SIMULATION OF THE EMERGENCY EVACUATION OF COMPLEX BUILDINGS USING ISI

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ABSTRACT

Evacuation is a vitally important component of emergency management. Effective evacuation planning and evacuation management can be the difference between safety and tragedy in an emergency situation. However, in an emergency evacuation of any large complex building, there is a tendency for serious congestion of evacuees to occur in some areas even while other nearby exit areas are experiencing relatively light usage. The consequences are very serious, involving a direct threat to public safety, and adding to the likelihood of the onset of panic amongst evacuees.

Recently a whole range of computer-based techniques have been developed to assist in both assessing the safety of existing or proposed buildings, and in evaluating the relative merits of alternative evacuation procedures and policies. This paper investigates the use of the simulation environment ISI, which uses the powerful SIMAN simulation language, in evacuation modelling. ISI is used to develop a library of simulation sub-models representing the components of typical buildings and to synthesise these sub-models into a detailed model of a typical complex building. The results of several model runs are compared in order to identify worst possible cases. The ease with which changes to the configuration or usage of the building as well as changes to evacuation procedures may be modelled is discussed. This technique is thus shown to provide a means of rapidly and conclusively establishing the best of a number of alternative strategies, and thus the approach is shown to offer tremendous advantages over conventional techniques.

APPROACHES TO EVACUATION MODELLING

A substantial body of research has been carried out into the derivation of theoretical and empirical relationships between density of occupants, evacuation speed and flow rates.

Studies like those of Pauls (Pauls 1980) and Togawa (Togawa 1955) have derived such relationships for occupants in confined spaces including stairwells and fire exits. Gipps (Gipps 1986) concentrates on open plan buildings such as airport terminals and derives similar types of relationships. Many studies have also been carried out into flow rates of both pedestrians and vehicles in more "macroscopic" evacuations. Some examples are research into natural and man-made disasters (Hobeika and Hwang 1986), hazardous chemical spills (Johnson 1985), nuclear power plants (Belardo et al. 1983) and natural disasters (Hobeika and Jamei 1985).

Many of these studies have further attempted to encode the empirical and theoretical relationships into computer programs which predict evacuation times for given building configurations and occupancies. These programs can be termed "computer models" of evacuation, as their intention is to mimic the behaviour of a real-world evacuation in some idealised form. The computer models described in the literature use a wide variety of tools and techniques, and some are quite sophisticated including factors such as smoke spread, toxic chemical and radiation effects, potentially blocked exits, human behaviour and many other potential problems.

The great majority of models presented to date focus either on shortest path calculations, or on exit flow rates for each building exit. In models based on shortest path calculations, the model calculates the theoretically most efficient paths for evacuees and determines evacuation time using these paths. The evacuation time produced is an optimal one, and evacuation planning and management aims at realising the optimum by guiding evacuees along these theoretically most efficient paths calculated by the model. In models based on exit flow rates, an expected flow rate for each exit is calculated, and the total evacuation time is thus calculated on the basis of a given building occupancy. Again the evacuation time predicted is an optimal one, which becomes the goal of planning and management activities.

Thus the majority of models in the literature have concentrated on predicting optimum evacuation times. The results may be used in conjunction with results of fire drills and indeed normal exit flow studies, in order to determine ways of making actual evacuations approach the efficiency of the predicted optimum. However, this approach does not in general reflect the reality of variability in evacuation times. Weinroth has observed that:

> "Little attention has been directed to the tendency for evacuation patterns and total required exit time to vary greatly from one circumstance to the next in the case of the same building, due to chance

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combinations of occupancy patterns and interaction with exit behaviour of evacuees" (Weinroth 1989)

In the same paper, Weinroth goes on to outline an approach dubbed "Evacuation Behaviour Modelling", which seeks to reverse the typical sequence of predicting an optimum evacuation time and striving to achieve this optimum in the real building. The Evacuation Behaviour Modelling approach attempts to model explicitly the variability in occupancy of building sectors and the variability in decisions taken by evacuees. By executing this model many times with random inputs, the problematic combinations of chance factors which lead to serious congestion are clearly identified. Corrective measures are then suggested and tested by incorporating them into the model. The next section describes the Evacuation Behaviour Modelling approach.

