Employing the Hydraulic Model in Assessing Emergency Movement

59

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Introduction

This chapter provides the engineer with a model to quantify egress performance. This model is formed from a set of numerical tools that vary in their scope and sophistication. Guidance is provided on the capabilities of these tools and on when they should be employed, making reference to the data on which these tools are based. Detailed examples are presented to clarify the application of these tools, along with a description of how the use of these tools fits in with other fire engineering calculations. This chapter will, therefore, allow the engineer to assess egress performance in a responsible and informed manner.

Prediction of evacuee movement is an essential component of performance-based fire safety analysis. Safe egress from fire is assumed to be achieved if the required safe egress time (RSET) is sufficiently shorter than the available safe egress time (ASET), where ASET is defined as the time until fire-induced conditions within a building become untenable. Methods to evaluate the development of fire-induced conditions and tenability criteria are addressed elsewhere in this handbook.

The model discussed in this chapter provides the engineer with a means to establish RSET (i.e., the time taken to reach safety) and therefore complete this component of a performance-based assessment. This model, albeit imperfect, quantifies the egress performance of a design and, importantly, enables comparisons to be made between different design variants to be made.

The hydraulic model is presented as a means of quantifying egress performance that can support an engineering approach and expert analysis. Hydraulic models are based on a simplification of egress behavior where the evacuating population is described by a set of equations. This population moves from egress component to egress component (e.g., from a corridor to a stairwell), with the speed of their movement dictated by the equations that form the model. Guidance is provided on how best to employ these equations, on the scenarios to which this model can be applied, and on the limitations of the approach.

The inherent structure of the hydraulic model described in this chapter tends to an optimistic estimate of evacuation time. It assumes that the exit paths will be continually used at maximum capacity from the moment of alarm to total evacuation. The model should be considered as a baseline calculation to be extended as appropriate to account for delays caused by human decisions, notifications, and other factors (see Chaps. 58 and 64).

For each evacuee the RSET can be subdivided into a number of discrete time intervals, the sum of which constitute the total RSET:

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$$\text{RSET} = t_d + t_n + t_{p-e} + t_e \qquad (59.1)$$

where

t_d = Time from fire ignition to detection; that is, the detection phase

t_n = Time from detection to notification of occupants of a fire emergency; that is, the notification phase

t_{p-e} = Time from notification (or cue reception) until evacuation commences; that is, the pre-evacuation phase

t_e = Time from the start of purposive evacuation movement until safety is reached; that is, the evacuation phase

The components described are considered the core elements of egress analysis (see Chap. 64 for further discussion), although it is recognized that other components will certainly contribute to evacuee performance (e.g. the Pre-Warning delay incurred through staff actions and their decision-making which may prolong notification of the general population).

The RSET elements t_d and t_n typically involve a technical solution and human interaction, including fire detection devices and fire alarm equipment, and also human intervention, such as the discovery of a fire by a staff member and notification of the population. The theory and design of detection systems are covered elsewhere in this handbook (see Chap. 40).

The element t_{p-e} relates to the individual and collective responses of the occupants; that is, the time between them being notified of the incident and the time to commence their evacuation. This can be prolonged by a number of complex activities (see Chaps. 58 and 64). These include receiving a cue; interpreting the cue; validating the cue; performing pre-evacuation activities; and determining an appropriate response (see Chap. 58). All of these contribute to the time spent in the pre-evacuation phase, prior to commencing purposive evacuation movement to a place of safety.

The element t_e is the time from when an individual initiates evacuation movement up to the point that he or she reaches safety. For an individual evacuee, t_{p-e} and t_e are basically sequential. Crudely speaking, it is typically assumed that for an individual evacuee, t_{p-e} and t_e are basically sequential. There is a period before the individual has determined that an evacuation response is required (through the perception of sufficient risk levels and the subsequent completion of preparatory actions) and a period where this response is conducted (i.e. where protective actions are taken). That is not to say that the individual need be static in either time period or that the performance of actions are not iterative or cyclical—only that at a certain point in time, the individual decides that the situation requires them to take protective actions and their subsequent actions broadly reflect an attempt to disengage from the current actions and take protective actions.

However, across a population, t_{p-e} and t_e are neither independent of each other nor mutually exclusive [1]. There may be significant overlap between these components given the varying conditions evident at different locations within the structure, the different levels of information available, and the differences in the abilities of the population [2].

RSET can be reduced into two sets of components: the phase prior to evacuee involvement, made up of t_d and t_n, and the escape phase (t_{esc}) where

$$t_{\text{esc}} = t_{p-e} + t_e \qquad (59.2)$$

It should be noted that, in reality, the evacuation phase can be interrupted through behavioral actions and developments in the incident scenario [3].

This chapter describes the basic hydraulic model enabling t_e to be calculated. It also describes the extension of the hydraulic model to also include t_{p-e} in the calculation and therefore allow an estimation of t_{esc} to be produced. A methodology is presented to enable the engineer to determine the RSET value as part of a performance-based assessment. It provides sufficient information for the engineer to calculate RSET under a number of different incident scenarios, while also making the engineer aware of the limitations and assumptions of the hydraulic model (Fig. 59.1).

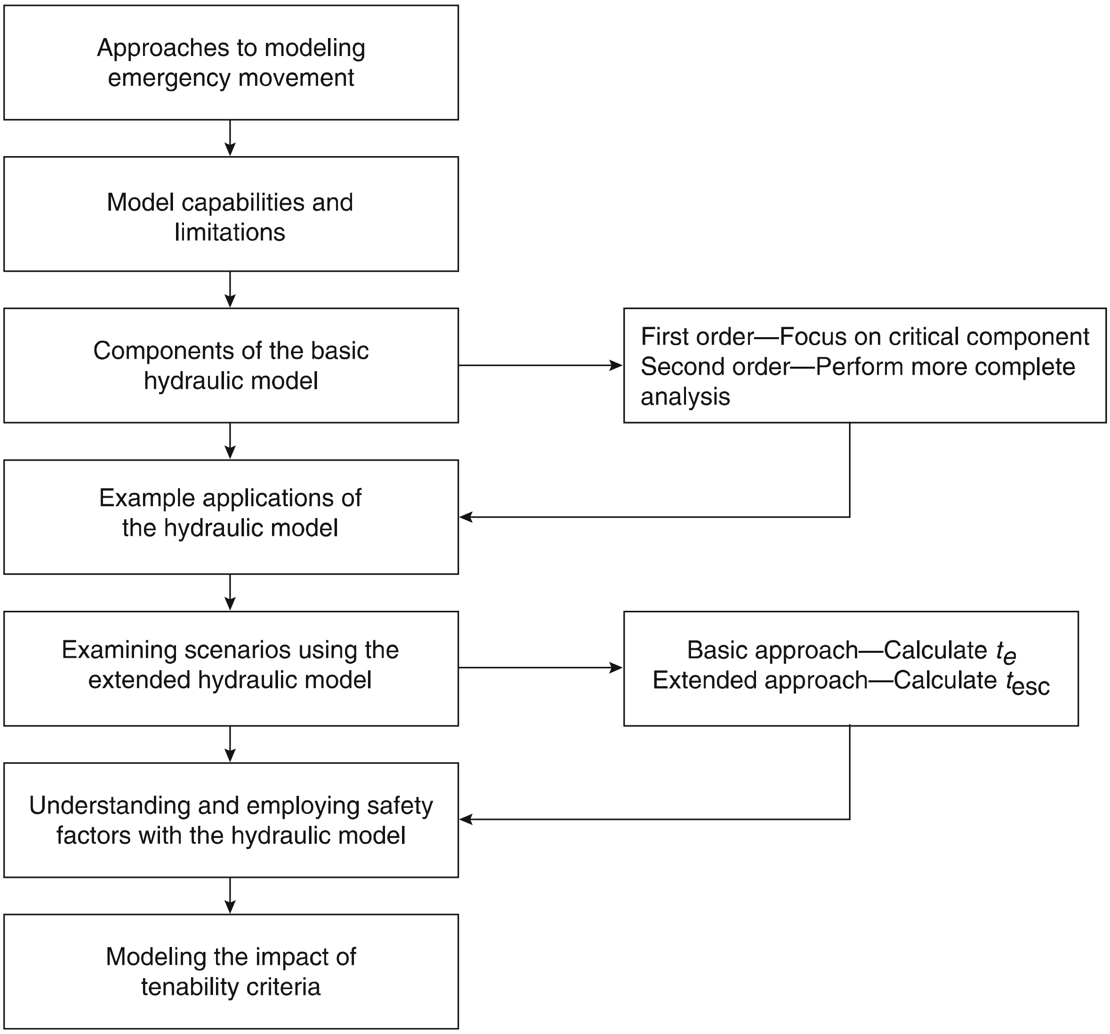


Fig. 59.1 Structure of this chapter

Establishing Egress Performance

Over the last few decades an increasing effort has been made into investigating human behavior in response to fire. This research has provided a clearer understanding of egress behavior and the factors that influence egress performance. As a consequence, human behavior can be taken into consideration when designing emergency procedures and modeling human performance. Prior to this time, human behavior was disregarded altogether, seen as immeasurable, and/or drastically simplified according to a few basic assumptions. The former understanding of human behavior was based on a number of assumptions: people's behavior would likely be panic based [4]; it would likely be selfish and competitive; and it would involve immediate and direct movement once the incident was discovered. Although some of these assumptions are contradictory, they have had a direct impact on the engineering calculations made for a long period of time and continue to exert some degree of influence on egress design decisions to this day [3].

