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BSI Standards Publication

Fire safety engineering — Assessment, verification and validation of calculation methods

Part 5: Example of an Egress model

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National foreword

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Part 5:
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Partie 5: Exemple d'un modèle d'évacuation

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Contents

Page

Foreword

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The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

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The committee responsible for this document is ISO/TC 92, *Fire safety*, Subcommittee SC 4, *Fire safety engineering*.

ISO 16730 consists of the following parts, under the general title *Fire safety engineering — Assessment, verification and validation of calculation methods*:

— *Part 3: Example of a CFD model (Technical Report)*

— *Part 5: Example of an Egress model*

The following parts are under preparation:

— *Part 2: Example of a fire zone model (Technical Report)*

— *Part 4: Example of a structural model (Technical Report)*

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Fire safety engineering — Assessment, verification and validation of calculation methods —

Part 5: Example of an Egress model

1 Scope

ISO 16730-1 describes what the contents of a technical documentation and of a user's manual should be for an assessment, if the application of a calculation method as engineering tool to predict real-world scenarios leads to validate results. The purpose of this part of ISO 16730 is to show how ISO 16730-1 is applied to a calculation method, for a specific example. It demonstrates how technical and users' aspects of the method are properly described in order to enable the assessment of the method in view of verification and validation.

The example in this part of ISO 16730 describes the application of procedures given in ISO 16730-1 for an evacuation model (EXIT89).

The main objective of the specific model treated in this part of ISO 16730 is the simulation of the evacuation of a high-rise building with a large occupant population.

2 Normative references

The following documents, in whole or in part, are normatively referenced in this document and are indispensable for its application. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 16730-1, *Fire safety engineering — Assessment, verification and validation of calculation methods — Part 1: General*

3 General information on the evacuation model considered

The name given to the evacuation model considered in this document is "EXIT89". EXIT89 is a computer model developed to simulate the evacuation of a high-rise building with a large occupant population. Some of the features of the model include

— the presence of disabled occupants throughout a structure,

— random delay times among occupants to simulate the spread of start times that will occur in large groups of people,

— the choice of using shortest paths or directed routes for evacuation so that the user can demonstrate the impact of a trained staff streamlining evacuation vs. the crowded use of familiar paths by an untrained, unassisted population,

— counterflows, either to simulate the impact of the operations of the fire service or to handle merging flows or the presence of obstructions in the travel path,

— a choice of options affecting travel speed, and

— occupant travel up or down stairs.

4 Methodology used in this part of ISO 16730

For the calculation method considered, checks based on ISO 16730-1 and as outlined in this part of ISO 16730 are applied. This part of ISO 16730 lists in Annexes A and B the important issues to be checked in a left-hand column of a two-column table. The issues addressed are then described in detail and it is shown how these were dealt with during the development of the calculation method in the right hand column of the Annexes A and B cited above, where Annex A covers the description of the calculation method and Annex B covers the complete description of the assessment (verification and validation) of the particular calculation method. Annex C describes a worked example, and Annex D adds a user's manual.

Annex A
(informative)

Description of the calculation method

A.1 Purpose

Definition of problem solved or function performed	— it handles large, complex buildings; — it tracks large occupant populations over time; — combined with a smoke model, it can predict effects of fire spread on evacuation. The evacuation model was designed — to be able to handle a large occupant population, — to be able to recalculate exit paths after rooms or nodes become blocked by smoke, — to track individuals as they move through the building by recording each occupant's location at set time intervals during the fire, and — to vary travel speeds as a function of the changing crowdedness of spaces during the evacuation, i.e. queuing effects. Other features allow the modelling of travel both up and down stairs, as well as the effect of counterflows.
(Qualitative) description of results of the calculation method	— Output includes — total evacuation time, — floor clearing times, — stairwell clearing times, — exit usage, and — details on location of each individual over time.
Justification statements and feasibility studies	At the time the evacuation model was first written, evacuation models tended to treat building occupants like fluid in a pipeline, with no behaviours such as delays in responding to alarms, etc. These hydraulic-style models were useful in calculating optimal evacuation times but would consistently calculate times that were short and unrealistic. The only model that treated occupants as individuals (EXITT) was based on a family group in a home setting. There was a need to develop an evacuation model that would fit into the framework of HAZARD I, but allow its application to be extended beyond dwellings, to more complex structures like high-rise buildings. The evacuation model developed here is capable of tracking a large population of individuals as they followed exit routes through large and complex structures. The evacuation model uses a shortest route algorithm to move individuals, calculates travel speeds based on densities at building nodes (or spaces), and used the decision and tenability rules of EXITT concerning reaction to smoke. Over time, new features shown to affect evacuation time, such as counterflows, were added to the model. Delay times for individuals or occupant groups can be selected from uniform or log normal distributions.

A.2 Theory

Underlying conceptual model (governing phenomena)	Time to escape is based on distance to exits and walking speed. Walking speed is based on density, as well as occupant characteristics. Predtechenskii and Milinskii developed formulae based on observations of occupant movement in smoke-free environments, taking into consideration age (adult/child), dress (summer/midseason/winter), and encumberances (baggage/knapsack/package/child in arms). In their book, they printed a table showing the results of calculations for people moving on horizontal paths, and up or down stairs, at normal speed and at emergency speed. This table was incorporated into the model. Observations of actual evacuations have shown that delay times tend to follow a lognormal distribution. Sometimes, circumstances can result in all occupants in a space delaying evacuation for a similar period of time. Whether alone or in a group, each individual has his/her own starting time. Model users can specify their own distribution, setting the mean and standard deviation for a lognormal distribution, or min/max for a uniform distribution.
Theoretical basis of the phenomena and physical laws on which the calculation method is based	— network representation of building; — local perspective; — no explicit behavioural considerations (uses delay times); — walking speeds based on crowd densities; — option for shortest route calculations or directed paths; — smoke input from CFAST output can be used to block nodes during an evacuation. The evacuation model uses formulae for travel speed that are based on research conducted in smoke-free environments. There are no physical laws applied.

A.3 Implementation of theory

Governing formulae	Travel speed calculations Density of a stream of people, D, is: $D = Nf/wL$ (m²/m²) where N is the number of people in the stream; f is the area of horizontal projection of a person; w is the width of the stream; L is the length of the stream. Walking speed on a horizontal path, V, is: $V = 112D^4 - 380D^3 + 434D^2 - 217D + 57$ (m/min) For movement down stairs: $V\downarrow = Vm\downarrow$ (m/min) where $m\downarrow = 0{,}775 + 0{,}44e^{-0{,}39D\downarrow} \bullet \sin(5{,}61D\downarrow - 0{,}224)$ For movement up stairs: $V\uparrow = Vm\uparrow$ (m/min) where $m\uparrow = 0{,}785 + 0{,}09e^{3{,}45D\uparrow} \bullet \sin 15{,}7D\uparrow$ for $0 < D\uparrow < 0{,}6$; $m\uparrow = 0{,}785 - 0{,}10 \sin(7{,}85D\uparrow + 1{,}57)$ for $0{,}6 \leq D\uparrow \leq 0{,}92$. In emergencies, the fear that makes people try to flee danger raises the speed of movement at the same densities. $Ve = \mu e \bullet V$ where $\mu e = 1{,}49 - 0{,}36D$ for horizontal paths and through openings; $\mu e = 1{,}21$ for descending stairs; $\mu e = 1{,}26$ for ascending stairs. The maximum possible calculated walking speed under “emergency” conditions is 1,36 m/s and under “normal” conditions is 0,91 m/s. The minimum possible calculated walking speeds are 0,18 m/s and 0,15 m/s, respectively.
Mathematical techniques, procedures, and computational algorithms employed, with references to them	Delay times are set for each location by the user and then additional delay times can be randomly assigned to individuals. Delay times can be selected from a uniform or lognormal distribution defined by the user.

Identification of each assumption embedded in the logic; limitations on the input parameters that are caused by the range of applicability of the calculation method	The travel speed calculations by Predtechenskii and Milinskii assume a maximum density of 0,92. They describe this as “verified under actual conditions”. The formulae for travel speed were based on observations in smoke-free environments. Because of the arrays that store information for nodes and stairwells, there is a limit of up to 10 stairwells in the building and 89 nodes on each floor (outside of the stairwells). Currently, the model can handle up to 26 000 occupants in 10 000 nodes over 1 400 time intervals. The time intervals are set at 5 s. Delay time implementation assumes that people don’t stop moving once they’ve begun their evacuation. Counterflow implementation assumes that the two flows only shrink the available floor space (there is no other interference in movement). Shortest route algorithm does not allow occupants to vary paths once the routing has been set, until a blockage occurs somewhere on the floor. Travel on stairs assumes that people do not leave the stairs and don’t slow down or rest. Choice of distributions for delay times is limited to uniform and lognormal distributions. Appropriate ranges of delay times can be found in the literature (for example, Reference [1]). Many of these delay times are reported from observations at drills, not actual fire emergencies.

Discussion of precision of the results obtained by important algorithms, and, in the case of computer models, any dependence on particular computer capabilities	Travel distances are calculated by breaking the floor space in a building into defined nodes, and then defining paths from node to node. The size of nodes affects travel paths. Larger nodes result in fewer, longer, but less precise travel paths. Smaller nodes allow more precise paths, but there is a limit to the number of nodes that can be defined for each floor. Movement from node to node is calculated at pre-set time intervals. The size of the time step affects precision of movement. The default setting is 5 s. NOTE The model uses a random number generator in Visual Fortran v6.5. From the online documentation: "The RANDOM_NUMBER generator uses two separate congruential generators together to produce a period of approximately 10**18, and produces real pseudorandom results with a uniform distribution in (0,1). It accepts two integer seeds, the first of which is reduced to the range [1, 2147483562]. The second seed is reduced to the range [1, 2147483398]. This means that the generator effectively uses two 31-bit seeds."[21] For more information on the algorithm, see the following: — *Communications of the ACM vol 31 num 6 June 1988, titled: Efficient and Portable Combined Random Number Generators by Pierre L'ecuyer.* The model selects delay times from either a uniform or a lognormal distribution. The user determines the min/max for a uniform distribution or the mean and standard deviation for a lognormal distribution. There is little data available for observed distributions, so the user shall decide if the entered distribution is consistent with the observations reported in the literature.
Description of results of the sensitivity analyses	The largest body size option is 50 % greater than the smallest, but the calculated times might not vary that much. Larger body sizes result in a calculated density for a certain number of occupants that is larger than would be calculated with the same number of occupants with a small body size. The larger density results in slower travel speeds. But, if there are few people predicted to be in a given space, or if that space is large, the calculated density might not differ very much for different body sizes. As a result, then, the calculated travel times is fairly similar. NOTE 1 The travel times are valid only for smoke-free environments. NOTE 2 Luggage carried and goods left on the route can influence the predictive correctness of computed results in view of their applicability to real-world evacuations. A project to evaluate the predictive capabilities of computer egress models found that the evacuation model provided reasonably accurate predictions of total egress time for office and apartment buildings 6 to 15 stories in height, can underpredict the total evacuation time for abuilding if prior knowledge of the occupant load is not provided, and is sensitive to the number of occupants, the size option, and calculated travel speed.