EVACUATION BEHAVIOUR MODELLING

The evacuation behaviour model (Weinroth 1989) concentrates on explicitly modelling the behaviour of groups of evacuees and the activities in which each group must engage in order to reach safety. Thus evacuation patterns and total evacuation time as predicted by the model should correspond closely to those of the real building. By running the model many times, evacuation times can be predicted as expected ranges for the real building, rather than theoretical optima. In addition to deriving ranges of evacuation times, it is also possible to identify combinations of chance factors which result in serious evacuation problems. Steps which can realistically be taken to avoid these combinations, or to cope with the problems which they generate can then be tested on the computer model prior to implementation. We will later present some of the advantages which this approach offers. First let us consider how the model works.

Discrete Event Simulation

The evacuation behaviour model is based on the technique of discrete event simulation (Thesen and Travis 1990), and in particular on process oriented discrete event simulation (Banks and Carson 1985). The term discrete event simulation simply means that the simulation is a chain of events which are modelled as occurring instantaneously at distinct points in time rather than gradual changes occurring over a period of time. This technique has previously been used in a whole spectrum of application areas (Emshoff and Sisson 1970). In process oriented simulation, a model is constructed by depicting the system as a network of connected functions or blocks. The model may be viewed as a kind of flowchart which describes the movement of objects or entities through the system. The blocks encountered by an entity as it progresses through the network control its flow. The block functions correspond to the different types of activity that may be engaged in by an entity such as arrival, time delay, waiting for a resource to become available, choosing one of a number of possible paths, leaving the model, etc..

Evacuation Behaviour Model Details

In the context of building evacuation the entities being modelled are evacuees, or in most cases groups of evacuees. The resources represent units which must be available to evacuees in order for them to progress towards safety, such as; exit doors, internal doors, halls, staircases, elevators and fire escapes. The simulation model or network depicts the paths which may be taken by groups of evacuees, the resources which they require in order to progress, and the route choices that are available to them at various points.

The evacuation behaviour model has the following features:

- Building Sectors. The building is broken down into a number of sectors, each of which has a certain occupancy. The occupancy of a sector can be taken as constant, sampled from real data or generated from a known probability distribution, as can the time for occupants of a sector to become aware of the need for evacuation. The occupants of a sector have the same starting point in the model, and thus the same route choices.

- Groups of Evacuees. Occupants of a particular sector may evacuate singly, or more likely evacuate in groups. These groups may have different attributes such as speed and group size.

- Evacuation Paths. An evacuation path is a route available to a group of evacuees. This consists of a number of blocks such as hallways, doorways, staircases, etc.. Each block has an associated resource capacity, which dictates the number of evacuees which may use the block simultaneously, and an associated travel time, which dictates how long it takes to exit the block. The travel time may contain a random component, or may be dictated by some attributes of the group such as group size and speed. Empirical and theoretical relationships such as those mentioned in the previous section may easily be coded into the travel times.

- Route Choices. At many points, evacuees are faced with a decision about two or more possible paths. At such points, the decision made by evacuees may be based on random choice (with different probabilities for each path), congestion (where one path is visibly more crowded than others), preferred order (where evacuees will almost always choose a particular path unless it is congested or blocked, or other factors. Adequate modelling of route choices is very important to the accuracy of the model.

Advantages and Disadvantages

The application of discrete event simulation to evacuation modelling presents distinct advantages over alternative methods and also opens up a number of interesting new applications. Some of the advantages are:

- The most significant advantage of discrete event simulation is its flexibility. Using commercial simulation software (see next section) the modeller may develop an evacuation model to any required level of detail, and include any effects which are important to evacuation performance.

- A large number of experiments can be carried out in a relatively short time, thus allowing all possible strategies for improvement to be evaluated.

- This approach is based on actual evacuation behaviour rather than an idealised optimum. Thus it is possible to directly compare simulation results with results of evacuation drills in order to ensure that the model is valid.

- When the model has been validated in this way, it is then possible to use the model with confidence to predict results for situations which cannot be safely replicated in a drill.

- The exercise of developing and running the simulation model results in a better understanding of the evacuation performance of the building being modelled.