In recent times, a more detailed and comprehensive understanding of human behavior in fire has been established (see Chaps. 58 and 64). This understanding has been derived from the examination of actual incidents, the collection of empirical evidence, and the development of behavioral theories. All of this has, to a large degree, refuted the assumptions that had previously dominated. This realization has allowed engineers (as well as behavioral researchers,

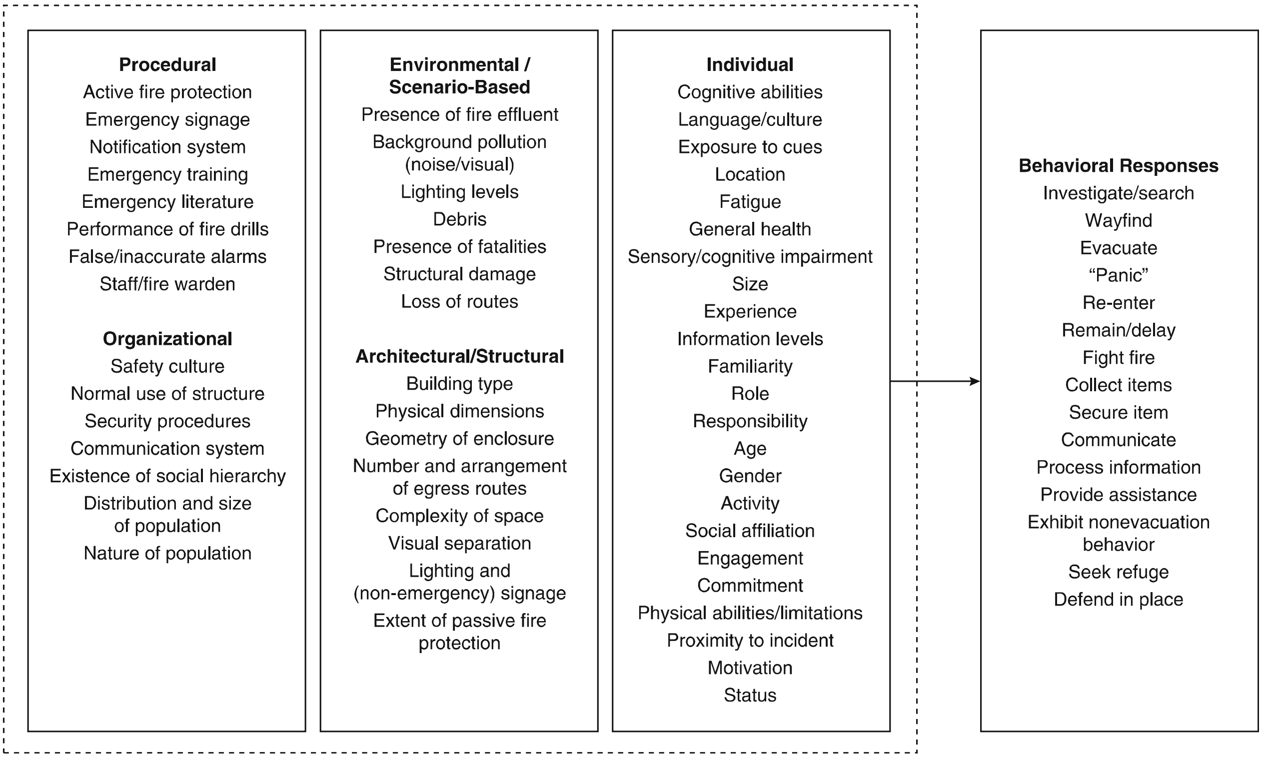


Fig. 59.2 Factors that can influence egress performance

procedural designers, and evacuation modelers) to take human behavior into account, albeit imperfectly, when trying to establish evacuation performance.

It is now felt that the evacuation process is not simply a matter of initiating an evacuation and then controlling the ensuing hysterical crowd response; instead, it is now viewed as a more multifaceted event in which people's responses are sensitive to the incident scenario, the information available, and the local conditions (among other things). The problem of understanding human behavior in fire is not the simple process previously assumed. Instead, it relies on a number of factors that can interact and can influence the outcome in different ways (Fig. 59.2). These factors also influence the engineering methods required to assess performance. Ideally these factors should be considered in any assessment of egress performance; however, the methods employed in this assessment are limited and, to different degrees, exclude many of the key factors influencing egress performance. It is critical that these limitations are understood by an engineer prior to the application of such methods.

Models

Several approaches are available to the engineer to establish egress performance; that is, estimate t_{esc}. Each of these approaches requires the application of a model: a simplified version of reality used as an indicator of actual egress performance. All of these approaches are limited. One or more of the following four model approaches are usually applied:

- *Model Approach A*: *The application of prescriptive codes*. The expertise embedded within the regulations is assumed to satisfactorily represent (or at least account for) the performance of the evacuating population. Generally, these codes focus on the physical constraints imposed by the structure and exclude behavioral and procedural factors.
- *Model Approach B*: *The performance of an egress trial*. An (un)announced trial is

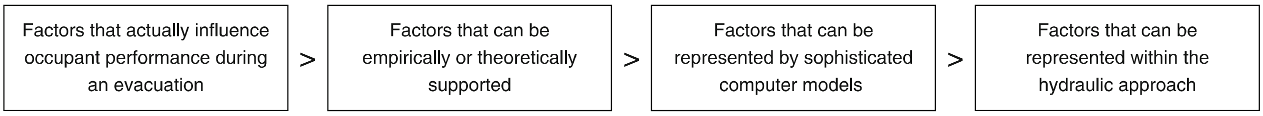


Fig. 59.3 Difference between the actual and modeled evacuation

conducted in order to assess the outcome of a simulated incident using the population of interest. This approach has a number of limitations: it is expensive; there are ethical issues in achieving realism in such an event; the trial produces only a single data point; and the structure has to be in place already [5].

- *Model Approach C*: *The application of a (computer-based) simulation model*. An attempt is made to incorporate our understanding of human behavior in fire within a computer-based model. This is then applied to a representative set of scenarios in order to establish egress performance. The quality of the results is highly dependent on a number of factors: the sophistication and validity of the model used, the expertise of the user, and the scenarios examined and their appropriateness [6].
- *Model Approach D*: *The application of an engineering calculation*. Here, empirical data are distilled into a representative set of equations. These equations are deemed to represent a simplified version of evacuation movement (instead of behavior), where the results are largely determined by the physical attributes of the components involved; for example, the people, the structure, and so on. As such, they largely overlook many of the complexities apparent in the human response to fire. These calculations can be applied at the level of the structure (see Chap. 64) or the level of the structural component. For instance, details of the structure can be included in an equation that generates an overall egress time; for example, the number of floors, the population size, and the egress width available.

  Alternatively, the attributes of a particular structural component (e.g., staircase, section of corridor, etc.) can be used. These describe the performance of the population when traversing the component in question. These results are then pieced together to form a network representation of a structure to describe the performance of the population when traversing an egress route.

In reality, none of these approaches include all of the factors that influence the outcome of an evacuation; that is, they represent only a subset of those factors mentioned in Fig. 59.2. Indeed, given the relatively immature state of the study of human behavior in fire, it would be not be possible for the models to include all of the factors affecting egress. It is vital to understand the limitations of these models in order to more reliably interpret and assess the results produced. There is a difference between the number of factors that actually affect an evacuation and the number that can be modeled. The gap between this prediction and reality is outlined in Fig. 59.3. The hydraulic model discussed here is an engineering calculation, that is, model approach D.