A.4 Input

Required input	— network description; — body size (three choices; chosen size applies to all occupants); — emergency/normal speed; — path option; — smoke data, if any; — counterflows, if any; — delay (number affected and time distribution); — presence of disabled people. Counterflows can be modelled, but the user chooses the affected nodes and the times they are impacted. Shortest route algorithm adapted from Reference [16] can be a user choice.
Source of the data required	See annex for details.
For computer models: any auxiliary programs or external data files required	if smoke spread data is used as input
Provide information on the source, contents, and use of data libraries for computer models	None needed here

Annex B
(informative)

Complete description of the assessment (verification and validation) of the calculation method

(Quantitative) results of any efforts to evaluate the predictive capabilities of the calculation method in accordance with Chapter 5 of ISO 16730-1	Much of the testing done during model development to verify that the model performs the internal computations correctly was not documented. Errors that occur during that process were corrected. Where necessary and appropriate, comparisons between model predictions and available data were made. One such evaluation is described in this Annex. Four sample validation exercises
References to reviews, analytical tests, comparison tests, experimental validation, and code checking already performed. If, in case of computer models, the validation of the calculation method is based on beta testing, the documentation should include a profile of those involved in the testing (e.g. were they involved to any degree in the development of the calculation method or were they naive users; were they given any extra instruction that would not be available to the intended users of the final product, etc.)	Reference[2] Reference[3] (selected publications) Reference[4] Reference[5]
The extent to which the calculation method meets ISO 16730-1	The V&V process for this particular model meets the requirements of ISO 16730-1. Comment: ISO 16730-1 provides a good framework for laying out the features and characteristics of a model; however, — the process is easier to envision for a formula-based method and — model development in a field with scant data makes V/V process difficult. A.3 calls for a discussion of the precision of results obtained by important algorithms. In the case of this evacuation model, the source work (from Predtechenskii and Milinskii) doesn't discuss the precision of their analysis, and since the model would essentially be compared with observed evacuation times in real fires, little of which is precisely known, it is not possible to provide a discussion of precision for the model.

Annex C
(informative)

Worked example (modelling contra flows during building evacuations)

C.1 Summary

This Annex describes the application of EXIT89, a building evacuation model for complex structures, to a high-rise office building evacuation, illustrating the use of the newest features of the model (the ability to model the movement up stairs and to model the presence of contra flows.) In the drill that was the basis for this model validation exercise, very few of the building occupants evacuated using their closest exit. Most of them, travelling inside the building, headed directly to the exit that emptied out to the meeting area (outside one of the upper levels), even if that required them to climb stairs to reach that level, or ignore closer exits that would require that they climb a hill or use outside stairs to reach the assembly point. Congestion resulted near that exit almost immediately. When occupants travelling up stairs to that level met occupants travelling down stairs, they merged in the shared corridor space leading to the exit door. The new contra flow option and the new option to model movement up stairs were used to simulate the exit path choices of the building occupants and the effect of the two travel flows merging. The building was evacuated in 286 s, with most of the occupants out of the building within 220 s. The model predicted an evacuation time of 185 s, with a very similar distribution of exit use.

C.2 General

During the evacuation of a large, complex structure with a large number of occupants, it is possible that some occupants have to travel up, rather than down, flights of stairs to reach exits or safe areas. There are also several circumstances, including the operations of fire service personnel in stairwells, that can impede the progress of occupants as they make their way to the outside of the building or another area of refuge.

C.3 Contra flows

There can be times during an evacuation when the available width of travel for escaping occupants is reduced by, for example, others travelling in the opposite direction, firefighters, or firefighting equipment in stairwells, or other obstructions that have built up along the path.[6][7][8] The contra flow option allows the user to account for this.

When firefighters arrive at a building, they can enter a doorway that is being used by evacuating occupants. Firefighters then advance, with hose lines, up stairwells and through corridors, in the process reducing the path available for evacuees. The model calculates travel velocities based on the density of occupants at each location. Contra flows have the effect of narrowing the available floor space for occupants, thereby increasing the density of the crowd in that space and decreasing travel velocity of occupants there.

The effect of contra flows is handled in a manner similar to the handling of user-specified smoke blockages. The user can determine, based on predictions of fire department response and incident scene activities, the time(s) at which locations along escape routes is restricted, as well as the degree to which the locations are restricted. For example, if fire department operations are expected to restrict a stairwell by 50 % 8 min after the occupants are first notified of the incident, the user incorporates this estimate by selecting the affected stairwell nodes and inputting the degree of restriction and time of occurrence for those nodes. If nodes later open up again, the same method is used for returning the nodes to their original size.

This method was developed and incorporated into the model so that movement counter to the movement of the fire service could be predicted. There are other situations where such space restrictions can occur.

One is that clutter can accumulate in the stairways while occupants are evacuating. According to an evacuee in the World Trade Center incident, in response to a question about obstructions encountered during escape, “People scattered personal debris like an army in retreat.”[9] The contra flow option allows the user to specify the degree to which the stairway is constricted by entering the percentage of space at the node that remains available for evacuees.

Another situation is the one that can arise when the paths of occupants from one area of a structure converge on the paths of other occupants. For example, in a building with occupied floors above and below a grade level exit, occupants evacuating the building can meet on ground level, thus reducing each other’s access to a clear path of travel. An illustration of such an event is covered in this Annex.

This feature does not address the type of contra flows that occur when some evacuees (as opposed to firefighters) move against the general travel flow. Although this simplifying assumption results in a somewhat more efficient evacuation than might occur in real life, the complexity of an evacuation model increases significantly if an attempt is made to allow any or all occupants to change direction repeatedly throughout an evacuation. Also, data are not currently available on the amount of travel space restricted by contra flows, so the example presented later in this Annex uses a mid-range value of 50 %. Since the user directly controls the value used, a range of percentages deemed appropriate by the user can be tested. This feature needs evaluation at some stage, but the capability remains an important contribution to the model’s ability to simulate realistic obstructions that can develop during an evacuation.

C.4 Travel up stairwells

The original version of the model assumed that occupants were escaping from the upper floors of a high-rise building to ground level. In reality, many buildings have significant occupant loads below ground level. Also, in a phased evacuation, only the occupants of the floor of fire origin and the two floors above and below that floor need to be evacuated. Occupants above the floor of fire origin can be directed to move to a higher floor so that they are not required to pass the fire floor. The model was revised to allow movement *up* stairs. Although it has been observed in actual fires that occupants travel upwards when they should travel downwards, this is not the behaviour that this added feature seeks to address.

The following simplifying assumptions have been made:

a) either all occupants will travel on horizontal paths or down stairs, or they will all travel on horizontal paths or up-stairs;

b) for buildings with levels above and below grade, the model will be run twice (once for those above grade and travelling down and once for those below grade and travelling up. Occupants on the grade level should be included in both runs, since their travel will impact, and will be impacted by, the presence of those using the stairs);

c) if the results show that the occupants travelling down will interfere with those travelling up when they all reach ground level, that is, if the simulations show that the two groups reach common nodes at the same time, another run should be made using the contra flow feature addressed above, restricting each group’s travel path at the appropriate points in time.

The description of the building network is handled in essentially the same way, whether the direction of travel is up or down. If a structure were entirely below grade, Floor 1 would be the highest level, with the other floors numbered sequentially going down. The user would then indicate in the input for the simulation that the direction of travel on the stairs is upward. Travel speeds were calculated using the velocity formulae from Predtechenskii and Milinskii, who provide formulae for travel both up and down stairs, as well as under normal and emergency conditions.[10] For this example, the velocities for upward travel were accessed by the model. When upper floors are being modelled, with travel down stairwells, Floor 1 is the lowest floor. The upper floors are then numbered sequentially. When the user indicates that stairway travel is downward, the velocities for downward travel are accessed by the model.

The addition of this feature of the model allows its application to a more complete simulation of a complex structure. This includes structures that are built entirely below ground, as well as those that have occupied floors above and below grade level. It also allows the simulation of occupant movement in a building where staged evacuations are planned, where people located on floors immediately above the fire are moved higher in the building, while those immediately below the fire move downwards.

C.5 Validation example

The final step in the development of a simulation model is to check its usefulness by comparing its predictions to actual experience. To test these new features, the predictions of the model were compared to the results of a complete evacuation of a seven-story office building, where some occupants travelled up stairways to reach exits.

C.5.1 Design of the experiment

This evacuation exercise was conducted in a seven-story office building in Newcastle-on-Tyne by the Tyne and Wear Fire Brigade with the cooperation of building management.[11] It provides an opportunity to validate the use of the upward travel and contra flow options in the model.

This building was built into the side of a hill, with exits to the outside on the lower five levels. A parking lot (car park) outside the fifth level above grade was designated as the meeting point in case of evacuation, and that fact had been stressed to employees in the weeks leading up to the drill. The occupants were instructed to leave when the fire alarm sounded and assemble in the car park. They were not trained in the importance of using the nearest exit, and management did not direct them to the nearest exits.

During the drill, fire brigade personnel counted and timed the occupants using different exits and surveyed the occupants afterwards to find out where they started their evacuation, which exit they chose and how long they delayed before beginning their evacuation. The fire brigade also simulated a fire situation by blocking occupants' access to one of the stairways in the building.

The evacuation was conducted as part of building management's regular schedule of evacuation tests. The fire brigade was invited to observe, and took the opportunity to collect data as part of their own continuing study of emergency evacuations.

C.5.2 Results from the evacuation drill

According to the report on the evacuation exercise,[11] an interesting and unexpected travel pattern resulted. During the evacuation, very few of the occupants left the building using their closest exit. Most of them, travelling inside the building, headed directly to the exit that emptied out to the meeting area, even if that meant that they had to climb stairs to reach that level or ignore closer exits that would require that they then climb the hill or use outside stairs to reach the assembly point. This means that all occupants on that fifth level used the same exit, as did many of the occupants from the level below, after walking up the stairs to reach that level. Approximately five occupants on the next level below that also travelled up stairs to reach the meeting point by walking through the building. Congestion resulted near that exit almost immediately.

The data from this evacuation exercise provided an opportunity to test the two newest features of the model: travel *up* stairs and the contra flow option. The use of the first option is fairly obvious. People who travel down stairs to the exits were modelled using the default travel speeds for movement down stairs. People who travel up to higher levels to exits were modelled using the new feature. There can be situations where people travelling down stairs in a building can never encounter people travelling up to the same level to reach the outside. In this evacuation exercise, however, there was a period of time when both occupant flows were moving in the same space simultaneously. To handle the effect of these two travel flows merging, the new contra flow option was used.

Of the 381 participants in the evacuation exercise, 242 responded to a post-drill survey. The survey questionnaire asked participants how long they delayed before beginning their evacuation. This multiple choice question provided three options: 0 s to 5 s, 5 s to 30 s, and over 30 s. The floor plans provided to the author along with the report on the exercise indicated the location of the survey respondents, the exits they used, and the delay times they reported.[12]

C.5.3 Modelling effort

The nodes and floors for this building network were numbered from 1 (the lowest level) to 7. There were exits to the outside on Levels 1 (one exit), 2 (four exits), 3 (one exit), 4 (two exits), and 5 (the exit closest to the meeting place). The nodes were assigned to occupied spaces and along the pathways via corridors. (Corridors were subdivided into smaller spaces.) A sample node layout for Level 5 can be found in Figure C.1. The fire brigade's report on the evacuation showed the location of survey responders and provided estimates of the number of occupants on each level.[12] This information, along with details of stairway usage and travel patterns on the levels, was used to distribute the simulated occupants on each level.

The model calculates travel speeds based on the density of occupied spaces. In order to calculate the density, there are options for "body size" that provide the user with some choice in velocities. The user also chooses whether "emergency" or "normal" walking speeds will be calculated. (These formulae come from the Predtechenskii and Milinskii work referenced above). Because this incident was a drill, for which the occupants had been prepared, the largest body size option and the "Normal" speed option were chosen. This combination results in the slowest evacuation times in crowded spaces, should result in the most conservative outcome in terms of evacuation time, and would be expected to match well with the unhurried behaviour of occupants participating in an anticipated fire drill.

In the survey conducted after the drill was completed, occupants were asked how long they delayed before beginning to move to the exit. They were given three options: 0 s to 5 s, 5 s to 30 s, or over 30 s. The locations of the respondents who delayed more than 30 s were indicated in the report. Most occupants reported delaying no more than 30 s. For the simulation, occupants at locations where respondents delayed more than 30 s were assigned a 30-s delay. Additional randomly selected delays of 0 s to 30 s were assigned by the model to all 381 occupants in the simulation.