However, there are disadvantages to this approach also:

- Using discrete event simulation, and particularly general purpose simulation languages, requires a high level of expertise. In contrast to this, shortest path and flow rate models are generally easy to use.

- A considerable lead time is also required to carry out such a simulation study.

- Inclusion of random effects such as variable sector occupancies, random delay times and random route choices makes the interpretation of simulation results more difficult. In comparing results of different strategies, statistical significance tests must be carried out to ensure apparent improvements are not simply due to these random effects. Autocorrelation of raw simulation output also makes some traditional statistical analysis techniques inappropriate.

The ISI software (Nolan et al. 1991) allows general purpose simulation tools to be customised to particular application areas. By providing the modeller with libraries of application specific building blocks, ISI considerably reduces both the expertise and the time required to carry out simulation studies without any loss of flexibility. The next section describes the ISI software.

INTELLIGENT SIMULATION INTERFACE (ISI)

Background

Despite the very large number of commercially available discrete event simulation tools (Estrine 1990), the vast majority can be broadly classified as either special purpose data-driven simulation systems or general purpose simulation languages (Law and McComas 1990). General purpose simulation languages are highly flexible in modelling approach, and can be used across a wide range of applications. However, their user base is restricted by the high level of expertise required. Shannon, Mayer and Adelsberger have treated this knowledge requirement in some depth (Shannon et al. 1985).

Special purpose simulation systems are aimed at reducing the level of expertise required for the use of simulation. This is achieved by restricting the applicable problem domain. The low level "building blocks" of general purpose simulation languages are replaced by a set of high level blocks which correspond closely to the elements of a real system in that problem domain. However, this approach suffers two distinct disadvantages, namely:

- Even within a particular application area, most real systems will contain some "non-standard" components which cannot be modelled by these very specific building blocks.

- The provision of building blocks whose internal workings are beyond the control of the end-user decreases the flexibility of modelling approach, and lacks the important facility to view a system at various levels of abstraction and study the effects (Nolan et al. 1988).

A potential solution to this problem is to provide tools which allow a hierarchical approach to simulation. Recently, many authors have published papers suggesting this approach (Aribaud et al. 1990, Martinolle et al. 1990, Pooley 1989). Hierarchical simulation, whereby a model represents explicitly the hierarchical nature of the real system, can offer tremendous advantages over conventional techniques. Some of these advantages are discussed next.

ISI Rationale

Hierarchical simulation is based on the object oriented programming approach. Fundamental to this approach is the concept of classes and instances (Cox 1986). A class is a grouping of objects which have common properties. Each member of a particular class is termed an instance of that class. Classes themselves may be deemed instances (subclasses) of other broader classes or superclasses, thus providing a hierarchical structure (see figure 1).

Physical systems may, in general, be viewed from this hierarchical standpoint. In the case of buildings, the doors, hallways, staircases, etc. which occur at various points in a building may be viewed as instances of particular classes. A class would exist for each of these. Additionally, many complex buildings may contain repeated combinations of these instances such as lecture theatres, hospital wards, shopping mall units, or indeed whole floors of some multi-storey buildings. These may be modelled as superclasses containing networks of instances of subclasses. Some of the advantages of this

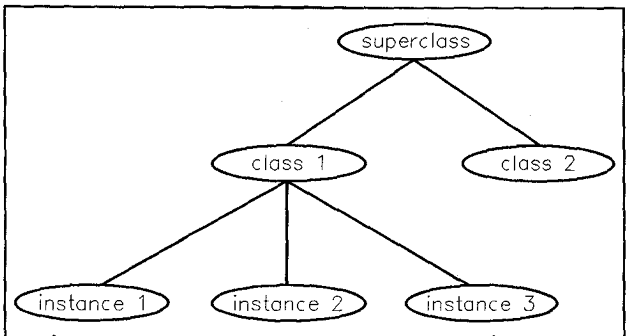


Figure 1: Superclass, class and instance

approach are listed below:

- The most important feature of the hierarchical approach is that it takes maximum advantage of repeated components within a system
- This approach allows modular components to be built and tested independently. This is particularly pertinent when several modellers wish to cooperate on a single model. In addition, this is a "reusable components" approach which allows sub-models to be used in many different models.
- The modular nature facilitates updating the model to reflect changes in the real system. This increases the useful lifetime of a model.
- A single expert user may develop libraries to represent typical elements of the system, which may subsequently be combined by non-expert users to build models.
- Communication is a vitally important aspect of any modelling project. With a hierarchical model approach, the model operation may be presented at various levels of detail, for technical and non-technical audiences.