Model Limitations

Many factors influence the outcome of an evacuation; models have the potential to incorporate a subset of these factors. This potential influence is based on the assumption that (1) sufficient theoretical support exists (i.e., that the factors have been identified and formalized); (2) there are data that can be incorporated into the model (i.e., that the factors can be quantified in some way); and (3) there are no limitations in the technology used to apply the model (e.g., hardware or software).

The hydraulic model is limited in the factors it can represent. Several aspects of the model should be noted:

- Behaviors that detract from movement are not explicitly considered.
- The numbers of people in a structural component are considered rather than their identity and their individual attributes.
- Movement between egress components is considered (e.g., from room to room), rather than within them.
- The results are deterministic and will therefore remain the same unless changes are made to the scenario or the assumptions employed.

The expert user can, to some degree, compensate for these limitations, but these limitations are inherent in the hydraulic model. Therefore, given the nature of the hydraulic model, it is able to represent only a small subset of behavioral factors (primarily related to those that influence movement).

Some time has been spent outlining the limitations of the hydraulic model along with the other modeling approaches available. As with any model, it is critical that the engineer is aware of these limitations prior to its use. When the hydraulic (or any other) model is employed, a brief description of these limitations should be presented along with the results produced and the conclusions drawn. However, despite these limitations, it is possible to employ the hydraulic model to establish egress performance in a consistent and informative manner. A hydraulic model can assess t_e by quantifying egress performance, and therefore provide insight into the effectiveness of a design. In a similar manner, the extended version of the model, described later in this chapter, is able to estimate t_{esc}.

In many cases, the hydraulic model is an acceptable method to model egress. Examples include where only a general estimate of egress time is required and where the hydraulic model is the most sophisticated model available to the engineer: the prescriptive codes may be too restrictive and not allow dedicated data to be incorporated; the resources available may not extend to the use of a complex simulation model; and egress trials may be precluded as the structure may not yet have been built. Where these other models are available, the engineer may want to apply several simultaneously (e.g., the hydraulic model and a computer simulation model) in order to have a stronger basis for the results [1]. Care should be shown in the application of the hydraulic model and the presentation of the results produced. With responsible use, it is able to produce reasonable results in many situations. In some situations a more sophisticated model should, ideally, be employed; for example, where complicated procedures are in place, where complex flows are expected, and where the population is heterogeneous (see Chap. 60).

In the next sections the use of the basic hydraulic model to estimate t_e (the evacuation time) is discussed. The empirical evidence supporting the hydraulic model is outlined, and the calculations involved are described. Two different versions of the basic hydraulic model are described: a simplified approach (first order) and the full approach (second order). Both act at the level of the structural component but do so to different degrees of computational rigor. The engineer must select one of these versions based on the project, his or her expertise, and the time available. Several examples are provided demonstrating how the hydraulic model can be applied. Finally, guidance is provided on how these calculations can be employed and, by extending the model, the types of scenarios that should be examined. An engineer should consider all of these issues when determining t_e (and then eventually t_{esc}).

Estimating t_e Using the Basic Hydraulic Model

This section describes the fundamental components of egress movement that form the basic elements of the hydraulic model; that is, the equations used in calculating the t_e component in Equation 59.1.

Research-based engineering calculations for predicting emergency population flow have emerged over the past few decades. The major contributors include Predtechenskii and

Milinskii [7], Fruin [8], and Pauls [9, 10]. A number of other contributions have been made to the field in recent years; [11–25] however, the methods presented here (originally developed by Nelson and MacLennan [26]) were based primarily on the major contributors highlighted above. A more complete list of the research performed relating to human behavior and movement is presented in Chaps. 58 and 64, as well as elsewhere [4, 27–37].

It should be noted that at the time of writing there is some discussion regarding the validity of several of the data-sets on which these models are based. This has led to data-sets being withdrawn from the SFPE handbook and from other publications (see Chap. 64). However, their contribution to the model described here is not removed given that the data-sets are broadly comparable, that they form a core component to the original model derived by Nelson et al. [26], that they have not yet been proven invalid (in an available, peer-reviewed publication), and that, perhaps more importantly, there is a lack of other equivalently comprehensive data-sets available.

As mentioned, the sources included here are, in most cases, compatible and supportive of each other. All are based on the relationship between the speed of movement and population density of the evacuating population stream. The equations derived from these sources are based on the following assumptions:

1. All persons start to evacuate at the same time.
2. Occupant flow does not involve interruptions caused by evacuee decisions.
3. The evacuees are free of impairments/disabilities that impede their movement.

Given the discussion presented in Chaps. 58 and 64 and from Fig. 59.2, these assumptions exclude a number of factors and behaviors that might detract from egress performance. These assumptions also have the effect of separating the egress components (presented in Equation 59.1) into distinct activities that are then treated separately during the calculations; in reality, these components would be coupled.

When representing an actual event, Equation 59.1 can be rewritten as

$$\mathrm{RSET} = t_d + t_n + t_{p-e} + (t_{\mathrm{trav}} + t_{\mathrm{flow}} + t_{n-e}) \tag{59.3}$$

where t_e is broken down in three constituent parts: t_{trav} is the time spent moving toward a place of safety, t_{flow} is the time spent in congestion controlled by flow characteristics, and t_{n-e} is the time spent in nonevacuation activities that do not directly contribute to the population moving to a place of safety. Even this equation is a simplification, although it does demonstrate that in the evacuation phase there is likely to be an amount of time spent in activities other than moving directly to an exit. Given the assumptions associated with hydraulic models, the RSET calculation using the basic hydraulic model produces the following equation:

$$\mathrm{RSET} = t_d + t_n + t_{p-e} + (t_{\mathrm{trav}} + t_{\mathrm{flow}}) \tag{59.4}$$

The behaviors that do not directly contribute to the evacuation are not modeled (t_{n-e}). Calculations based on these assumptions require compensatory actions in order to account for the factors not included. These actions are discussed later in this chapter.

Fundamental Movement Calculations

The modeled evacuation time (i.e., the time predicted by the hydraulic model) utilizes a series of expressions that relate data acquired from tests and observations to a hydraulic model of human flow. These primarily relate to the following considerations: effective width, population density, speed, flow characteristics, time for passage through a component, and transitions between components. Each of these considerations is discussed in detail by Proulx [38]. By taking these considerations into account, egress movement can be quantified using the hydraulic model. Figure 59.4, shows a typical relationship between the source data and the derived equation. Although the expressions indicate absolute relationships, there is considerable

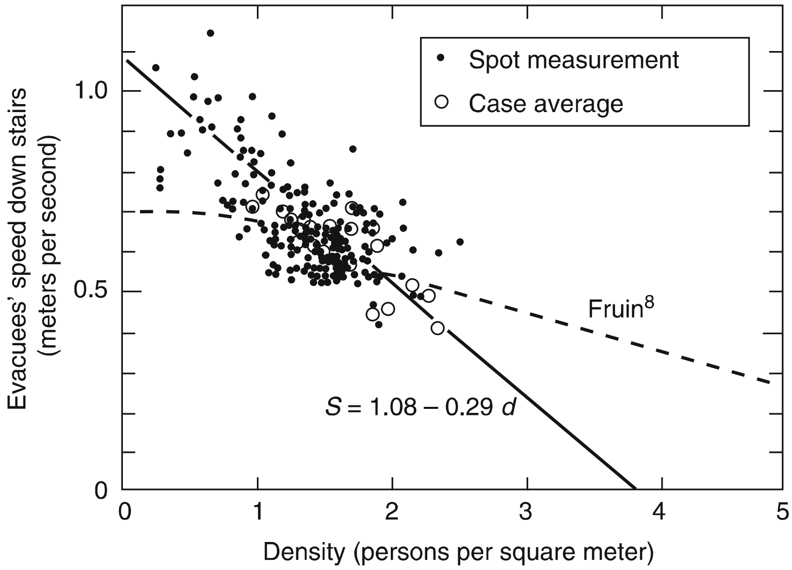


Fig. 59.4 Relation between speed and density on stairs in uncontrolled total evacuations (Dashed line from Fruin [8])

variability in the data. The engineer may wish to take this into account during the calculation process.

The equations and relationships presented in the following paragraphs can be used independently or collected together to solve more complex egress problems. Several examples outlining the use of these equations are presented later in this chapter.

Effective width, W_e The effective width is the usable width of the component, or W_e. Persons moving through the exit routes of a building maintain a boundary layer clearance (i.e., maintain a distance between themselves and the object in question) from walls and other stationary obstacles they pass (see Fruin [8], Pauls [9, 10], and Habicht and Braaksma [39]). This clearance is needed to accommodate lateral body sway and assure balance. Personal preference dictates that people attempt to maintain space around themselves assuming that the population density is sufficiently low.