To illustrate the effect of different options in the model, two evacuation scenarios were run. They were

— the shortest route option, where the model calculates the closest exit to each occupied location, and

— the full simulation using travel up stairs and contra flows, where the travel paths were determined from the report on the evacuation exercise.

The first scenario provides a baseline for the evacuation time that might be expected if occupants used the nearest exit, although it is often not appropriate to assume that that behaviour will occur.[13] The network was defined as shown on the sample floor plan in Figure C.1 and the shortest route option was selected.

The second scenario, the simulation using travel up stairs and contra flows, had to be modelled in three phases, with each phase including two runs. The first phase was run to find the times when the occupants travelling down stairwells would encounter the occupants travelling up stairwells. The second phase accounted for the occurrence of contra flows at that point in time, and was run to find the times when the occupants travelling up and down were no longer sharing the same spaces. The third phase combined these results, with the contra option in play for the duration of time that the two flows were in the same spaces.

In the first run of the first phase, the building network included all occupants who moved downwards and/or horizontally to an exit. In the second run of that phase, only the occupants of Level 5 and those on Levels 3 and 4 who travelled up to Level 5 were included. Occupants of Level 5, therefore, were included in both runs because they would have contributed to the crowdedness of occupants travelling up or down stairs. (In no part of the evacuation exercise was it reported that occupants were simultaneously travelling up and down the stairs between two levels). The output files from these two runs were then checked to find the times when occupants travelling upward reached locations occupied by occupants travelling down or horizontally.

For the second phase, that pair of data sets was run again, this time with the contra flow option coming into effect at the times predicted when those travelling up stairs would reach spaces in use by those travelling downwards, and assuming that the space available to the competing flows was reduced to 50 %. Without data to indicate what degree of reduction would be appropriate, 50 % was selected as a mid-range option. The user can select any number between 0 % and 100 %. The outputs of these two runs were compared, this time to find the times when the flows ceased to compete.

The process of obtaining these times can be better understood by reviewing the detail on Table C.1.

The two simulations were run the third time with the contra flow option exercised at the affected locations for the span of time predicted by the first two phases. The results are presented in Table C.2, which shows the observations reported for the actual evacuation.

C.5.4 Results from the simulation

Table C.2 shows the observations from the evacuation drill in the first two columns. As mentioned earlier, the majority of occupants used the exit closest to the meeting place (Exit 10), resulting in congestion at that exit and longer evacuation times than at any other exit.

The next two columns show the evacuation times predicted with the shortest route option selected. This option simulates the type of result that could be expected if occupants had been trained, and were then directed, to use the nearest exit. The results show a dramatic redistribution of exit usage, reducing the usage of Exit 10 and greatly increasing the use of the exits near lower street levels. This result occurs because of the usage of stairwells in the building that would have brought people down to the exits at lower levels (Exits 3 and 4). These were the exits that were vastly underutilized during the evacuation exercise because evacuees would then have had to climb up a hill to reach the meeting point. The shortest route results reflect the influence that management and training can have on the outcome of an evacuation, compelling the movement of occupants to nearest exits. As shown by the congestion that occurred near Exit 10, where most occupants headed without any interference from staff, the investment in training and staff can be worthwhile in enhancing life safety.

Table C.1 — Steps in modelling the evacuation of the high-rise office building with contra flows

For this example, three sets of runs were required to model the impact of occupant travel up *and* down stairs to reach a common exit point. The first step was to determine at what point(s) in time the occupants travelling upwards would meet the occupants travelling downwards. Then, in a second set of runs, those times were used as the onset of contra flows that would impact ease of travel through those common nodes. An examination of the output from that set of runs was determined when the sharing of these common travel paths ceased. In a third set of runs, the times for the onset and cessation of common travel were used to bracket the effect of sharing the affected common nodes. Based on the definition of the travel paths set in the input, there was one node that would be used in common on the 4th level and six that would be used in common on the 5th level.
Phase 1: **Occupants travelling upward and occupants travelling downward were modelled separately.**
The resulting output showed the location of each occupant throughout the simulation. Inspection of the output showed that the first 3rd-level occupant reached one of the common 4th-level nodes at 30,1 s. The other common nodes were reached by 3rd-level occupants at 34,6 s, 71,2 s, 48,6 s, 37,5 s, 55,7 s, and 86,7 s, respectively. All of these nodes had already been reached by occupants descending from higher levels, so these times, rounded to the nearest second and then down to the nearest 5 s, were used in the next set of runs as the time contra effects began.
Phase 2: **Occupants travelling upward and occupants travelling downward were modelled separately again, but times with the effect of contra flows occurring at those common nodes at 30 s, 35 s, 70 s, 45 s, 35 s, 55 s, and 85 s, respectively.**
The resulting output was examined to find the times when occupants travelling from lower levels were no longer at the same nodes as occupants travelling down stairs. These times were observed to be 62,5 s, 102,7 s, 142,5 s, 108,3 s, 94,3 s, 127,3 s, and 151,4 s, respectively. All of these nodes were still in use by occupants descending from upper levels, so these times, rounded to the nearest second then up to the nearest 5 s, were used in the final set of runs as the time contra effects ended, and the node area available for egress returned to the originally defined size.
Phase 3: **Occupants travelling upward and occupants travelling downward are modelled separately again, but times for the effect of contra flows were set to start as in Phase 2 and to end at the common nodes at 65 s, 105 s, 145 s, 110 s, 95 s, 130 s, and 155 s, respectively.**
The results from this pair of runs provided the final simulation predictions for this example.

Table C.2 — Use of exits observed and calculated

	Observed		Predicted using calculated shortest routes		Predicted using contra flows and travel up stairs	
	Number of people	Time last exit used s	Number of people	Time last exit used s	Number of people	Time last exit used s
Exit 1	2	45,0	2	36,0	2	36,0
Exit 2	6	48,0	6	39,0	6	39,0
Exit 3	6	90,0	107	174,0	6	65,0
Exit 4	40	105,0	124	164,0	36	116,0
Exit 5	0	—	7	86,0	0	—
Exit 6	23	115,0	27	137,0	21	101,0
Exit 7	0	—	—	—	—	—
Exit 8	48	190,0	6	75,0	38	146,0
Exit 9	8	90,0	11	79,0	11	73,0
Exit 10	248	220,0	91	129,0	261	185,0
		last few at 286				
Total exited	381	286,0	381	174,0	381	185,0

The last two columns show the results of the runs using user-specified routes, travel up stairs and contra flows that account for the times when evacuees travelling up stairs encounter those who travelled down stairs. This simulation used the data collected during the exercise and attempted to move people toward the exits they reportedly used on that occasion. For that reason, the distribution of exit usage is closer to the observed usage than the shortest route example just discussed.

The results of this simulation compare quite well with the actual evacuation exercise, although the total evacuation time is under-predicted by 35 s. (The last few evacuees in the drill left the building 66 s after the majority of occupants). The variation in the number of occupants using each route is due to the variability in behaviour that real people exhibit (for example, travelling against traffic away from exits, changing direction during their evacuation) that this model does not simulate. The results are very good, however, and demonstrate the effectiveness of the model in simulating a complex evacuation pattern in a high-rise building.

C.6 Conclusion

The input data set developed for this validation example was intended to recreate the conditions present in the exercise to the extent possible, and very good results were obtained. If undertaking an evaluation of a building design, a user of the model would have to generate model predictions for a wide range of evacuation scenarios. For example, not knowing the distribution of occupants' starting positions, their mobility, or delay times, the user would run the model many times, varying these occupant characteristics in different combinations. Variations in exit availability, capacity, and use would also need to be modelled. The results of the simulations could then be plotted. An actual evacuation of the building should fall somewhere along the resulting curve.

The pre-movement times reported or derived in this and other evacuation exercises have been used as the basis for delay times in validation examples. For this example, delays of up to 30 s were randomly assigned to the occupants, some of whom were located at nodes where delays of 30 s had been set on the basis of survey results. As a result, some occupants in the simulation had total delay times of as long as 53 s. If the user wanted to simulate the potential effectiveness of a well-trained occupant population, the delay times could be reduced to a maximum of 30 s. This reduction might shorten the overall evacuation time, although in some cases it is possible that more congestion can occur sooner if starting times are not staggered. Running a simulation with this modification in the input data provides a prediction as to the actual impact of this change in delay times on the total evacuation time.

Further predictions of changes in evacuation results that might be expected with a better-trained and supervised occupant population are presented in Table C.2, where the results of a simulation using the shortest route option can be compared with the observations for the same high-rise building.

The department store evacuation[14] modelled in another paper[15] showed the effect of the occupants' use of emergency exits at the direction of staff. If a designer were unable to assume such staff actions, he or she would need to test the impact on evacuation times if the building population only used the exits with which they would be familiar. That evacuation simulation would show greater congestion at those familiar exits, with resulting increases in total evacuation time.

This discussion of the modifications to the input file, which would be necessary in evaluating a building design, is intended to illustrate the impact of the changes in assumptions for a wide range of evacuation scenarios. Since a range of representative evacuation scenarios was not conducted for each case study building, it is not possible to show the predictive capabilities of the model here for these scenarios.

This Annex describes just one of the evacuation exercises used to demonstrate the capabilities of the model.[15] These case studies were selected because they were particularly well-documented and their simulation would demonstrate the major features of the model. The modelling was done against actual data in an attempt to recreate the results observed in the exercise. If using the model in the context of design evaluation, a user would need to run additional scenarios. For example, the simulation described in this Annex was based on an evacuation exercise where one of the stairways was made unavailable to the occupants. If the design of this building was being evaluated, it would have been appropriate to remove each stairwell in succession, in order to examine what impact that would have. This sort of evaluation was not done in this part of 16730, as no actual observations were available for comparison.