The concept for ISI evolved from a joint University/Industry R&D project on the requirements for the engineering use of simulation, which included a survey of existing and potential users of simulation (Nolan et al. 1988). It was evident that although a special purpose simulation system is useful as a "first-cut" in some applications, a simulation tool which includes the flexibility of a general purpose language, the ease of use of a special purpose system and a hierarchical approach to modelling would be ideal for detailed simulation studies.

In response to this need, ISI was developed as an interface to the SIMAN simulation language. SIMAN is a very powerful general purpose simulation language (Pegden et al. 1990). ISI provides a menu-driven graphical environment which leads the modeller through all stages of a simulation project; model building, data input, experiment construction, graphical model run and output analysis. Most importantly, ISI offers hierarchical modelling facilities whereby libraries of sub-models (known as macros) may be developed. The ISI software is described in detail elsewhere (Lane et al. 1989, Nolan and Fegan 1987). The use of ISI and SIMAN in evacuation behaviour modelling is discussed in the next section.

ISI IN EVACUATION BEHAVIOUR MODELLING

The previous section presented ISI as a hierarchical simulation tool which uses the SIMAN general purpose simulation language. The advantages of the ISI approach were discussed in a general sense. In this section, some of the features of SIMAN and ISI which are particularly useful in evacuation behaviour modelling are presented.

SIMAN Features

SIMAN has a variety of different block functions which are used to model the types of activities which may be engaged in by entities in their progress through a system. More than fifty such constructs are provided by SIMAN, and in the region of forty for controlling the experiment to be performed on the model. Some of these are dedicated to the simulation of manufacturing and material handling systems, but the majority may be used in many other application areas. In the context of evacuation behaviour modelling, two sets of blocks are of particular interest. They are "hold blocks" which model different types of activities which require entities to wait in a particular location and "decision blocks" which model entities choosing one from several possible paths on the basis of some criterion.

Some of the SIMAN block functions which may be used to model the delays encountered by evacuees in their progress towards an exit are shown in Figure 2.

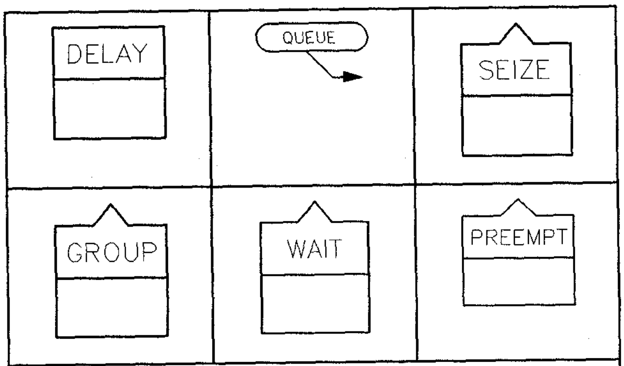


FIGURE 2: SIMAN Blocks for evacuee delays

The DELAY block may be used to represent a group of evacuees entering into an activity which requires a certain time to complete. This may be traversing a corridor, exiting through an unobstructed door, descending a stairs, or any such activity. The duration of the delay may be given in a variety of formats, such as a fixed number, a value sampled from a statistical distribution, a function of some group attribute (such as group size, number of disabled persons in group or group speed) or an arbitrary expression containing combinations of these factors. The QUEUE block can represent a number of groups waiting for a certain system condition to become true prior to engaging in an activity. An example is an access area where groups must wait in turn for a doorway to become available. A queue may be assigned a finite capacity, and a rerouting choice (termed balking) for when the queue is filled to its capacity. The SEIZE block represents a group accessing a certain resource which is necessary for their progress (such as a hall, a staircase, a door, etc.). This block must be preceded by a queue, where groups wait until the resource becomes available. The GROUP block is used to merge a number of individuals into a single group of evacuees, or to merge groups of evacuees into larger groups. In many cases it is more suitable to model evacuees as acting in groups rather than singly. The group block may also be used in guided evacuations where evacuees are instructed to act as groups or to assemble at assembly points. At a WAIT block, groups of evacuees remain in the preceding queue until a certain signal is given. This block may be of use in guided evacuations where evacuees must await given conditions before continuing. The PREEMPT block is used to remove a resource from its normal operation either temporarily or permanently. This is of great use in modelling the deterioration of the building structure during the evacuation, with certain routes becoming blocked.