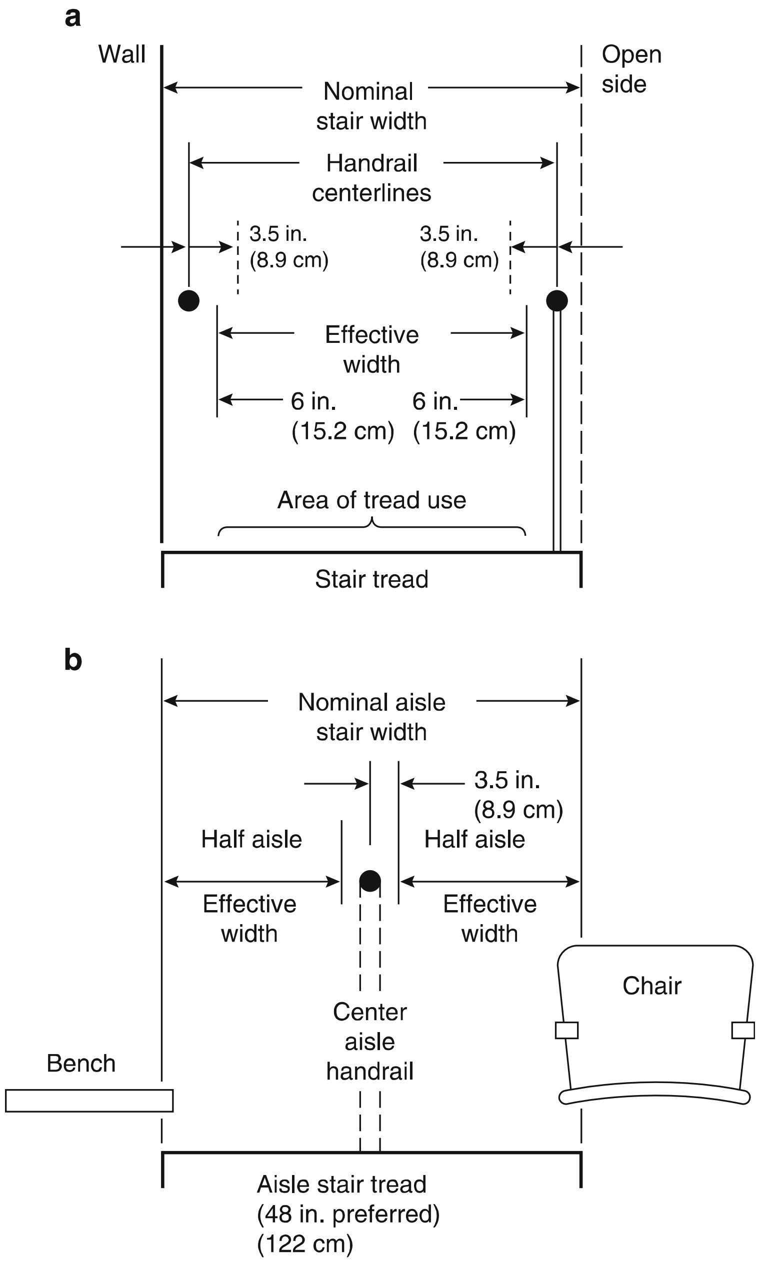
Discussion of this crowd movement phenomenon is found in the works of Pauls [9, 10], Fruin [8], and Habicht and Braaksma [39]. The useful (effective) width of an exit path is the clear width of the path less the width of the boundary layers. Figures 59.5 and 59.6 depict effective width and boundary layers. Table 59.1 is a listing of boundary layer widths. The effective width of any portion of an exit route is the clear width of that portion of an exit route less the sum of the boundary layers. Clear width is measured

1. From wall to wall in corridors or hallways
2. As the width of the treads in stairways
3. As the actual passage width of a door in its open position
4. As the space between the seats along the aisles of assembly arrangement
5. As the space between the most intruding portions of the seats (when unoccupied) in a row of seats in an assembly arrangement

The intrusion of handrails is considered by comparing the effective width without the handrails and the effective width using a clear width from the centerline of the handrail. The smaller of the two effective widths then applies. Using the values in Table 59.1, only handrails that protrude more than 2.5 in. need be considered; that is, if the handrail protrudes less than 2.5 in. into the stair width, then the overall calculated width will still be less than the 6 in. reduction produced by the stairwell. Minor midbody height or lower intrusions such as panic hardware are treated in the same manner as handrails.

Population Density, D Population density, D, is the measurement of the degree of crowdedness in an evacuation route. The calculations in this

Fig. 59.5 Measurements of effective width of stairs in relation to walls, handrails, and seating



chapter are based on population density expressed in persons per square foot (or persons per square meter). It should be noted that researchers employ several different units when describing population density. These units include the number of people per unit of space, the space available per person, and the proportion of floor space occupied [7]. In reality, the population density will be dependent on the size of the individuals present. These sizes may vary greatly. Here, the sizes are assumed to be uniform or averaged across the population.

Unless specifically stated, the entire population of the first egress component (i.e., the component from which the egress movement starts) is included in any flow calculation. This will demonstrate the capacity limits of the route element. If the evacuating population is widely dispersed within an egress component (i.e., it would take them significantly different times to reach connected egress components), the calculation is based on an appropriate time step that reflects the time of their arrival. At each time increment, the population density of the exit route is based on

Fig. 59.6 Public corridor effective width

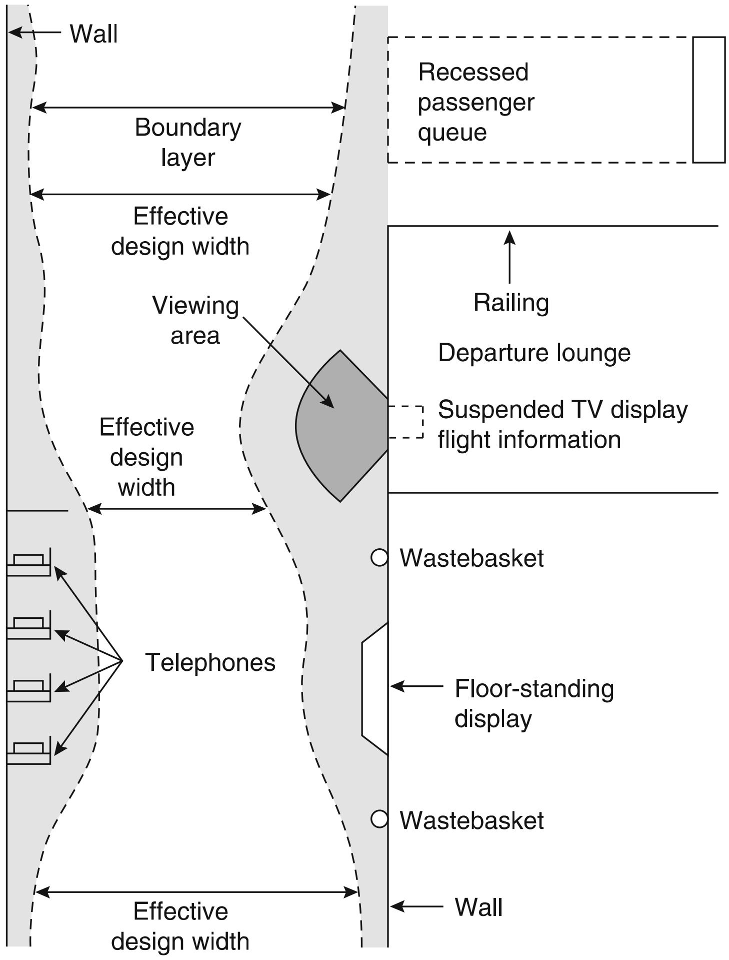


Table 59.1 Boundary layer widths

Exit route element	Boundary layer (in.)	(cm)
Stairways—wall or side of tread	6	15
Railings, handrails[a]	3.5	9
Theater chairs, stadium benches	0	0
Corridor, ramp walls	8	20
Obstacles	4	10
Wide concourses, passageways	<18	46
Door, archways	6	15

[a]Where handrails are present, use the value if it results in a lesser effective width

those that have entered the route minus those that have passed from it. In such situations the engineer may wish to separate the components into subcomponents; for example, a corridor could be broken into several components reflecting the different performances of the population. In this case, the density calculations would then be based on the entire population of each of the new components.

The population density factors in subsequent portions of the egress system are determined by calculation. The calculation methods involved are contained in the section of this chapter titled "Transitions."