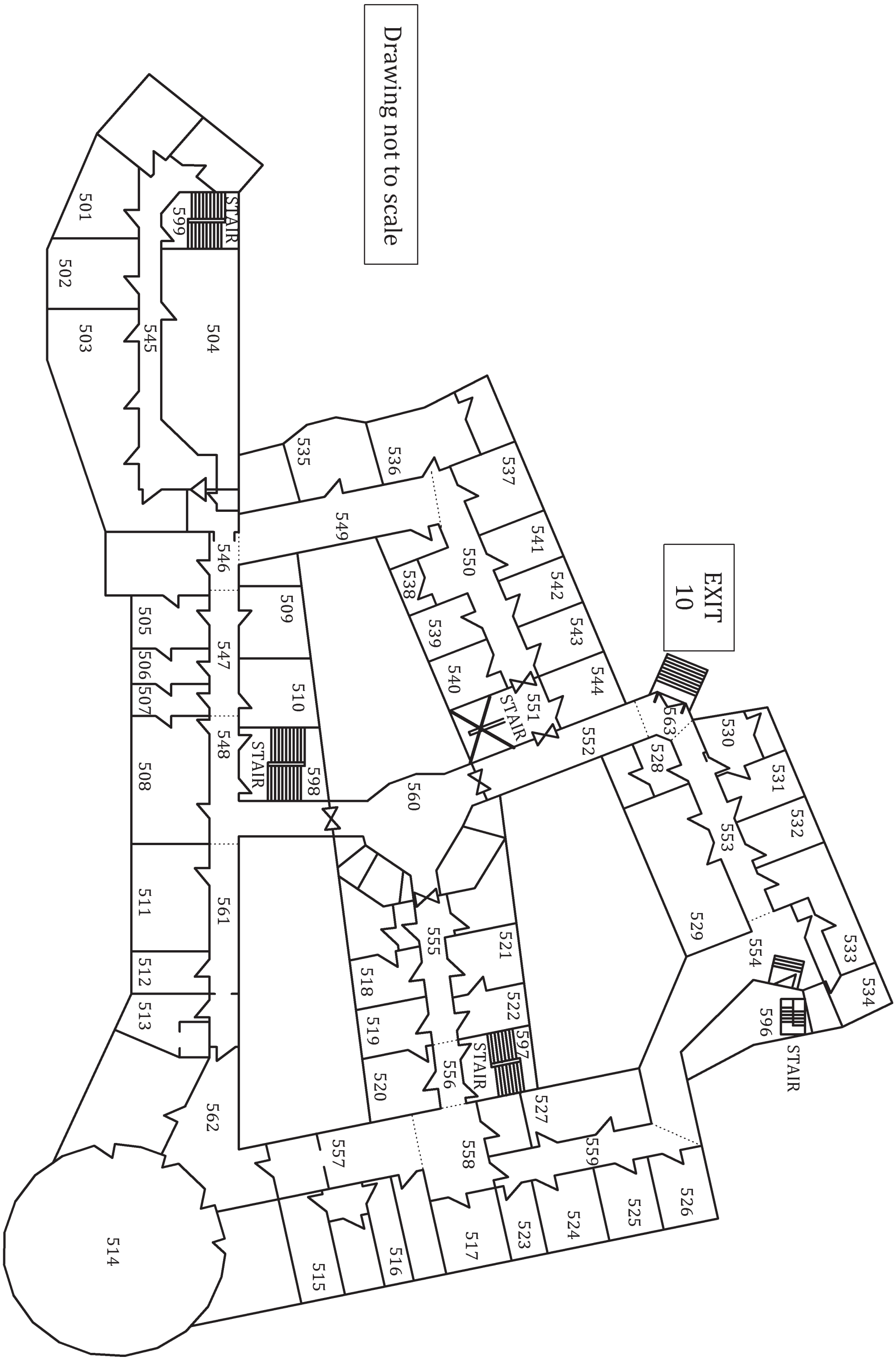


Figure C.1 — Floor plan, with network nodes, for Level 5 of the high-rise office building with upward travel and contra flows

Annex D
(informative)

User's manual

D.1 Description of the program

This model requires as input the network description of a building, geometrical data for each room or defined space and for openings between these rooms or spaces, and smoke data if the effect of smoke blockages is to be considered. It either calculates the shortest route from each building location to a location of safety (usually outside) or reads in user-defined routes through the building. It moves people along the calculated or defined routes until a location is blocked by smoke. Affected exit routes are recalculated and people movement continues until the next blockage occurs or until everyone who can escape has reached the outside.

Evacuation can begin simultaneously for all occupants or can be delayed, with delays set for each node. Additional delays can be randomly assigned to occupants using either a uniform or lognormal distribution defined by the user. Smoke data can be used to predict when the activation of a smoke alarm would occur and evacuation will begin then or after some user-defined delay beyond that time. Disabled people can be included among the occupants of the building. If contra flows or other path obstructions develop during evacuation, that also can be modelled.

The program was written originally in FORTRAN to run on an IBM mainframe. A PC-version was developed by Daniel Alvord at the National Institute for Standards and Technology Building and Fire Research Laboratory. The PC-version has the capability to read in CFAST-generated smoke data.

D.2 Technical discussion

D.2.1 Characteristics and assumptions of the model

The model was developed to serve as the evacuation model in HAZARD I for applications involving large and high-occupancy buildings, such as high-rises. It was designed

1) to be able to handle a large occupant population,

2) to be able to recalculate exit paths after rooms or nodes become blocked by smoke,

3) to track individuals as they move through the building by recording each occupant's location at set time intervals during the fire, and

4) to vary travel speeds as a function of the changing crowdedness of spaces during the evacuation, i.e. queuing effects. Other features were added later to allow the modelling of travel both up and down stairs, as well as the effect of contra flows.

The size of the building and its population that can be handled is limited by the size of the storage arrays. The dimensions of the storage arrays currently allow for up to 26 000 occupants in a total of 10 000 nodes or building spaces on up to 100 floors, over 1 400 time intervals. These can be changed by the user to handle larger problems. Due to the naming convention for nodes that the program relies on, each floor can have up to 89 nodes and the building can have up to 10 stairways.

The model has a local perspective rather than a global one, meaning that people do not have knowledge of events on other floors. If and when smoke blockages occur, evacuation routes are changed only on the affected floors.

Another assumption is that once people enter a stairwell, they will stay in that stairwell until they reach the discharge point from the stairwell, unless it becomes blocked by the fire's progress, in which case they will move out of the stairs and onto the nearest floor. In real situations, people can head for the roof or leave the stairs to go onto lower floors for no apparent reason.

Evacuation can be modelled from upper floors downward, or from lower floors upward. For example, if modelling the evacuation of a structure with floors above and below grade, the evacuation of the upper floors can be modelled with occupants travelling to lower floors and out. The below grade floors would be modelled separately, with occupants travelling to the floor of discharge and out.

The model does not explicitly include the behavioural considerations that are included in some other evacuation models. These behaviours include investigation of the fire, rescue of small children, alerting or waking other capable adults, and assisting other occupants who might require help. Since the model was designed to handle high-rise buildings or smaller buildings with large populations, the author decided to have the user assign the delay times at each occupied space in order to reflect the wide range of activities that could be taking place in a building under consideration and variations in the readiness or ability of the occupants to make decisions to evacuate. Additional delays can be assigned randomly to individuals. The user determines the percentage of occupants to have these added delays and can choose whether the times follow a uniform or lognormal distribution. D.2.3 describes the process to follow to use this option.

Walking speed in the model is calculated as a function of density. How this is handled is discussed in D.2.4. Disabled occupants are modelled by setting their walking speed as a user-specified percentage of the model-calculated "normal" walking speed.

The input to the model includes a network description of the building. Nodes can be rooms or sections of rooms or corridors, whichever result in the most realistic travel paths. The nodes defined, though, should correspond to the rooms or a subset of the rooms described in CFAST, if CFAST output is used as the smoke data input for the model.

The definition of each node includes its usable floor area, the height of the ceiling, the capacity of the node, its initial occupant load, the number of disabled occupants at that node, the number of seconds occupants of that room will delay before beginning evacuation, and the node occupants will move to if the user chooses the option of having occupants move along defined routes. The definition of each arc includes the distance between nodes and the width of the opening between the nodes. Arcs are bi-directional so a connection between two nodes only has to be described once.

For modelling the effects of smoke, the model can be used in two different ways. The user can input the names of nodes that become blocked by smoke and the time those blockages occur. Or, the user can take the smoke data output from CFAST as input to the model. CFAST calculates and writes to a disk file the optical density of the hot upper layer at each node at each time interval and the height from the floor of the cooler lower layer. In the first case, evacuation begins throughout the building at time 0, plus any delay time specified at nodes by the user or randomly assigned by the model. In the second case, evacuation begins throughout the building when the smoke level reaches that defined for smoke alarm activation, plus any delay time specified at nodes by the user or randomly assigned by the model. By not specifying any blockages, the user can model evacuation of a building with no fire occurring.

The program can print out the movement of each occupant from node to node. It also records the location of each occupant at each time interval so that the output can be used as input to a toxicity model such as TENAB. TENAB calculates the hazards to which each occupant was exposed using CFAST output for combustion products and determines when incapacitation or death occurs. The user can suppress this output and have the model only print out a summary showing floor clearing times, stairway clearing times, and the last time each exit was used and how many people used each exit.

D.2.2 Shortest route calculations

The user has the option of specifying the routes occupants will take or using shortest routes calculated by the model. The shortest route option would be an appropriate way to model an evacuation with a well-trained population or with well-trained staff assisting, since it will move occupants to the nearest exit.

Shortest routes are calculated for each floor, from each node to the stairways or to the outside. The shortest route algorithm used is that described in Reference [16] as the shortest and simplest of those they reviewed. The algorithm begins by identifying the origin of a network and then fans out from the origin, identifying the shortest routes to all the other nodes until the destination is reached.

The adapted version of the algorithm used in the model is described below. The model calculates the shortest routes on each floor to the stairways or the outside or other locations of safety. Locations of safety can include horizontal exits or areas on the other side of fire doors. In order for the model to recognize these locations of safety, the user identifies them as part of the building description input data. These nodes are referred to as intermediate exits (IEs) in the following discussion. An array is created which consists of the connected node that occupants at a given node will move to in evacuating the building. For example, if the path from node 102 to the outside goes through nodes 104 and 107, then the connected node for 102 is 104, the connected node for 104 is 107, and the connected node for 107 is the outside. The route down each stairway is then established by defining the connected node for each stairway node as the one below it.

The shortest route subroutine begins by identifying all the IEs on a floor of the building. These nodes are placed on the list of *solved nodes*.

Step 1 Identify all unsolved nodes connected to the solved nodes.

Step 2 For each of the unsolved nodes identified in Step 1, calculate the distance between the unsolved node and its connected solved node(s) and add that distance to the distance from the solved node to its closest IE.

Step 3 The unsolved node with the shortest distance to the IE is added to the list of solved nodes; its connected node is that solved node and its distance to the IE is stored.

Return to Step 1 until all nodes are solved.

This is repeated for each floor.

One advantage of the approach used in the model is that the blocking of a node by smoke only requires the recalculation of the routes on that floor, rather than all routes throughout the building. If a stairway node is blocked by fire, the routes on that floor and the floor above will be recalculated. This causes occupants in the stairway on higher floors to move out of the stairway when they reach the node above the smoke-blocked node.

Another advantage of this approach is that it more closely approximates the local perspective of an occupant in the building. Other shortest route routines “see” all possible routes to the outside and so they make decisions based on information not available to a real person.

The user also has the option of naming the node to which occupants will move from each node in the network. It is often observed in actual evacuations that people follow the route they are most familiar with and this option allows the user to model that behaviour. It also allows the user to model travel observed in an evacuation. If that option is used and a node becomes blocked by smoke, the routes on the affected floor(s) will be recalculated using the shortest route subroutine.

D.2.3 Adding optional delay times

Additional delays can be assigned to individuals, according to the random distribution chosen by the user. These delays can be assigned to any proportion of the occupants in the building. For a uniform distribution, the user sets the range (minimum and maximum values) for the distribution. For the lognormal distribution, the user sets the mean and standard deviation of the distribution. Sample lognormal distributions are shown in D.7.

D.2.4 Calculation of walking speeds

The method chosen for the model uses walking speeds calculated as a function of density based on formulae from Reference [17]. Body size is included in their density calculations. Using dimensions of people (adults, youths, and children) in various types of dress, both empty-handed and encumbered with packages, knapsacks, baggage, or babies, they calculated the area of horizontal projection of a person. This measure is the area of an ellipse whose axes correspond to the width of a person at shoulder level and breadth at chest level. Tables of mean values for different age groups and types of dress are given in the text. Their formula for density of a stream of people, *D*, is:

$$D = Nf/wL \text{ (m}^2\text{/m}^2\text{)} \quad \text{(D.1)}$$

where

N is the number of people in the stream;

f is the area of horizontal projection of a person;

w is the width of the stream;

L is the length of the stream.

Their model established a maximum density of 0,92. Although a higher density can be observed in real situations, 0,92 is the maximum they used in empirical expressions for walking speeds. Based on their observations recorded in thousands of situations, they developed the following formulae for normal circumstances. For the mean values of velocity as a function of density for horizontal paths:

$$V = 112D^4 - 380D^3 + 434D^2 - 217D + 57 \text{ (m/min)} \quad \text{(D.2)}$$

for $0 < D \leq 0{,}92$

For movement down stairs

$$V{\downarrow} = Vm{\downarrow} \text{ (m/min)} \quad \text{(D.3)}$$

where

$m{\downarrow} = 0{,}775 + 0{,}44e^{-0{,}39D{\downarrow}} \bullet \sin(5{,}61D{\downarrow} - 0{,}224)$

For movement up stairs

$$V{\uparrow} = Vm{\uparrow} \text{ (m/min)} \quad \text{(D.4)}$$

where

$m{\uparrow} = 0{,}785 + 0{,}09e^{3{,}45D{\uparrow}} \bullet \sin 15{,}7D{\uparrow}$ for $0 < D{\uparrow} < 0{,}6$;

$m{\uparrow} = 0{,}785 - 0{,}10 \sin(7{,}85D{\uparrow} + 1{,}57)$ for $0{,}6 \leq D{\uparrow} \leq 0{,}92$.

