          <ref>2</ref>
          <node_type>Safe</node_type>
          <!-- dimensions are not required for a safe node -->
   </node>
   <connection exists="Yes">
          <name>TheLink</name>
          <node_ref>1</node_ref>
          <node_ref>2</node_ref>
          <length>100</length>
          <connection_type type="Stairs">
                 <tread>0.33</tread>
                 <riser>0.17</riser>
          </connection_type>
   </connection>
</map>
```

(2a) POPULATE file used in the high-density node situation:

```
<_populate_database>
   <_version>1.00</_version>
   <_definition>
      <_people>200</_people>
      <_log>No</_log>
      <_node _type="range">1</_node>
      <_person_type>
         <_name>Normal</_name>
         <_probability>100</_probability>
      </_person_type>
   </_definition>
</_populate_database>
```

(2b) POPULATE file used in the low-density node situation:

```
<_populate_database>
   <_version>1.00</_version>
   <_definition>
      <_people>50</_people>
      <_log>No</_log>
      <_node _type="range">1</_node>
      <_person_type>
         <_name>Normal</_name>
         <_probability>100</_probability>
      </_person_type>
   </_definition>
</_populate_database>
```

(3) SIMULATION file:

```
<simulation>
    <version>1.00</version>
    <time_max>12000</time_max>
    <time_step>1</time_step>
    <max_node_density>2.0</max_node_density>
    <door_flow>MacLennan</door_flow>
    <occupant_density_model local_occupant_density="2.0">
     node</occupant_density_model>
</simulation>
```

(4) SCENARIO file:

```
<scenario>
    <version>1.00</version>
    <simulations>1</simulations>
    <seed>0</seed>
    <dump_evacuation_times>Yes</dump_evacuation_times>
    <random_start_position>No</random_start_position>
    <files>
           <simulation>simulation.xml</simulation>
           <post_process>pp template.xml</post_process>
           <populate>populate.xml</populate>
    </files>
</scenario>
```

Evacuation time calculations from Nelson and MacLennan:

The calculations below are from Nelson & MacLennan (1995). The stair used has the riser height if 0.18 m, tread width of 0.28 m and width of 1 m.

(a) For the high-density scenario,

Density = 2.0 ppl/m^2

$$\begin{aligned} k_t &= 51.8(G/R_s)^{0.5} \\ &= 51.8(0.28/0.18)^{0.5} \\ &= 64.6 \end{aligned}$$

$$\begin{aligned} F_a &= k_t D_0(1-0.266D_0)(W-B) \\ &= 64.6(2)(1-0.266(2))(1.3-0.3) \\ &= 60.46 \\ &\approx 61 \text{ ppl/min} \end{aligned}$$

$$\begin{aligned} t_{ev} &= \frac{n}{F_a} \\ &= \frac{200}{61} \\ &= 3.30 \text{ min} \\ &= 198 \text{ seconds} \end{aligned}$$

(b) For the low-density scenario,

Density = 0.5 ppl/m^2

$$\begin{aligned} k_t &= 51.8(G/R_s)^{0.5} \\ &= 51.8(0.28/0.18)^{0.5} \\ &= 64.6 \end{aligned}$$

$$\begin{aligned} F_a &= k_t D_0(1-0.266D_0)(W-B) \\ &= 64.6(0.5)(1-0.266(0.5))(1.3-0.3) \\ &= 28.0 \\ &= 28 \text{ ppl/min} \end{aligned}$$

$$\begin{aligned} t_{ev} &= \frac{n}{F_a} \\ &= \frac{50}{28} \\ &= 1.78 \text{ min} \\ &= 107 \text{ seconds} \end{aligned}$$

Appendix C: FEDG Simple Scenario Testing

Input files

(1) MAP file:

```
<map>
   <description>FEDG Example</description>
   <version>1.00</version>
   <node exists="Yes">
         <name>Room</name>
         <ref>1</ref>
         <length>10</length>
         <width>10</width>
   </node>
   <node exists="Yes">
         <name>Stairs</name>
         <ref>2</ref>
         <width>0.9</width>
         <length>10.0</length>
   </node>
   <!-- The exit node -->
   <node exists="Yes">
         <name>Exit</name>
         <ref>3</ref>
         <node_type>Safe</node_type>
         <!-- dimensions are not required for a safe node -->
   </node>
   <connection exists="Yes">
         <name>TheLink</name>
         <node_ref>1</node_ref>
         <node_ref>2</node_ref>
         <length>20.0</length>
         <connection_type type="Door">
               <width>1.0</width>
         </connection_type>
   </connection>
   <connection exists="Yes">
         <name>TheClimb</name>
         <node_ref>2</node_ref>
         <node_ref>3</node_ref>
         <length>10.0</length>
         <connection_type type="Door">
               <width>1.0</width>
```

```
          </connection_type>
          <connection_type type="Stairs">
                 <tread>0.28</tread>
                 <riser>0.18</riser>
                 <!-- width not yet implemented -->
                 <width>0.9</width><!--effective width-->
          </connection_type>
    </connection>
</map>
```

(2) POPULATE file:

```
<_populate_database>
   <_version>1.00</_version>
   <_definition>
      <_people>90</_people>
      <_log>No</_log>
      <_node _type="single">1</_node>
      <_person_type>
         <_name>Normal</_name>
         <_probability>100</_probability>
      </_person_type>
   </_definition>
</_populate_database>
```

(3) SIMULATION file:

```
<simulation>
    <version>1.00</version>
    <time_max>1200</time_max>
    <time_step>1</time_step>
    <max_node_density>2.0</max_node_density>
    <door_flow>MacLennan</door_flow>
    <occupant_density_model local_occupant_density="2.0">
    node</occupant_density_model>
</simulation>
```

(4) SCENARIO file:

```
<scenario>
    <version>1.00</version>
    <simulations>500</simulations>
    <seed>0</seed>
    <dump_evacuation_times>Yes</dump_evacuation_times>
    <random_start_position>yes</random_start_position>
    <files>
            <simulation>simulation.xml</simulation>
            <post_process>pp template.xml</post_process>
            <populate>populate.xml</populate>
    </files>
</scenario>
```

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