Speed, *S* Speed is defined as the movement velocity of exiting individuals, or *S*. Observations and experiments have shown that the speed of a group or an individual in a group is a function of the population density. The relationships presented in this chapter have been derived from the work of Fruin [8], Pauls [9, 10], and Predtechenskii and Milinskii [7]. If the population density is less than approximately 0.05 persons/ft^2 (0.54 persons/m^2) of exit route, individuals will move at their own pace, independent of the speed of others. If the population density exceeds about 0.35 persons/ft^2 (3.8 persons/m^2), it is assumed that no movement will take place until enough of the crowd has passed from the crowded area to reduce the population density. Between the population density limits of 0.05 and 0.35 persons/ft^2 (0.54 and 3.8 persons/m^2), the relationship between speed and population density is assumed to be represented by a linear function. The equation of this function is

$$S = k - akD \tag{59.5}$$

where

S = Speed along the line of travel

D = Population density in persons per unit area

k = Constant, as shown in Table 59.2

= k_1; and a = 2.86 for speed in ft/min and density in persons/ft^2

= k_2; and a = 0.266 for speed in m/s and density in persons/m^2

Table 59.2 Constants for Equation 59.5, evacuation speed

Exit route element		k_1	k_2
Corridor, aisle, ramp, doorway		275	1.40
Stairs			
Riser (in.)	Tread (in.)		
7.5	10	196	1.00
7.0	11	212	1.08
6.5	12	229	1.16
6.5	13	242	1.23

1 in. = 25.4 mm

Figure 59.7 is a graphic representation of the relationship between speed and population density. The speeds determined from Equation 59.5 are along the line of movement; that is, for stairs the speeds are along the line of the treads. Table 59.3 provides convenient multipliers for converting vertical rise of a stairway to a distance along the line of movement. The travel on landings must be added to the values derived from Table 59.3. To be conservative, it should be assumed that the population does not increase velocity when traversing a landing between stairs but continues on at the same reduced rate associated with stair movement.

Although, in reality, population densities of greater than 0.175 persons/ft^2 (1.9 persons/m^2) can be achieved, it is suggested that these densities should not be assumed in an engineering design [3]. This density produces the maximum achievable flow rate; beyond this density, the flow rate falls rapidly. If the population density increases significantly beyond 0.37 persons/ft^2 (4 persons/m^2), then crush conditions might develop [9, 10, 40]. This suggested maximum compares to the occupancy levels suggested in NFPA *101*®, *Life Safety Code*®, of 0.142 persons/ft^2 (1.54 persons/m^2) to 0.003 persons/ft^2 (0.022 persons/m^2) depending on the type of occupancy [41]. The suggested maximum

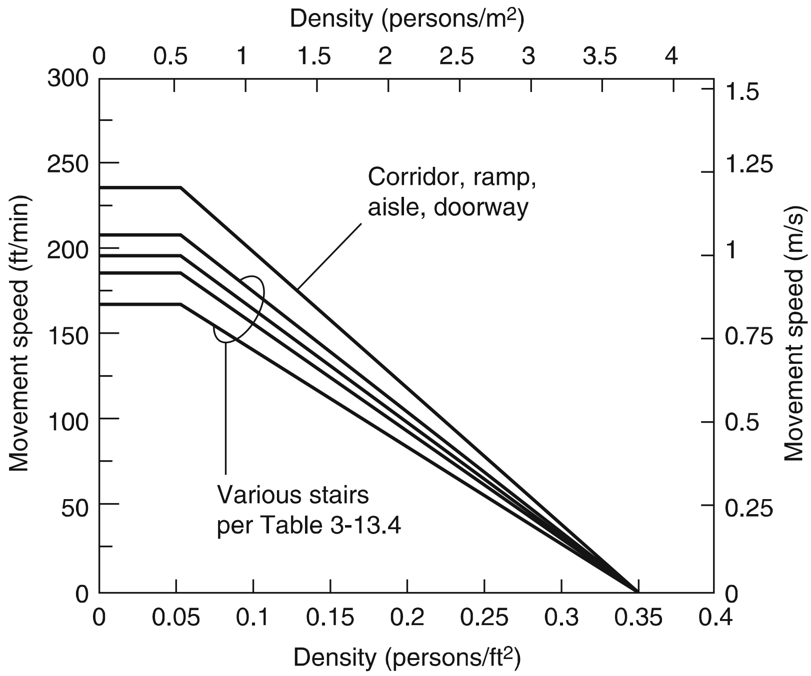


Fig. 59.7 Evacuation speed as a function of density. S = k − akD, where D = density in persons/ft^2 and k is given in Table 59.2. Note that speed is along line of travel

Table 59.3 Conversion factors for relating line of travel distance to vertical travel for various stair configurations

Stairs riser (in.)	Tread (in.)	Conversion factor
7.5	10.0	1.66
7.0	11.0	1.85
6.5	12.0	2.08
6.5	13.0	2.22

1 in. = 25.4 mm

density is therefore beyond the heaviest occupant load suggestion in the *Life Safety Code* and should therefore be adequate for all occupancy types.

A conservative approach is therefore adopted regarding the population densities that might be achieved during the movement of the population. As can be seen in Fig. 59.7, a maximum population density of 3.76 persons/m^2 is assumed. This limit constrains the movement of the population. The relationship between speed/flow and density is similarly affected by this constraint, with achievable population densities below those that might be expected in reality and curtailed earlier than might be expected.

The maximum speed is possible, but not inevitable, when the density is less than 0.05 persons/ft^2 (0.54 persons/m^2). These maximum speeds are listed in Table 59.4.

Within the range of dimensions listed in Tables 59.2, 59.3, and 59.4, the evacuation speed on stairs varies approximately as the square root of the ratio of tread width to tread height. There is not sufficient data to appraise the likelihood that this relationship holds outside this range.

Specific flow, F_s Specific flow, F_s, is the flow of evacuating persons past a point in the exit route per unit of time per unit of effective width, W_e, of the route involved. Specific flow is expressed in persons/min/ft of effective width (if the value of $k = k_1$ from Table 59.2), or persons/s/m of effective width (if the value of $k = k_2$ from Table 59.2). The equation for specific flow is

$$F_s = SD \tag{59.6}$$

Table 59.4 Maximum (unimpeded) exit flow speeds

Exit route element		Speed (along line of travel) (ft/min)	(m/s)
Corridor, aisle, ramp, doorway		235	1.19
Stairs			
Riser	Tread (in.)		
7.5	10	167	0.85
7.0	11	187	0.95
6.5	12	196	1.00
6.5	13	207	1.05

1 in. = 25.4 mm

where
F_s = Specific flow
D = Population density
S = Speed of movement

The flow rate unit is often referred to in persons/ft/minute or persons/m/second. This change in units will have no impact on the results.

F_s is in persons/min/ft when density is in persons/ft^2 and speed in ft/min; F_s is in persons/s/m when density is in persons/m^2 and speed in m/s.

Combining Equations 59.5 and 59.6 produces

$$F_s = (1 - aD)kD \tag{59.7}$$

where k is as listed in Table 59.2.

The relationship of specific flow to population density is shown in Fig. 59.8. In each case the maximum specific flow occurs when the density is 0.175 persons/ft^2 (1.9 persons/m^2) of exit route space. It is possible to establish F_s from Equation 59.7 and solve for D. There is a maximum specific flow associated with each type of exit route element; these are listed in Table 59.5.

Special Consideration for Door Mechanism In Table 59.5 and Fig. 59.8 the maximum achievable specific flow rates for corridors and doorways are considered equivalent. This is based on the original calculations made by Nelson and MacLennan [26]. However, this is based on the assumption that the entire effective width