In emergencies, such as earthquakes or fire, the fear that makes people try to flee danger raises the speed of movement at the same densities. Predtechenskii and Milinskii found the following relationship between the two velocities:

$$V_e = \mu_e \bullet V \tag{D.5}$$

where

$\mu_e = 1{,}49 - 0{,}36D$ for horizontal paths and through openings;

$\mu_e = 1{,}21$ for descending stairs;

$\mu_e = 1{,}26$ for ascending stairs.

Repeatedly calculating velocities using these formulae for every occupant throughout a fire simulation would be extremely time-consuming. Fortunately, tables of velocities by density were given for normal, emergency, and comfortable movement along horizontal paths, through openings and on stairs. The model allows the user to select between normal and emergency velocities.

The area of horizontal projection of a person estimated from Soviet data are 1,217 3 ft^2 (0,113 0 m^2), the mean dimensions of an adult in mid-season street dress. The user can select other values from measurements of Austrian and American subjects. (See D.2.5 for details on body size data). Velocities are calculated for both segments of the arc between two nodes, based on the different densities and floor areas for the two nodes. If a value for D greater than 0,92 is calculated, D is set equal to 0,92. The value calculated for D is used to look up the velocity from the tables. The table holds velocities along horizontal paths and up and down stairs.

The model does not simulate occupants crawling through smoke by reducing their travel speed. This can be done by exercising the contra flow option described below starting at the time when such smoke conditions occur.

D.2.5 Body size data

Predtechenskii and Milinskii's work used body sizes calculated from the measurements of Soviet subjects. Subsequent work, Reference [18], using Austrian subjects found significant differences in the results. The value of 0,113 0 m^2 described above compares to the Austrian result for subjects between the ages of 10 years and 15 years without coats. The value for Austrian subjects between ages 15 years and 30 years wearing coats was 0,186 2 m^2 and without coats was 0,145 8 m^2. The value for adults over age of 30 years without coats was 0,174 0 m^2.

A table of mean body dimensions representative of US male and female workers between 18 years and 45 years of age was obtained from *Occupational Safety and Health in Business and Industry*. From this table, mean values for shoulder breadth (0,455 m for men, 0,417 m for women) and chest depth (0,231 m for men, 0,234 m for women) were obtained. In order to add the additional bulk of clothing, the table of Soviet data were checked. That table included values for summer dress, mid-season street dress, and winter street dress. The values increased by 0,02 m between each category of clothing. Based on this, then, the American values for shoulder breadth and chest depth were increased by 0,02 m. To obtain one "American" value for horizontal projection of a person, the mean values for men and women were averaged. The resulting value was 0,090 6 m^2, far smaller than that calculated for Soviet or Austrian subjects. The choice between the three sets of data is an input option set by the user. Evaluation of simulation results have shown that the longest, most conservative evacuation times under crowded conditions result from using the Austrian value option. All three should be used in order to obtain a range of results for a given data set.

D.2.6 Smoke levels

As mentioned above, there are two ways to handle smoke. In the first, the user determines at what node and when blockages due to smoke will occur. In the second, smoke densities and depths of smoke layers are read in from a file created by CFAST. Using the same method as EXITT[19] of calculating the psychological impact of smoke, S, Formula (D.6) is used:

$$S = 2 \times OD \times D/H \tag{D.6}$$

where

OD is the optical density of the smoke in the upper layer;

D is the depth of the upper layer;

H is the height of the ceiling.

EXITT uses $S > 0{,}5$ to stop an occupant and $S > 0{,}4$ as a threshold to prevent entering a room, in both cases unless there is enough clear air in the lower layer to crawl. Since this model does not yet handle crawling, a value of $S > 0{,}5$ is used to block a node which traps everyone currently at that node.

Smoke alarms operate when $S \geq 0{,}015$ and the depth of the upper layer is greater than 0,5 ft (0,15 m). The model currently assumes that notification of all occupants occurs when levels needed for smoke alarm activation are reached at any node, and evacuation begins after any user-specified delays. Refinements of the program to define the range of a smoke alarm and to otherwise modify the rules determining the notification of occupants have not yet been done.

D.2.7 Contra flows

In modelling a fire situation, it is often too simplistic to assume that evacuees will flow unimpeded down the stairwells. Fire service personnel use the stairs to gain access to upper floors and often need to lay hoselines up the stairwells while occupants are leaving. In these cases, it is important for a model to allow for such contra flows.

If contra flows occur, the user shall determine in what locations they will occur and at what time. The degree to which the area of a node is constricted shall also be estimated by the user. In the simplest cases, the contra flow option is exercised in stairwell nodes at times estimated for fire service movement up the stairwell. And it would be reasonable to reduce the area of stairwell space available to evacuees to no more than 50 %.

This option can also be used to simulate other situations where occupant flow through a node or series of nodes will be impeded. Such situations can arise when debris scattered by escaping occupants clutter the path, slowing occupants, or when smoke conditions might force occupants to crawl. These situations would be treated in the same way as contra flows (the user enters in the input file the nodes that are affected, the times that the effect occurs, and the change in available area at those nodes).

D.2.8 Moving the occupants

When the user chooses the shortest route option, the initial shortest routes throughout the building are calculated before any smoke data are read in. Where the user enters the location and time of smoke blockages, notification to begin evacuation occurs at time 0. If the user uses CFAST data, the model reads in the smoke data and determines where and when blockages would occur and when smoke alarm activation would occur and evacuation would begin.

The model begins by calculating, based on the initial distribution of occupants, how long it would take to travel from each occupied node to its connected node. Then, for each occupant, it looks at how long that occupant has been at that node and how long it takes to traverse the arc. If the occupant has been waiting long enough to traverse the arc, the occupant is moved to the next node, and the waiting time at that node is set to 0. Waiting times are actually portions of the arc traversal times. If there are still occupants in the building, the model recalculates time to traverse arcs based on the updated densities at nodes.

The sequence is repeated until the time is reached when a node is blocked by smoke. At that point, the affected node is removed from the network, any occupants at that node are counted as trapped, and shortest routes are recalculated for the affected floor (or floors if the node is in a stairway). People movement is then resumed until the next blockage or until everyone is either out or trapped.

Queuing is handled by the decreased walking speeds that result from increased densities as more occupants move into a room or stairway. The program does not allow occupants to select less crowded routes. They simply join the queue at nodes along the shortest route.

D.3 Developing the input

The process of converting information about the building and its occupants into an input file the program can read is described in this subclause. The input file format is described in D.5. The list of program variables can be found in D.6. The smoke output from CFAST, if used, is written to a file that is read in by the model.

The first line in the input file is a 72-character title line that the user can use to describe the model that is being run. The next several lines allow the user to select among several options. First, the user indicates whether the measurements in the input are metric or standard. Next, the user picks the body size measurement to be used in the density calculations. The next option allows the user to specify whether occupants will be travelling at emergency or normal (slower) velocities. Next, the user indicates whether the program should calculate the shortest paths between nodes or whether the user will be specifying the node to which occupants will move from each node. Next, the user indicates whether there will be data from CFAST (option 1) or whether there will be user-defined blockages or no blockages at all (option 2). The next option allows the user to indicate whether or not the contra flow option will be used. Next, the user selects full output, which prints out every time someone moves from one space to another, or summary output. On the next input line, the user enters the number of stairways there are on the floor plan. And finally, for that section, the last option indicates whether the user is modelling evacuation *down* stairs or modelling evacuation from below grade *up* stairs.

On the next three lines, the user indicates whether or not additional delay times should be randomly distributed among the occupants. If yes, the user then specifies for what percentage of the occupants there will be additional delays and whether the times will follow a uniform or lognormal distribution. The user specifies the range of time (in seconds) those delays should be chosen for a uniform distribution or the mean and standard deviation for a lognormal distribution.

D.3.1 Building network

The next section of the input stream holds the network description of the building layout. Constructing the building network is the most complicated and time-consuming part of setting up the data stream. A network is a collection of nodes connected by links or arcs. The nodes represent locations in the building and the links represent the travel paths along the network. A floor plan of the building is required in constructing the network.

The first step is to decide where the nodes should be placed. Not all spaces in the building need to be included, but areas not included are not considered in the evacuation. Unoccupied areas such as storage rooms, or spaces through which evacuees will not pass, do not need to be described.

Usually, each compartment is represented by a node, although large spaces should be represented by more than one node when doing so allows a more realistic representation of travel paths without excessively increasing the size of the network. For example, in a hotel, a long corridor with several rooms opening onto it would have more than one node describing the sections of the corridor. Common sense is an important criterion in determining node placement, but it is also possible to test the appropriateness of the placement by using data from fire drills. Too many nodes unnecessarily clutter the network and increase the program’s execution time. Too few nodes can result in unrealistic travel paths and a loss of detail in the output.

Usually, nodes are placed in the centre of the location they describe; however, in a complicated floor plan, it can be appropriate to place the node off centre. For example, where corridors intersect, although it is possible to create a node strictly at the intersection and have the adjacent corridor sections be separate nodes, it might also make sense to create a corridor node that includes the intersection and place the "centre" in the intersection. As long as all travel paths through that node will pass through that "centre", the travel paths calculated will be realistic. (This will often be necessary if the user is limited by the maximum 89 nodes that can be defined for a floor). A node can also be placed at a point in the space further from the next space, if that would provide a more conservative estimate of travel time in the space.

For stairways, the centre of the node is taken as the stairway landing at floor level. The boundaries of a stairway node are the landings halfway up to the floor above and halfway down to the floor below.

Once the nodes have been positioned in the spaces they describe, the network input section can be developed.

The node names are three- or four-digit integers where the first one or two digits are the floor number and the last two digits uniquely number the spaces on that floor. Numbers 90 to 99 are reserved for stairways. There can be up to 89 occupant spaces on each floor. Locations of safety, including outside the building, are named "000". (When the user is modelling travel up stairs, and the shortest route option is selected, the highest level floor is treated at Floor 1 and the other floors are numbered sequentially moving downward. When modelling travel up stairs and using the directed route option, the model is not sensitive to floor numbering).

Each arc on the network is described by the two connected nodes, the distance from the first node to the opening between the two locations (called XLNGS1), the width of the opening (called RESWTH), and the distance from the opening to the second node (called XLNGS2).

The procedure for computing these distances is as follows.

a) The nodes are placed in the spaces they represent.

b) The opening is the dividing line between two connecting spaces. Between two compartments, the opening width would be the width of the doorway. For two nodes along the corridor, the opening width would be the width of the corridor. If a large room is divided into two or more spaces, the opening width is the width of the room along the invisible line dividing these spaces.

c) For horizontal paths, the lengths of the two segments of the arcs are measured in straight lines from the node to the centre of the opening.

The following method from Predtechenskii and Milinskii should be used to calculate paths on stairways.

For calculating the length of the inclined path, L,

$$L = L'/\cos \alpha \tag{D.7}$$

where

L' is the horizontal projection of the length of the inclined path;

α is the angle of inclination to the horizontal.

Since most slopes are between 1:1,75 and 1:2, with an angle between 30° and 32°, the value of cos α is approximately 0,85.

For two-flight stairs,

$$L = 2L'/\cos\alpha + 4b \tag{D.8}$$

where

b is the length of the landing (width of path).