Accurate modelling of the points at which evacuees must choose a path from a number of alternatives can be of vital importance to the realism of the results obtained. In the case of complex buildings, evacuees may be faced with quite a number of alternatives at several points in their evacuation. A very powerful feature of SIMAN is the variety of blocks available for modelling this type of branching. Some of these are shown in figure 3.

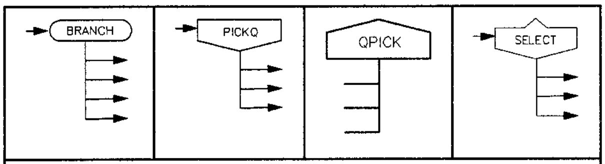


FIGURE 3: SIMAN Blocks for branching

The BRANCH is an extremely flexible routing mechanism, with each of the output paths having a rule to decide when it is chosen by entering evacuees. The rule may be a simple probabilistic choice or an arbitrarily complex conditional expression involving perhaps system variables and attributes. The PICKQ block can be used to model arriving evacuees choosing between a number of different waiting areas. The choice may be random, cyclic, based on crowding in the waiting areas or based on a preferred order. The QPICK block is the opposite of the PICKQ, and decides which of a number of waiting areas next feeds a group of evacuees through a shared access area. The SELECT block is quite similar to a PICKQ, except that waiting groups are competing for access to a resource such as a doorway rather than a queuing area.

ISI Features

ISI provides a menu-driven graphical environment for SIMAN modelling. Moreover, it provides hierarchical modelling facilities as discussed in the previous section. This facilitates the development of a set of high level blocks corresponding to the components of typical buildings, using low level SIMAN blocks like those in figures 2 and 3. The process of building simulation models is then simply a matter of connecting these components together as a network. The parameters of these blocks are then entered using pop-up menus; initial occupancies, transit times, route choices, etc. When the process is complete, SIMAN code representing the model is automatically generated. When this model is being run, graphical icons representing evacuees are shown in their progress towards the exits. Bargraphs display the levels of congestion throughout the building. When the run is complete, results are presented to the user in a variety of business graphics formats. Results presented include the following:

- Total evacuation time
- Evacuation profile # safe vs. time
- Total evacuation time for each sector
- Total evacuation time for each exit
- Evacuation bottlenecks
- Utilisation profiles for doors, hallways, stairs, exits

By altering the model logic or data, it is possible to evaluate a wide range of scenarios; alterations in building use, additional escape routes, marked exit routes affecting choice sets, use of evacuation marshalls, alternative alarm systems, etc.. The results of different scenarios may be compared using statistical analysis techniques and by means of superimposed plots.

These features combine to considerably decrease the level of expertise required for the use of discrete event simulation in evacuation and significantly reduce the time required to complete a simulation study. Thus most of the disadvantages of this technique, as listed in an earlier section, are avoided. The next section outlines an example application of ISI in evacuation.