Fig. 59.8 Specific flow as a function of population density

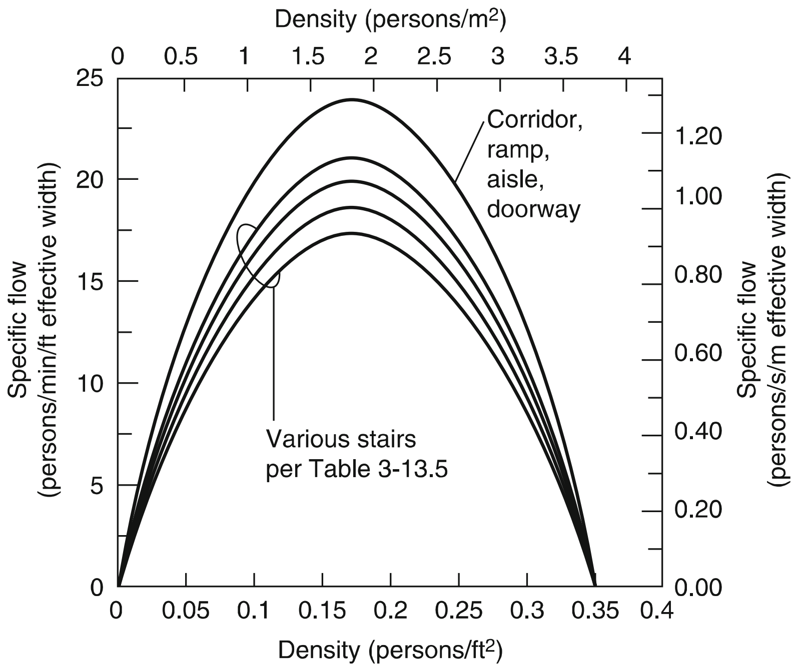


Table 59.5 Maximum specific flow, Fsm

Exit route element		Maximum specific flow: Persons/min/ft of effective width	Persons/s/m of effective width
Corridor, aisle, ramp, doorway		24.0	1.3
Stairs			
Riser	Tread		
(in.)	(in.)		
7.5	10	17.1	0.94
7.0	11	18.5	1.01
6.5	12	20.0	1.09
6.5	13	21.2	1.16

of the doorway is available and that the passage of the population through the doorway is not influenced by the door mechanism itself. If the door leaf is not mechanically held open, then the traversing population may be forced to hold it open, delaying their passage. These actions have the potential for slowing the evacuees' movement through the opening, producing a reduced flow rate. It may also reduce the width available to the width of a single person (i.e., the width required for the person holding the door and passing through the exit), rather than the full available width of the exit leaf. In this case, the exit width available may be dynamic and reduced even from the calculated effective width.

These factors may act to limit the flow through the doorway. When doors on an egress route are not mechanically held open, these factors should be considered. In such circumstances, where the interaction with the door leaf influences performance, it may be more conservative to assume a maximum achievable flow rate based on the number of door leaves available rather than the actual width (effective or otherwise) of each door leaf; that is, increasing the door leaf size may not produce a linear increase in the achievable flow, given the need to hold the leaf open and the reduction in the available door width due to the position of the closing leaf. A *maximum* flow rate of 50 persons/min/door leaf is suggested for doors that are not mechanically held open [3, 8]. Fruin originally noted flow rates between 40 and 60 persons/min through exits with door leaves; however, the lower flow rate of 40 persons/min was produced during observations involving slow-moving occupants and so is discounted [3].

The data used to support the flow rate through doors are several decades old and may not accurately reflect the movement and shape characteristics of current populations; for example, the impact that the increasing levels of obesity in some parts of the world might have on the capacity of egress routes and on movement rates

[42]. In addition, the data from which these relationships were derived were collected from nonemergency pedestrian movement and/or egress drills. The functions described should not be assumed to necessarily provide conservative predictions; the engineer should therefore factor this into the design recommendations made.

Calculated flow, F_c The calculated flow, F_c, is the predicted flow rate of persons passing a particular point in an exit route. The equation for calculated flow is

$$F_c = F_s W_e \tag{59.8}$$

where
F_c = Calculated flow
F_s = Specific flow
W_e = Effective width of the component being traversed

Equation 59.8 is based on the assumption that the achievable flow rate through a component is directly proportional to its width.

Combining Equations 59.7 and 59.8 produces

$$F_c = (1 - aD)kDW_e \tag{59.9}$$

F_c is in persons/min when k = k_1 (from Table 59.2), D is in persons/ft^2, and W_e is in ft. F_c is in persons/s when k = k_2 (from Table 59.2), D is persons/m^2, and W_e is m.

Time for passage, t_p The time for passage, t_p, is the time for a group of persons to pass a point in an exit route and is expressed as

$$t_p = P/F_c \tag{59.10}$$

where t_p is time for passage (t_p is in minutes where F_c is in persons/min; t_p is in seconds where F_c is persons/s). P is the population size in persons.

Combining Equations 59.9 and 59.10 yields

$$t_p = P/[(1 - aD)kDW_e] \tag{59.11}$$

There are several transition configurations that may arise during an engineering calculation that involve the interaction between flows of people. These transitions need to be identified, as they require a different approach and have an impact on the overall calculation produced. The transitions can be categorized into merging or branching flows.

Transitions Transitions are any points in the exit system where the character or dimension of a route changes or where routes merge or branch. Typical examples of points of transition include the following:

1. Any point where an exit route becomes wider or narrower. For example, a corridor may be narrowed for a short distance by a structural change, an intruding service counter, or a similar element. The calculated density, D, and specific flow, F_s, differ before reaching, while passing, and after passing the intrusion.
2. A point where the terrain changes; that is, the point where a corridor enters a stairway. There are actually two transitions: one occurs as the egress flow passes through the doorway, the other as the flow leaves the doorway and proceeds onto the stairs.
3. The point where two or more exit flows merge; for example, the meeting of the flow from a cross aisle into a main aisle that serves other sources of exiting population. It is also the point of entrance into a stairway serving other floors.
4. Where a flow branches into several other flows. A decision has to be made regarding the proportion of the incoming flow that uses each of the outgoing flows, that is, into several other egress components. The proportion of the flows will be influenced by a number of different behavioral and procedural issues (refer to Chaps. 58 and 64, and also to Predtechenskii and Milinskii [7]). The proportion of flow using each of the egress components may be apportioned evenly, according to the capacity of the components, or according to behavioral/procedural issues, such as familiarity. Once this apportionment has been established, then each of the flow calculations proceed as before and can be conducted independently of each other.

The following rules apply when determining the densities and flow rates following the passage of a transition point:

1. The flow after a transition point is a function, within limits, of the flow(s) entering the transition point.
2. During the transition between two components, it will be necessary to establish the density in the new component; that is, it is assumed that sufficient information is available on the previous component to enable this calculation to be made. The density in the new component will be calculated by solving for D in Equation 59.9; this will produce a quadratic in D. In order to do this, the flow rate into the component will need to be known. Unless the maximum value is achieved, there will normally be two solutions of D produced: one above and one below $D_{\max}$ (where $D_{\max}$ is the density value that produces the maximum flow). Nelson and MacLennan [26], and Predtechenskii and Milinskii [7], and Milke [40] state that the smaller of the D values should be employed; that is, less than or equal to $D_{\max}$. If the larger D value (greater than $D_{\max}$) is used, it implies that the flow rate between the two components both rises and falls during a single transition. This is not considered to be reasonable.
3. The calculated flow, F_c, following a transition point cannot exceed the maximum specific flow, F_{sm}, for the route element involved multiplied by the effective width, W_e, of that element.
4. Within the limits of rule 2, the specific flow, F_s, of the route departing from a transition point is determined by the following equations:
   (a) For cases involving one flow into and one flow out of a transition point,

$$F_{s(\text{out})} = \frac{F_{s(\text{in})} W_{e(\text{in})}}{W_{e(\text{out})}} \tag{59.12}$$

   where

   $F_{s(\text{out})}$ = Specific flow departing from transition point

   $F_{s(\text{in})}$ = Specific flow arriving at transition point

   $W_{e(\text{in})}$ = Effective width prior to transition point

   $W_{e(\text{out})}$ = Effective width after passing transition point

   (b) For cases involving two incoming flows and one outflow from a transition point, such as that which occurs with the merger of a flow down a stair and the entering flow at a floor,

$$F_{s(\text{out})} = \frac{F_{s(\text{in}-1)} W_{e(\text{in}-1)} + F_{s(\text{in}-2)} W_{e(\text{in}-2)}}{W_{e(\text{out})}} \tag{59.13}$$

   where the subscripts (in-1) and (in-2) indicate the values for the two incoming flows.

   (c) For cases involving other geometry formations merging together, the following general relationship applies:

$$\begin{aligned}&\left(F_{s(\text{in}-1)} W_{e(\text{in}-1)}\right) + \cdots + \left(F_{s(\text{in}-n)} W_{e(\text{in}-n)}\right)\\ &= \left(F_{s(\text{out}-1)} W_{e(\text{out}-1)}\right) + \cdots + \left(F_{s(\text{out}-n)} W_{e(\text{out}-n)}\right)\end{aligned} \tag{59.14}$$

   where the letter n in the subscripts (in-n) and (out-n) is a number equal to the total number of routes entering (in-n) or leaving (out-n) the transition point.
5. Where the calculated specific flow, F_s, for the route(s) leaving a transition point, as derived from the equations in rule 4, exceeds the maximum specific flow, F_{sm}, a queue will form at the incoming side of the transition point. The number of persons in the queue will grow at a rate equal to the calculated flow, F_c, in the arriving route minus the calculated flow leaving the route through the transition point.
6. Where the calculated outgoing specific flow, $F_{s(\text{out})}$, is less than the maximum specific flow, F_{sm}, for that route(s), there is no way to predetermine how the incoming routes will merge. The routes may share access through the transition point equally, or there may be total dominance of one route over the other. For conservative calculations, assume that the

route of interest is dominated by the other route(s).