For three-flight stairs,

$$L = L'(3/\cos\alpha + 1) + 4b \tag{D.9}$$

If the slope is less than 1:8, it can be considered horizontal.

In constructing the network, a decision has to be made as to whether the situation to be modelled will use only legal or allowed means of egress, or if any means used or likely to be used is included.

The description of the links can now be added to the input section. The links can be entered in any order. Whether travel along a path would be bi-directional or one-way, each link should only be entered once.

The link description is entered in this way:

INODE is the from-node;

XLNGS1 is the distance from the first node to the centre of the opening;

RESWTH is the width of the opening;

XLNGS2 is the distance from the centre of the opening to the second node;

JNODE is the to-node.

The end of this segment of the input file is indicated by a record showing a from-node called 99999 with all associated entries coded as zeroes.

D.3.2 Node descriptions

The second part of the network input consists of the node descriptions. Each description includes the node name, its usable floor area, the height of the ceiling, the number of people that space can hold (not used yet so any value can be entered), the number of people at that node when the evacuation begins, the number of people at that node who are disabled, a flag that indicates whether or not the node is an IE, the amount of time occupants at that node will delay evacuation (in seconds), and the node occupants of that room will travel to if directed routes are used instead of calculated shortest routes. Any node connected to a location of safety, any node not on the ground floor that is part of the stairway, and ground-floor nodes that connect to the outside are indicated by setting the IE flag equal to one. Otherwise, the flag should be zero.

When the user indicates that one or more of the occupants at a node are disabled, a value is entered that indicates at what percentage of the calculated speed for an able-bodied person a disabled occupant will travel. A different percentage can be entered for each person.

The node descriptions shall be entered in ascending order in this way:

N is the node being described;

NAREA is the usable floor area at that node;

H is the height of the ceiling at that node;

NCAP is the capacity of the node;

NOCC is the number of people there initially;

ND is the number of disabled people;

IE is the flag;

EVACTM is the time that occupants of that node will delay before beginning evacuation;

ITO is the node along a directed path that occupants will move to (optional).

There has to be one record for each node mentioned in the list of network links.

If any occupants of a node are described as disabled, an input line shall follow the node description giving the percentage of “able-bodied” speed that each disabled occupant will travel. Up to 15 disabled occupants at that node can be described on each line.

D.3.3 Entering blockages by user

If a smoke spread file from CFAST is not available, the user can enter smoke blockages. In that case, at the end of the input data, the user enters the name of the blocked node and the time from the start of evacuation that the blockage occurred (in seconds). More than one node can be blocked at a time. To indicate the end of this section of the input, the user should enter a final record with 99999 for each entry.

To model the evacuation with no fire, the user just enters that last record.

D.3.4 Using smoke data from CFAST

CFAST is restricted to using a much smaller network than this model. Because of that, the user shall exercise some caution in setting up the runs so that the output from CFAST is compatible to the input file. First, the time step used in CFAST shall be 5 s, as this model cannot now interpolate between its primary time step of 5 s and a different one used in CFAST. The user also shall specify the mapping that matches each CFAST compartment to the corresponding building node of this model. Since this model only requires a ceiling height and a usable floor area to define a node’s physical structure, while more detailed information is used to define a CFAST compartment, this should not be a problem.

This model reads the CFAST output file, checking for each CFAST node the smoke densities in the upper layer and the level of the upper layer at each time step to calculate in order to determine, for the corresponding nodes, the time of smoke alarm activation and node blocking as described in D.2.5.

D.3.5 Entering effects of contra flows

This input section is only required if the user has set the flag at the beginning of the input file to indicate that contra flows will occur. Contra flows have the effect of reducing the available floor space for occupants, therefore increasing the density and reducing travel velocities. This is handled in a manner similar to the handling of user inputted smoke blockages. The user can determine, based on a predictions of fire department response and incident scene activities, the time(s) at which locations along escape routes will be restricted, as well as the degree to which the locations are restricted. If routes open up later, when the contra flow ceases, the nodes can be set back to original areas.

If the user simulates a contra flow that restricts the area of a node by 50 %, the value entered for the restriction effect is 0,50. If after some period of time the obstruction disappears, the user enters a value of 2,0 at that time to cause the area of the node to increase back to its original size.

D.4 Logic flow of the model

This subclause describes briefly the logic of the model. The program begins by printing some identifying information, displaying the options selected by the user and the probability data, if any, to be used to calculate random delay times for occupants.

The list of network links is read in next. After each link is read into the array where they are stored, the reverse direction along the link is stored in the array. Only links to the outside are not reversed. These arrays are then sorted in order by from-nodes.

The node descriptions are then read in. An array of occupant locations by time interval is created using the number of occupants at each node. The array of times to delay evacuation is also created at this time. If the user specified that some occupants at a node are disabled, the program then reads in the percentage of "able-bodied" speed at which each such occupant travels. These percentages are storied in an array called SFR. The value stored for able-bodied occupants is initialized at 1,0. The program prints out the identity and initial location of each disabled occupant and that person's SFR value.

If the user selected the option of randomly assigning additional delays to a percentage of the occupants, that is done in the next section. The program then prints out the total delay time for each occupant.

If the user selected the option of having the model calculate shortest routes, the program then calculates the shortest paths on each floor to stairways or to the outside, based on the network description that was read in. Paths on stairways are then set. Since all nodes in a stairway end with the same two digits, this subroutine simply links, for example, node 398 to node 298 and node 298 to node 198 to move occupants up or down the stairs.

If the user is manually entering the location and time of smoke blockages, these data are read in and an array that stores the conditions at each node over time is updated to record the blockage. If the data are read in from CFAST, the psychological impact of the smoke is calculated to determine if blockage has occurred. When it does, the array of conditions at each node is updated. The time that smoke alarm activation would occur is also stored in that array. If the user entered a delay in evacuation for occupants of that node, that entry will be modified so that it represents the delay after smoke alarm activation.

If the user has determined that contra flows will occur, the next input section includes a list of the affected nodes, the time at which they are affected, and the change in available area at those nodes at those times.

The final part of the processing in the input section of the model is a subroutine that checks the travel paths for both user-defined egress and shortest paths to make sure that all nodes reach the outside. This routine identifies loops that would prevent occupants from ever reaching the outside.

The evacuation then begins. The program checks the array of hazard levels throughout the building until it finds a location where the smoke levels block a node. The program then moves the occupants as described in D.2.6 along the defined or calculated shortest paths until the time when a node is blocked. The program then removes from the network all nodes blocked at that time and recalculates the shortest routes on the affected floors. The program then checks for the next time interval when a node is blocked, repeating the cycle until all occupants have escaped or are trapped.

If contra flows occur at any time during the simulation, the area of the affected node(s) will be changed at that point, based on the restriction effect entered by the user.

D.5 Input file format

This subclause describes the format of the input data stream, in summary form. It contains the FORTRAN formats for the input used in the mainframe version, and information concerning the order in which the input shall be entered. The process of building the input file is covered in more depth in the body of this part of ISO 16730.

The variables themselves are described in D.6.

Description of input

Title of run - card 1 (A72)

Field	Variable	Description
1	TITLE	Title of run can appear anywhere within these 72 characters.

User options - cards 2 through 10 (7(29X,I1,/),29X,I2,/29X,I1)

Field	Variable	Description
1	IUNITS	Choice of measurement units used
		1 – metric
		2 – standard
2	ISIZE	Choice of body size data
		1 – Austrian (0,145 8 m^2)
		2 – Soviet (0,113 0 m^2)
		3 – American (0,090 6 m^2)
3	ISPEED	Choice of velocity
		1 – emergency
		2 – normal
4	IOPT	Exit routing option
		1 – calculated shortest routes
		2 – directed paths entered by user
5	ISMK	Source of smoke data
		1 – CFAST output
		2 – User-defined blockages or no smoke
6	ICNTRA	Contra flows
		1 – yes
		0 – no
7	IFULL	Output option
		1 – full output showing each move
		2 – summary output
8	NSTR	Number of stairways in floor plan
		(Shall be an integer from 0 to 10)
9	IUPDN	Direction of travel on stairs
		1 – down
		2 – up

Optional random delay - cards 10 to 13 (24X,I1,8X,I3,/,43X,I1,/,20X,F4.0, 18X,F4.0)

Field	Variable	Description
1	IDLY	Random delay option 1 – yes, assign additional delays randomly 2 – no random delays
2	IPROB	Probability of delaying (i.e. the percentage of occupants who will be assigned additional delay times)
3	IDIST	Indicates distribution to sample from 1 – uniform distribution 2 – lognormal distribution
4	PARA1	Minimum value for uniform distribution or standard deviation for lognormal distribution (seconds)
5	PARA2	Maximum value for uniform distribution or mean for lognormal distribution (seconds)

Network link descriptions - one card for each arc (I5,3F6.1,I5)

Field	Variable	Description
1	INODE	From-node (use 9999999999 to indicate end of list)
2	XLNGS1	Distance from the centre of the first node to the centre of the restriction or opening between nodes
3	RESWTH	Width of restriction or opening between nodes
4	XLNGS2	Distance from centre of the restriction or opening between nodes to the centre of the second node
5	JNODE	To-node

Node descriptions - one card for each node (I5,F5.0,F6.1,4I5,F6.1,I5)

Field	Variable	Description
1	N	Node being described
2	AREA	Floor area of node
3	H	Height of ceiling at node
4	NCAP	Capacity of node (not used yet, enter anything)
5	NOCC	Number of occupants at that node
6	ND	Number of occupants at that node who are disabled
7	IE	Indicates if a node is an intermediate exit (i.e. a location such as a stairwell or the node before an exit that people will head to in leaving the building) 1 – is an IE 0 – is not an IE
8	EVACTM	The length of time people at this node will wait after notification before they begin evacuation
9	ITO	Node to which occupants will move if directed route option was selected

Description of disabled occupants - immediately follows any node description where ND ≠ 0. Up to 15 disabled occupants in the node can be entered on each line. (15F5.2)

Field	Variable	Description
1 - ND	FACTR	Percentage of “able-bodied” speed at which each disabled occupant will travel

Node mapping - if ISMK = 1 - one card for each CFAST node (2I5)

Field	Variable	Description
1	CFASTND	CFAST node (enter 9999 to indicate the end of this input section)
2	EXIT89ND	Corresponding EXIT89 node

Smoke blockages - if ISMK = 2 - one card for each blockage (I5,F5.0)

Field	Variable	Description
1	N	Node at which blockage occurs (enter 9999 to indicate end of this input section)
2	TIME	Time at which blockage occurs

Contra flows - if ICNTRA = 1 - one card for each affected node (I5,F5.0)

Field	Variable	Description
1	N	Node at which effect of contra flow occurs(enter 99999 to indicate end of this input section)
2	TIME	Time at which effect occurs
3	EFFCT	Change in size of node area due to onset or cessation of contra flow (for example, to reduce the available area by half, enter 0.50; to return the available area back to its original size, enter 2.0)

D.6 Description of program variables

The variables for this program are described in this subclause.

Variable	Description
AREA (NBL)	Input variable. The floor area of the node being described.
CFASTND	CFAST node to be mapped to an EXIT89 node.
CONTRA (NBL, NINC)	This array holds the change in size of a node's area for any affected node at each time interval.
DENSTY	The body size used in the density calculations for travel speed.
EFFCT	Change in size of node area due to onset or cessation of contra flow.
ENDDAT	Logical variable indicating that the end of the data file has been reached.
ETIME (NUMOCC)	1. In the input section, this array holds the time that each occupant will delay evacuation after receiving notification of a fire. 2. During the people movement phase of the program, this array holds the length of time that each occupant has been moving along the path from one node to the next.
EVACTM	Input variable. The time the occupants of a node will delay before beginning evacuation.
EXIT89ND	EXIT89 node being mapped to a CFAST node.
FACTOR (15)	Input variable. When the user has indicated that some occupants of a node are disabled, this array holds the percentages of "able-bodied" speed at which each disabled occupant will travel. Up to 15 people can be described on each line. These data are stored in the array called SFR().
FACTR	Percentage of "able-bodied" speed at which each disabled occupant will travel.
FULL	Logical variable indicating that the user has selected full printed output.
H (NBL)	Input variable. Height of the ceiling at each node.
ICNTRA	Input variable. Indicates if contra flows will be modelled (1) or not (0).
ICONN (NBL)	For each node, the node connected to it along the exit route. Either calculated by shortest route routine or input by the user.
IDIR (NBL+1)	Directory for the nodes in the network link list, JNODE().