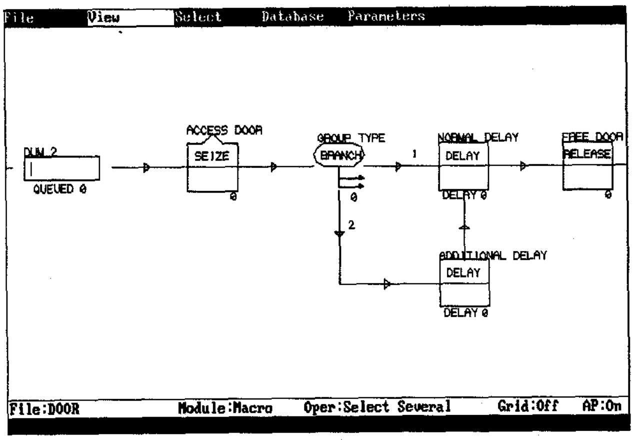
EXAMPLE

A simulation model of a complex university building, which was presented by Weinroth (Weinroth 1989) is used here in order to demonstrate the ISI approach to evacuation behaviour modelling and, in particular, the usefulness of the hierarchical modelling technique. The details of the building network are omitted here, as the intention of this section is simply to demonstrate the ease with which a complex model may be built, tested and analysed using ISI.

The building in question houses an entire college of a university, and is a five-storey, split-level building of an asymmetrical design. The capacity of the building is in excess of 1600 occupants. An important feature of the building is that at many points evacuees are faced with two, three or four different escape routes. For the purposes of the model, Weinroth broke down the evacuees into eleven different groupings. Within each of the groupings, evacuees are faced with a similar initial choice set. The model may be constructed from the following components:

- Groups of evacuees becoming aware of the need for evacuation. The time taken for evacuees to become aware is variable, and depends on the quality of the alarm system.
- Hallways must be traversed by each group. The time taken for traversal depends on the group size.
- Several staircases connect each pair of floors. The time taken for descent or ascent of a staircase depends on group size and is adapted by Weinroth from Pauls (Pauls 1980).
- Evacuees must exit through doors both internally and externally. The time taken is modelled as a constant 1.5 seconds per evacuee, and is thus a function of group size. There is a 10% chance of an extra delay due to an accident or disabled evacuee.
- At many points, evacuees must choose a route from a choice set. These sets use preferred ordering, where evacuees will always choose the first option if it is available, the second option if the first is unavailable, and so on. As discussed in the previous section, SIMAN can also handle a wide variety of alternative choice mechanisms.

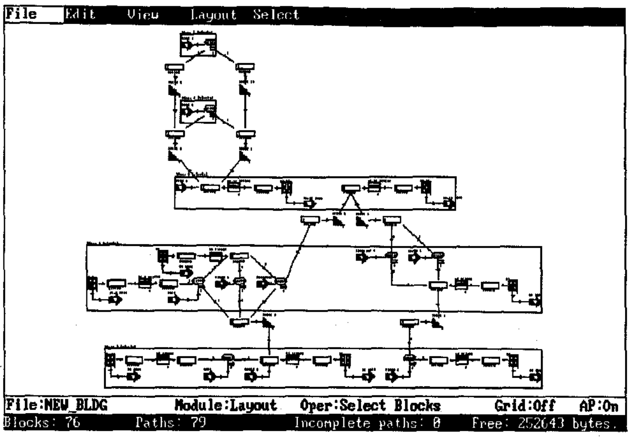
The representation of each of the components above requires a network of statements in a general purpose simulation language. This network is replicated for each occurrence of the component. In contrast, the ISI macro facility allows this hierarchical nature to be exploited. A library of macros containing the above components is developed. The macro for a door is shown in figure 4. Groups of evacuees wait in the queue until the door "resource" can be seized. With a probability of 10%, evacuees enter a delay corresponding to an accident or disabled evacuee. All evacuees then enter a delay corresponding to exiting through the door. The door resource is then made available to the next waiting group.



File:DOOR Module:Macro Oper:Select Several Grid:Off AP:On

Figure 4: ISI Macro for a door

Macros are developed for the other components in a similar manner. These are then connected to form a model of a complete building. The model for the university building is shown in figure 5. A zoomed view, showing part of the model of the second floor is shown in figure 6.



File:NEW_BLDG Module:Layout Oper:Select Blocks Grid:Off AP:On

Blocks: 76 Paths: 79 Incomplete paths: 0 Free: 252643 bytes.