A simple example is presented in order to clarify the required calculations [40]. This simple example is followed by a more comprehensive example illustrating the two different hydraulic models: first- and second-order hydraulic models.

Example 1 A 1.8 m (approximately 6 ft) wide (descending) 7/11 stair has 10 risers and leads to a 10 m long (approximately 33 ft), 1.8 m wide corridor (approximately 6 ft). At the end of the corridor, there is a 1.3 m (approximately 4 ft 3 in.) wide door (Fig. 59.9). This door is mechanically held open. How long does it take for 50 people starting at the top of the stairs with an initial density of 1.5 p/m^2 (p = persons) to exit from the door at the end of the corridor?

Solution The velocity can be calculated according to Equation 59.5:

$$S = \mathrm{k} - \mathrm{ak}D$$

For 7/11 stair, k = 1.08:

$$\begin{gathered} 1.08 - (0.266)(1.08)(1.5) \\ \therefore S = 0.65 \ \ \mathrm{m/s}(128 \ \ \mathrm{ft/min}) \end{gathered}$$

The time to traverse the stair can then be calculated. The distance to be covered is

$$\begin{gathered} 10 \ \ \text{risers} = 70 \ \ \text{in.} = 1.78 \ \ \text{m}; 10 \ \ \text{treads} = 110 \ \ \text{in.} = 2.79 \ \ \text{m} \\ \text{diagonal length} = 3.31 \ \ \text{m(approximately} \ \ 10 \ \ \text{ft} \ \ 10 \ \ \text{in.)} \end{gathered}$$

Therefore, the time to cover the stairs is 3.31/0.65 = 5.1 s.

The width of the stair can be calculated using Table 59.1 (1.8–0.3 m). Given that the density (1.5 p/m^2) and the velocity (0.65 m/s) are known, the flow rate on the stair using Equation 59.9 can now be determined:

$$\begin{gathered} F_c = F_s W_e = (\mathrm{k} - \mathrm{ak}D)DW_e \\ F_c = 1.46 \, \mathrm{p/s} \end{gathered}$$

This value produces a specific flow rate less than the maximum value and so it can therefore be used during the calculation.

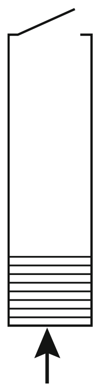


Fig. 59.9 Geometry used in Example [1]

The time delay for the last person to start on the stair can be calculated as follows. With a flow rate of 1.46 p/s on the stair (and thus of the queue entering the stair), the time for the queue to dissipate is calculated using Equation 59.10:

$$t_p = P/F_c$$

The time for the population at the top of the stairs to enter the stairs is then

$$50/1.46 = 34.2 \ \ s$$

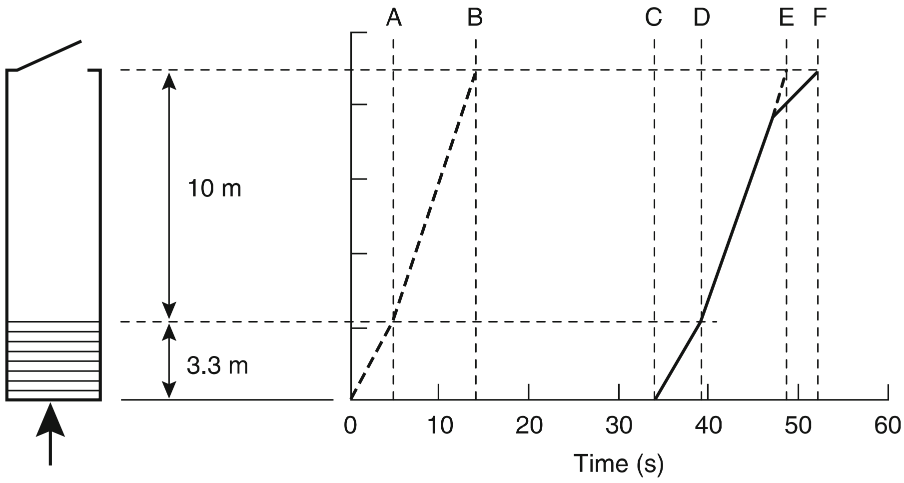
The time for the entire population to enter the staircase and the time to traverse the staircase are now known. Given this, the time taken for the last person to enter and traverse the staircase can be determined. The time to traverse the corridor now needs to be calculated.

The flow rate into the corridor is 1.46 p/s; that is, that produced on the staircase. Equation 59.9 states that

$$F_c = F_s W_e = (\mathrm{k} - \mathrm{ak}D)DW_e$$

where F_c can be set to 1.46; this equation can now be solved for D.

Fig. 59.10 Movement of people through the components



For a corridor, k is set to 1.40. Given the corridor is 1.8 m in width, the effective width is $W_e = 1.4$ m (4 ft 7 in).

Therefore, solving for D

$$0.266D^2 - D + (1.46/1.4 \times 1.4) = 0$$
$$0.266D^2 - D + 0.744 = 0$$

Solving for D, it is therefore either 1.03 or 2.72 p/m^2.

$$\therefore D = 1.03 \text{ or } 2.72 \text{ p/m}^2 (0.1 \text{ or } 0.25 \text{ p/ft}^2)$$

From the previous discussion regarding selecting D values, a value of 1.03 p/m^2 (0.1 p/ft^2) should be chosen.

Given that the density is known and the relationship between density and velocity is expressed in Equation 59.5:

$$S = \mathrm{k} - \mathrm{ak}D$$

the velocity, S, can be calculated as being 1.02 m/s (201 ft/min). The time to traverse the corridor is therefore 10/1.02 = 9.8 s. The flow through the doorway at the end of the series of components can now be determined. Given the narrowing at the door, the formation of the queue should be examined. The specific flow rate at the door is calculated using Equation 59.8:

$$F_s = F_c/W_e = 1.46/1.0$$

$F_s = 1.46$ p/s/m (27 p/min/ft) $> F_{sm}$, where the value of F_{sm} is 1.3 p/s/m (24 p/min/ft). The time for the population to flow through the doorway is then calculated using Equation 59.10:

$$t_p = N/F_s W_e = 50/(1.3/1.0) = 38.5 \text{ s}$$

The final solution is not simply formed from adding these values together, as some of them occur simultaneously. The final result is better explained by referring to Fig. 59.10.

The dashed line indicates the movement of the first person. This person is not influenced by queuing at any point and is therefore constrained only by the velocity values derived from the densities calculated on the different components. This person therefore spends 5.1 s traversing the stairs and 9.8 s traversing the corridor, reaching the final exit after 14.9 s (marked A and B in Fig. 59.10). The entire population entered the staircase after 34.2 s (marked C in Fig. 59.10) and has reached the end of the stairs after 34.2 + 5.1 = 39.3 s (marked D in Fig. 59.10). The last person from this group will have reached the exit at 49.1 s, assuming that person did not encounter any congestion approaching the door (marked E in Fig. 59.10). Given that the first person has reached the exit after 14.9 s and that the congestion at the final exit lasted for 38.5 s, this congestion is not clear until 53.4 s (marked F in Fig. 59.10, indicating the end of the solid curve). Therefore, the last person to arrive interacts with the congestion at some point prior to reaching the door; that is, the congestion still exists when that person arrives. The evacuation time is then determined by the time taken for the congestion to clear at the final exit (e.g., 53.4 s).

First- and Second-Order Hydraulic Models

The various calculations discussed in the previous section can be combined in order to assess the movement component of the evacuation process; that is, to calculate t_e. By applying these calculations, the necessary movement components (e.g., flow rates, velocities, population densities, and travel speeds) can be established enabling the overall movement time to be found.

First-Order Hydraulic Model

There are several ways in which these movement calculations can be used; two are described here. The first-order hydraulic model represents a simplified approach: instead of calculating the flow of people between individual components, this method focuses on the component that places the most severe constraint on the flow of people around the structure and then uses this constraint to determine the movement time. The engineer is required to establish the time to reach the controlling component; the time for the population to traverse this component; the time for the last person to leave the controlling component; and the time for the last person to reach safety from the controlling component [43]. This process is outlined in Fig. 59.11a. This approach makes greater use of the maximum flow rates and densities allowed, given the reduced level of calculation required. The controlling component will depend on the nature of the structure; for example, the controlling component could be a stair, an exit from the stair, an exit from a room, and so on.