Variable	Description
IDIST	The type of distribution from which delay times will be selected.
IDLY	Input variable. Indicates whether or not additional delays will be randomly assigned to occupants.
IE (NBL)	Input variable. For each node, this is a flag that indicates whether or not that node is a destination for occupants on that floor. Its value is 1 if it is; otherwise, it is set equal to 0.
IEND	Subscript for the last node on the floor (used in shortest route subroutine).
IFDIR (NFLR+1)	Directory for the location of nodes for each floor within the array INODE().
IFLAG (NFLR)	This array indicates whether or not a floor is empty (1 – empty; 0 – occupied).
IFLR	Floor being considered by the shortest route subroutine.
IFLSTR (NSTR)	This array indicates whether or not a stairway is empty (1 – empty; 0 – occupied).
IFULL	Input variable. Indicates whether user wants full output (1) or summary output (2).
INC	Holder for the increment at which an event occurred.
IND (NBL)	This array indicates whether or not a node is blocked.
	1 – blocked
	0 – open
INEXT	For the calculation of shortest routes, this variable indicates which node is the first node on the next floor.
INODE (NLINK)	1. In input section, the from-nodes in the network.
	2. After the input section, the first NBL elements are the node names.
IOPT	Input variable. Indicates whether the user wants the program to calculate shortest paths (1) or will input the nodes to which occupants will travel (2).
IPROB	Input variable. Indicates the percentage of occupants for whom random delays will be assigned.
ISIZE	Input variable. Indicates which source of body size data the user wants to use (1 – Austrian, 2 – Soviet, 3 – American).
ISMK	Input variable. Indicates either that smoke data will be provided by a CFAST output file (1) or that the user will input smoke blockages or there will be no smoke (2).
ISPEED	Input variable. Indicates whether travel velocities should be emergency (1) or normal (2).
ISTRT	Subscript for the first node on the floor (used in shortest route subroutine).
ITEMP	Dummy variable used to read through input section when too many network links are entered.
IUNITS	Input variable. Indicates whether measurements are metric scale (1) or not (2).
IUPDN	Input variable. Indicates whether travel on stairs will be down (1) or up (2).

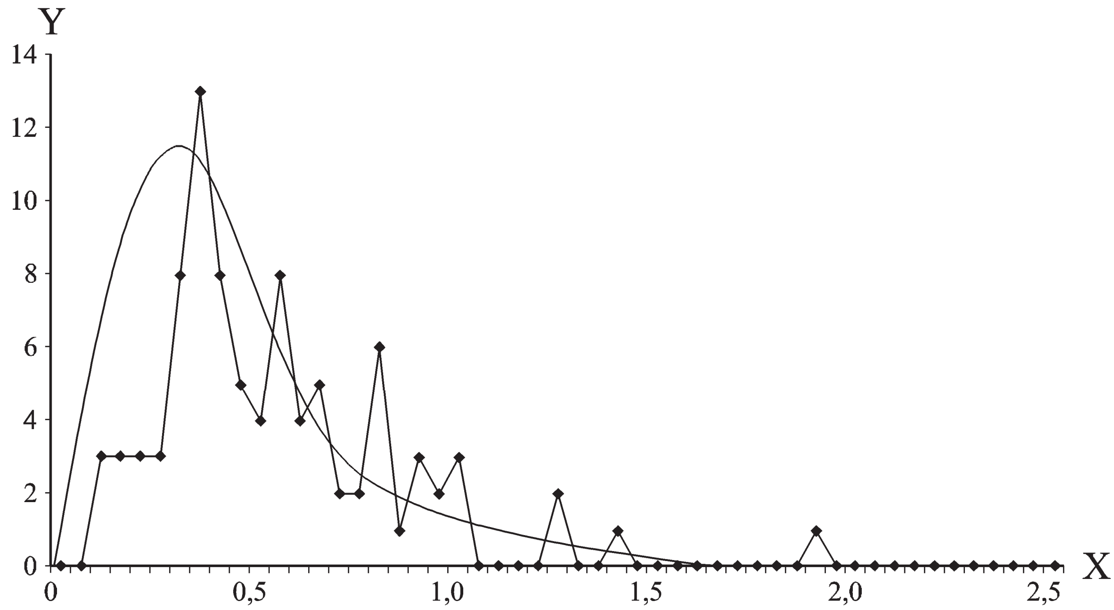
Variable	Description
J (NBL)	Used in the shortest route subroutine to indicate whether or not a node is "solved."
JNODE (NLINK)	1. In input section, the to-nodes in the network. 2. After input section, it holds the link list indexed by IDIR.
LENGTH (NBL)	Used in the shortest route subroutine to hold the length of the path from each solved node to the nearest IE.
LEVHAZ (NBL, NINC)	This array holds the hazard level at each node at each time interval. It serves as a holder for the times when smoke conditions reach the level that will block access to the room (LEVHAZ = 4), or when smoke conditions reach the level that will activate a smoke alarm (LEVHAZ = 1).
MAXLNK	The maximum number of links on the network given the dimensions of the arrays. Set at beginning of the program.
MAXNBL	The maximum number of nodes allowed given the dimensions of the arrays. Set at the beginning of the program.
MAXOCC	The maximum number of occupants given the dimensions of the arrays. Set at the beginning of the program.
METRIC	Logical variable used to indicate whether or not metric measurements were used in the input.
N	Counter used as subscript when reading in list of links.
NAREA (NBL)	Input variable. The usable floor area of a node.
NBL	The number of nodes or building locations in the network. Calculated by program based on input.
NBL1	NBL + 1
NCAP (NBL)	Input variable. The capacity of a node. (Not used yet.)
NDISAB	Total number of disabled occupants. Calculated during input section.
NFLR	Number of floors in building. Calculated when directory of floor nodes, IFDIR(), is being built.
NINC	Number of time increments over which the simulation will be run. Set at the beginning of the program.
NLINK	The number of links in the network. (This will be less than or equal to twice the number of arcs described in the input section and will be calculated by the program.)
NOCC (NBL)	The number of occupants at a node.
NSTR	Input variable. Number of stairways.
NTRAPT	Number of people trapped in the building by smoke.
NUMOCC	The total number of occupants in the building. Calculated by the program based on input.
OCCLOC (NUMOCC,NINC)	The location of each occupant at each time interval.

Variable	Description
PARA1	In input section for assigning additional delay times, used for the minimum value of a uniform distribution or the standard deviation of a lognormal distribution (in seconds).
PARA2	In input section for assigning additional delay times, used for the maximum value of a uniform distribution or the mean of a lognormal distribution (in seconds).
RESWTH (NLINK)	Input variable. The width of the opening between nodes.
SFR (NUMOCC)	This array holds the “speed factor” for each occupant. The value for each able-bodied occupant is initialized at 1,0. The value for disabled occupants is an input variable.
SMOKEDET	Time smoke alarms activate (determined from CFAST output).
TABLE (92,3,2)	Table of velocities calculated by Predtechenskii and Milinskii’s method. The first subscript is calculated density (1 to 92), the second indicates the level of the travel path (1 – horizontal; 2 – down stairs; 3 – up stairs), and the third indicates user-specified travel speed (1 – emergency; 2 – normal).
TEXIT (2,NBL)	This array stores in the first column the number of people who used each exit in the first and in the second column the time at which the last person passed through that exit. (Entries are only recorded in the array for the nodes that access locations of safety.)
TFLR (NFLR)	The time at which each floor was cleared.
TIME	1) In input section, the time at which the associated node will be blocked by smoke. This input section is used when the user is specifying blockages, rather than reading them in from a CFAST file. 2) In input section, the time at which the associated node will be impacted by the onset or cessation of contra flows.
TIMINT	The time increments at which progress of the fire and/or evacuation are recorded. Set at beginning of program.
TIMRM (NBL)	This array holds, for each node, the time it will take the occupants of that node to travel to the connected node, given the current densities of the two nodes.
TITLE (18)	Input variable. The title of the run.
TRUN	The running time of the building evacuation.
TSTR (10)	The time at which each stairway was cleared.
XLNGS1 (NLINK)	Input variable. Distance from the centre of the first node on an arc to the centre of the opening between nodes.
XLNGS2 (NLINK)	Input variable. Distance from the opening between two nodes on an arc to the centre of the second node.
XMAX	Maximum value (in seconds) for uniform distribution from which random delay times for occupants will be selected.
XMIN	Minimum value (in seconds) for uniform distribution from which random delay times for occupants will be selected.

D.7 Sample lognormal distributions

This subclause provides some sample lognormal distributions in order to assist the user in defining distributions with the appropriate mean and standard deviation. These examples are for illustrative purposes only and are not intended as recommended distributions.

Figure D.1 shows the experimental results from the evacuation of a retail store with a food hall.[20] The observed results were found to follow a lognormal distribution. The experimental results and the theoretical curve are shown on the graph.



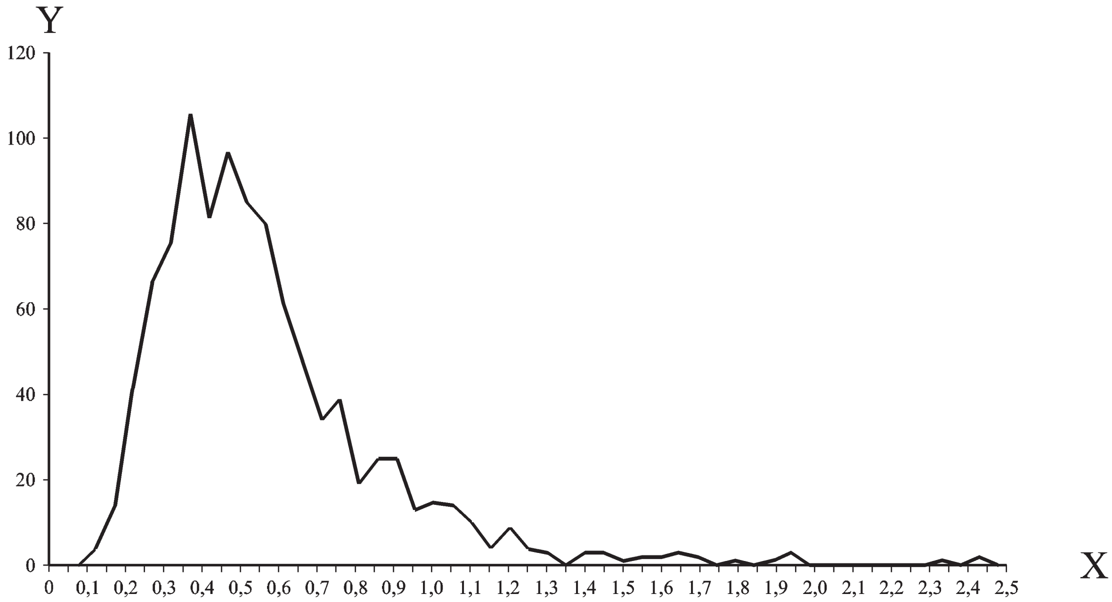
Key

X time (min)

Y frequency

Figure D.1 — Experimental and theoretical pre-movement times in a department store evacuation

Using the lognormal algorithm included in EXIT89, a distribution of 1 000 random numbers with a mean of 0,54 and standard deviation of 0,31 was generated. The plotted results are shown in Figure D.2.