Figure 5: ISI Model for building

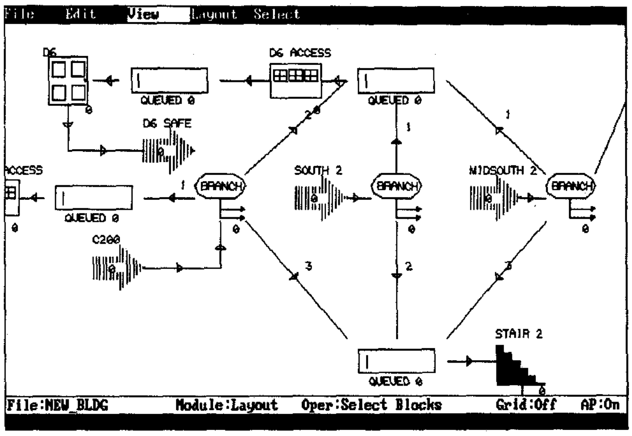


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Figure 6: Zoomed view of model

This model is then run a number of times in order to find a range of evacuation times. Experiments may then be performed in an attempt to reduce the evacuation time, perhaps by reducing the time for evacuees to become aware of the need for evacuation by installing a new alarm system, or by using fire marshalls to guide evacuations. Typical result plots, produced by the ISI output processor, are shown in figures 7 and 8.

DISCUSSION

In this paper, a number of computer-based techniques have been presented which assist both in assessing the safety of existing or proposed buildings, and in evaluating the relative merits of alternative evacuation procedures and policies. These techniques concentrate for the most part on determining optimal evacuation patterns which may then be used in order to suggest improvements to existing siutuation. An alternative approach known as Evacuation Behaviour Modelling has been reviewed. This approach seeks to reverse the typical sequence

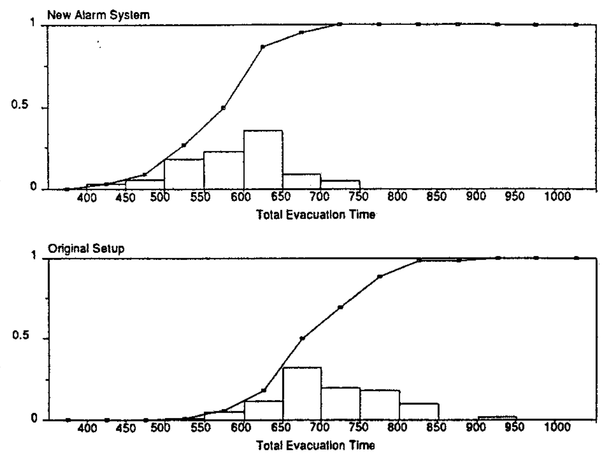

Figure 7: Histogram of evacuation times

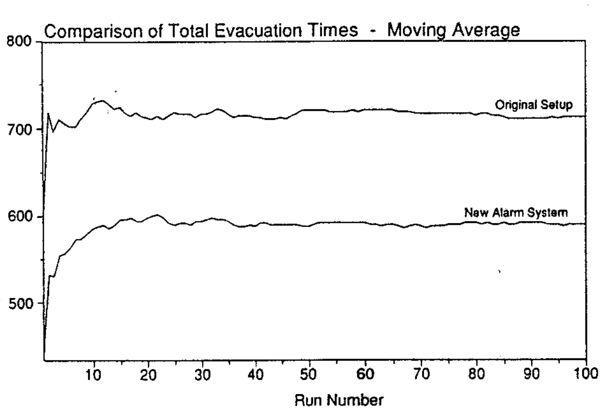

Figure 8: Total evacuation times

by modelling explicitly the variable factors in the real building. Executing the model many times with random inputs then reveals the combinations of chance factors which lead to problematic situations. Evacuation Behaviour Modelling is seen to offer some important advantages over other techniques.

Some of the advantages and disadvantages of applying general purpose discrete event simulation languages to Evacuation Behaviour Modelling have been explored. The high level of expertise and long lead times associated with typical simulation studies have been shown to be a major drawback in their application. A potential solution to this problem based on adopting a hierarchical approach to simulation has been presented.

The ISI interface to SIMAN general purpose simulation language has been presented. This software allows a hierarchical approach to be adopted in simulation studies, which is shown to have distinct advantages over alternative approaches. The example presented, which describes a typical evacuation problem, illustrates the ease with which complex models may be generated and meaningful simulations run using ISI and SIMAN.

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