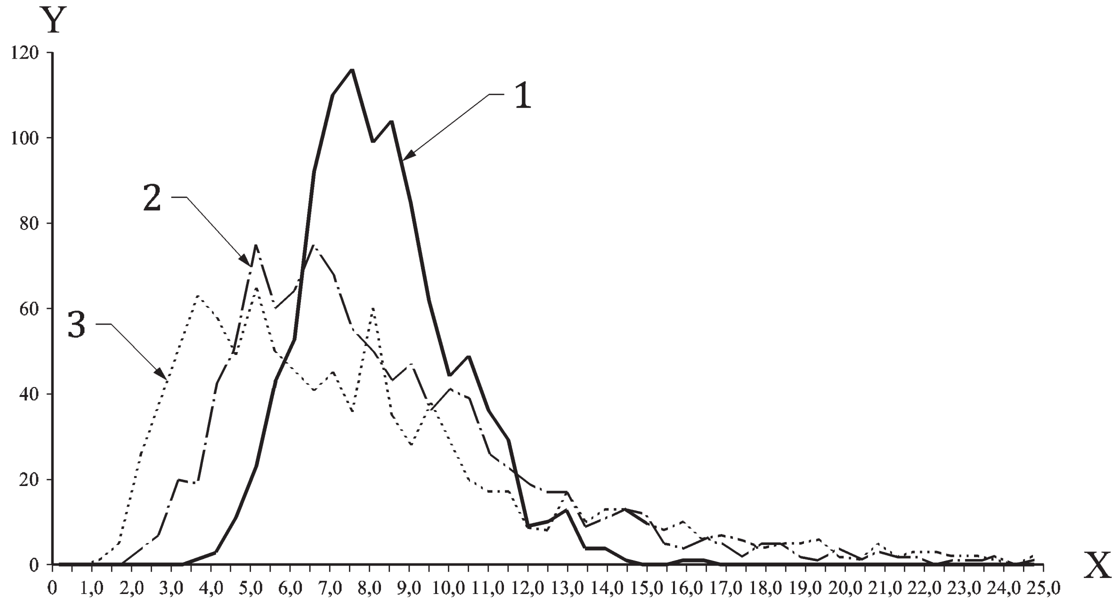


Key

Y frequency

Figure D.2 — Lognormal distribution with mean 0,54 and std dev 0,31

Figure D.3 shows three distributions with a mean of 8,0 and standard deviations of 2,0, 4,0, and 6,0.



Key

Y frequency

1 std dev = 2

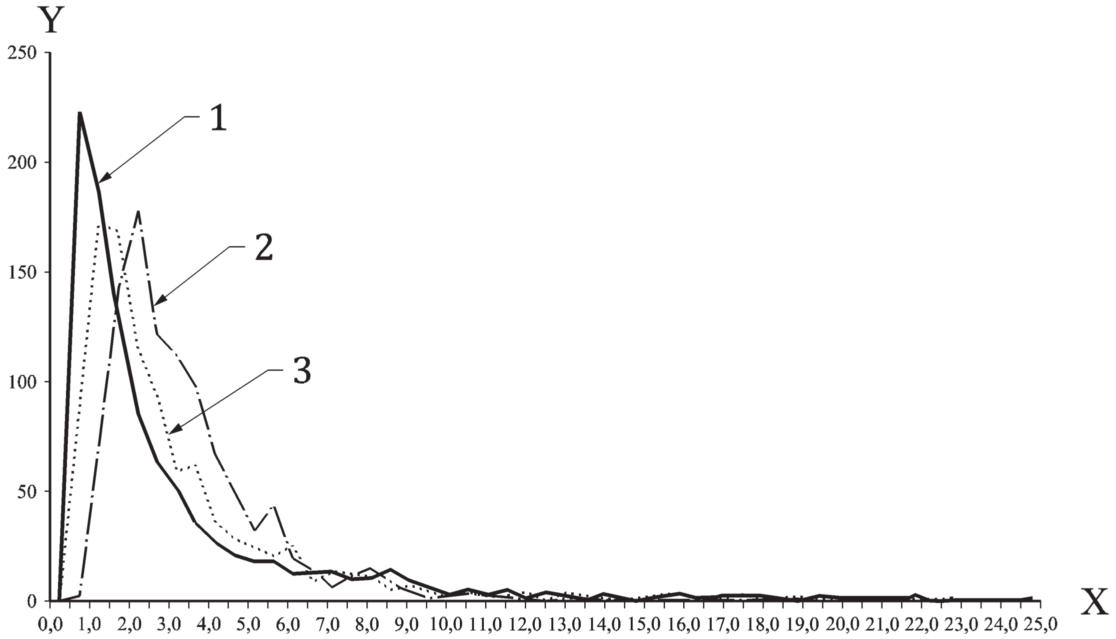
2 std dev = 4

3 std dev = 6

Figure D.3 — Example lognormal distribution mean = 8,0

The choice of standard deviation has a marked effect on the shape of the distribution. The graph does not clearly show the length of the tails of the distribution. The distribution with a standard deviation of 2 ranged from 3,43 to 16,33. The distributions with standard deviations of 4 and 6 had ranges of 1,58 to 37,34 and 0,76 to 52,23, respectively.

Figure D.4 shows three distributions with a mean of 3,0 and standards deviations of 2,0, 4,0, and 6,0. The random numbers generated for the distribution with a standard deviation of 2,0 ranged from 0,39 to 19,98. For the other two distributions, the ranges were 0,13 to 56,30 and 0,03 to 100,09, respectively.



Key

Y frequency

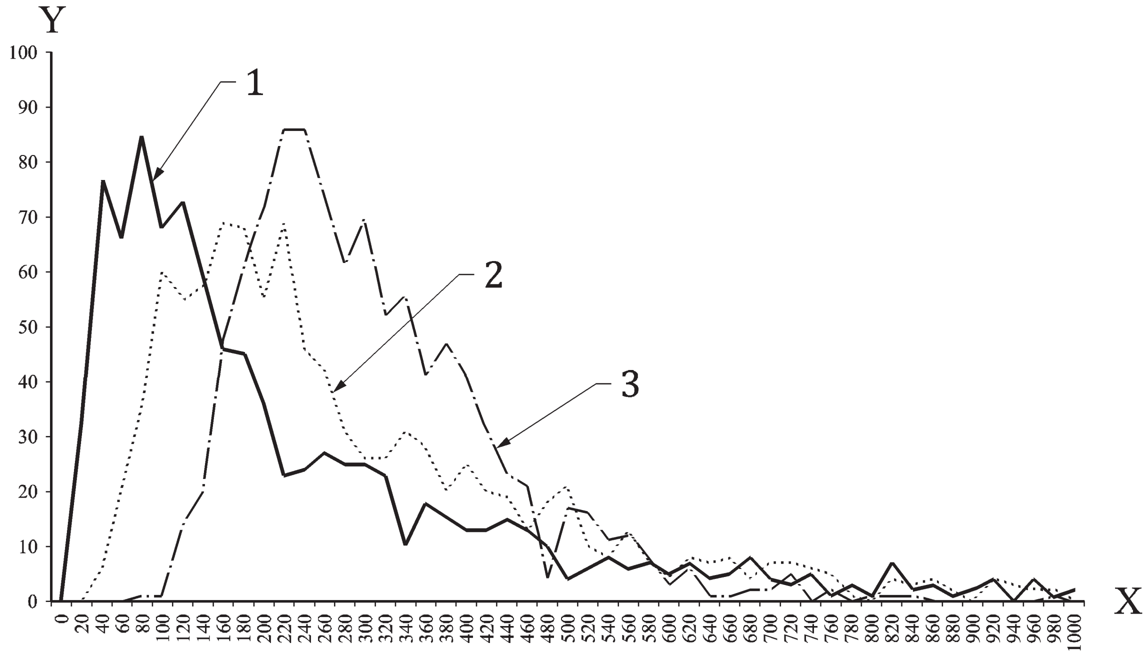
1 std dev = 6

2 std dev = 2

3 std dev = 4

Figure D.4 — Example lognormal distribution mean = 3,0

Since this model requires delay times to be defined in seconds, Figures D.5 and D.6 display some example distributions with mean times of 5 min and 8 min, shown in seconds. As with the previous graphs, three standard deviations are displayed for each mean, to show the effect on the distribution of 1 000 randomly generated numbers. For the graph showing a mean of 5 min, the ranges for distributions with standard deviations of 2 min, 4 min, and 8 min were 70 s to 16 min, 24 s to 37 min, and 6 s to 82 min, respectively. However, the tails on these distributions can be quite long. The values at the 95th percentile, for example, were 9 min, 12 min, and 17 min, respectively.



Key

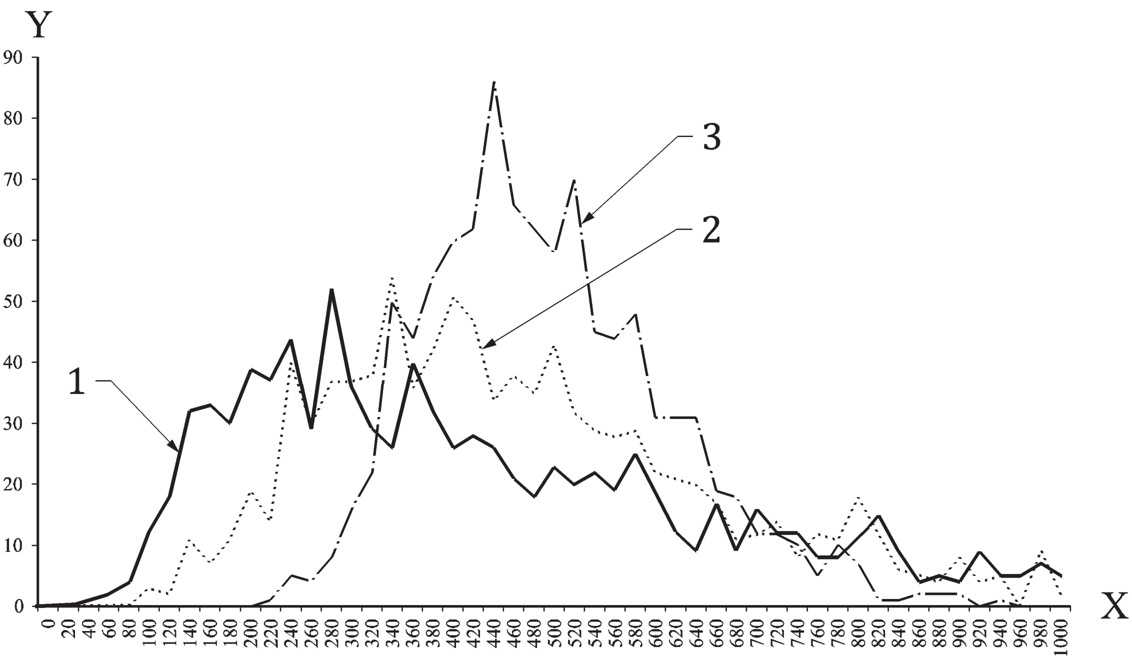
Y frequency

1 std dev = 480

2 std dev = 240

3 std dev = 120

Figure D.5 — Example lognormal distribution mean = 300,0



Key

Y frequency

1 std dev = 360

2 std dev = 240

3 std dev = 120

Figure D.6 — Example lognormal distribution mean = 480,0

For Figure D.6, showing a mean of 8 min, the ranges for distributions with standard deviations of 2 min, 4 min, and 6 min were 3,6 s to 15,6 min, 1,4 s to 41,4 min, and 38 s to 65,8 min, respectively. The values at the 95th percentile were 11,8 min, 15,1 min, and 19,1 minutes, respectively.

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