Second-Order Hydraulic Model

The second-order hydraulic model requires that the flow of people between each of the structural components (i.e., between areas where the physical constraints affecting egress performance change) is calculated. This is more labor intensive than the first-order approach, requiring a larger number of calculations to be made; however, it does require fewer assumptions and provides information on the movement between each of the structural components in the egress route rather than a subset of them. A second-order analysis is by no means a trivial task and requires judgment based on the structure examined and the incident scenario. This process is outlined in Fig. 59.11b.

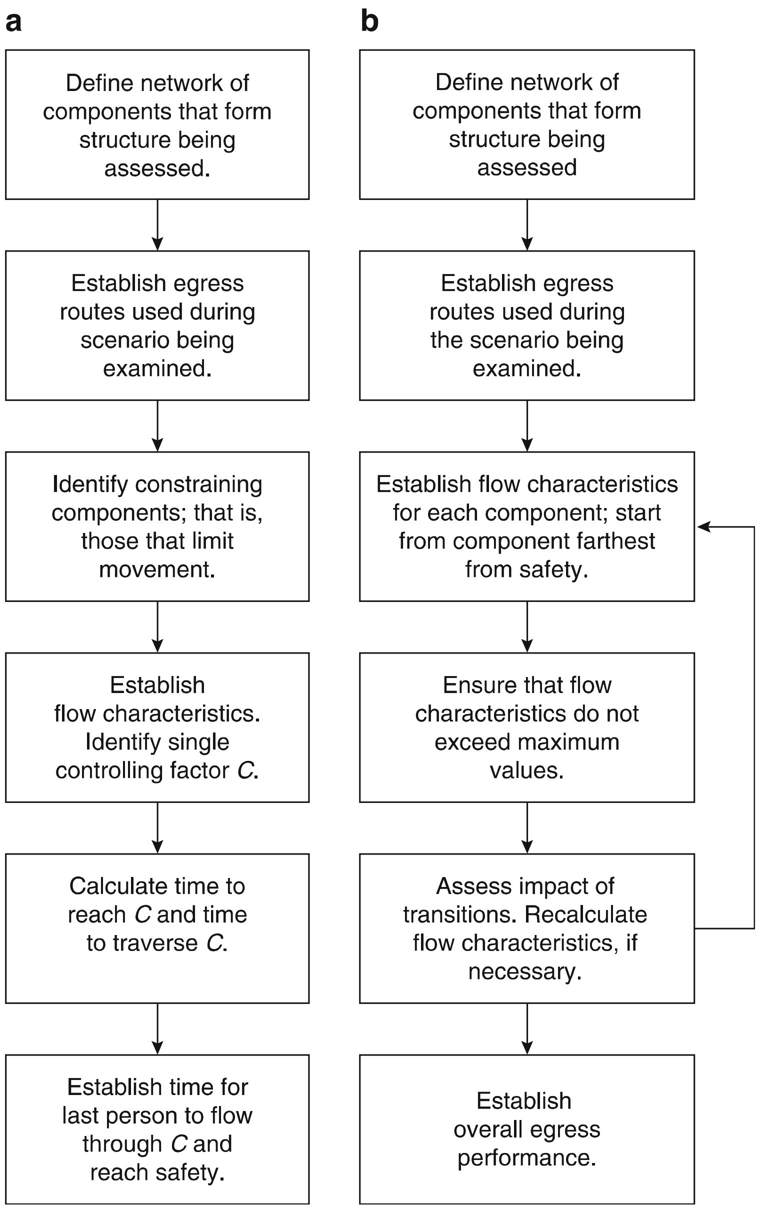
Example Applications

The first- and second-order hydraulic models can be better understood through the description of two example applications. (More examples can be found elsewhere [43].) A relatively simple example is presented, although even in this case the difference between the effort required in applying the two versions of the model is apparent.

Example 2 Consider an office building (Fig. 59.12) with the following features:

1. There are nine floors, 300 ft by 80 ft (91 m by 24 m).
2. Floor-to-floor height is 12 ft (3.7 m).
3. Two stairways are located at the ends of the building (there are no dead ends).
4. Each stair is 44 in. (1.12 m) wide (tread width) with handrails protruding 2.5 in. (0.063 m).
5. Stair risers are 7 in. (0.178 m) wide and treads are 11 in. (0.279 m) high.
6. There are two 4 ft by 8 ft (1.2 m by 2.4 m) landings per floor of stairway travel.
7. There is one 36-in. (0.91-m) clear width door at each stairway entrance and exit. These are assumed not to be mechanically held open.
8. The first floor does not exit through stairways.
9. Each floor has a single 8-ft (2.4-m) wide corridor extending the full length of each floor. Corridors terminate at stairway entrance doors.

Fig. 59.11 (**a**) First-order hydraulic model; (**b**) second-order hydraulic model



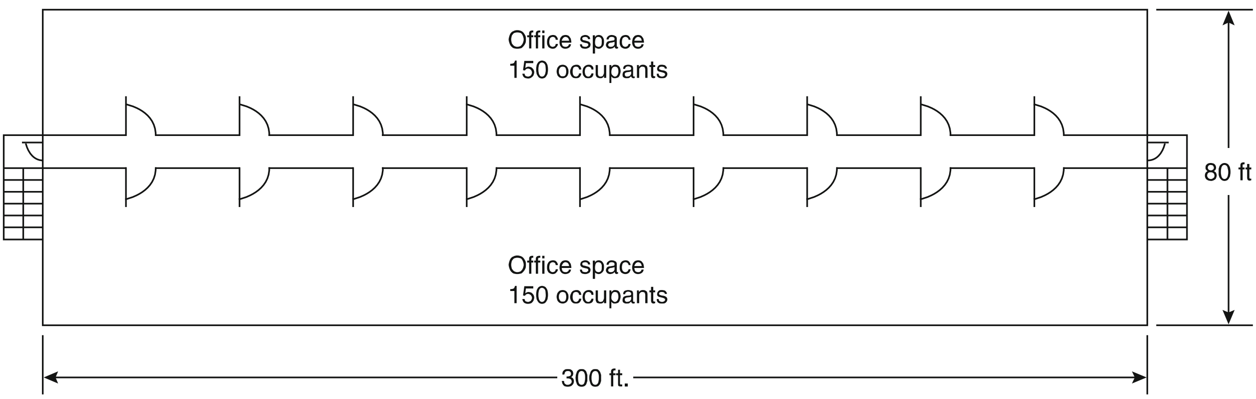


Fig. 59.12 Floor plan for example

10. There is a population of 300 persons/floor.

Solution A First-Order Approximation.

1. Assumptions.

   The prime controlling factor will be either the stairways or the door discharging from them. Queuing will occur; therefore, the specific flow, F_s, will be set to the maximum specific flow, F_{sm}. All occupants start evacuating at the same time. The population will use all facilities in the optimum balance.

2. Estimate flow capability of a stairway.

   From Table 59.1, the effective width, W_e, of each stairway is 44 − 12 = 32 in. (2.66 ft) (813 mm [0.81 m]). The maximum specific flow, F_{sm}, for the stairway (from Table 59.5) is 18.5 persons/min/ft (1.01 persons/s/m) of effective width. Specific flow, F_s, equals maximum specific flow, F_{sm}. Therefore, using Equation 59.6, the flow from each stairway is limited to 18.5 × 2.66 = 49.2 persons/min.

3. Estimate flow capacity through a door.

   Again from Table 59.5, the maximum specific flow through a 36-in. (0.9 m) door is 24 persons/min/ft (1.31 persons/s/m) of effective width. Also, the effective width, W_e, of each door is 36 − 12 = 24 in. (2 ft) (609 mm [0.61 m]). Therefore, using Equation 59.8, the flow through the door is limited to 24 × 2 = 48 persons/min. This is less than the maximum flow rate through an exit that is not mechanically held open (50 p/min). Because the flow capacity of the doors is less than the flow capacity of the stairway served, the flow is controlled by the stairway exit doors (48 persons/stairway exit door/min).

4. Estimate the speed of movement for estimated stairway flow.

   From Equation 59.5 the speed of movement down the stairs is $212-(2.86 \times 212 \times 0.175) = 105\ \text{ft/min}(0.53\ \text{m/s})$. The travel distance between floors (using the conversion factor from Table 59.3) is 12 × 1.85 = 22.2 ft (6.8 m) on the stair slope plus 8 ft (2.4 m) travel on each of the two landings, for a total floor-to-floor travel distance of $22.2+(2 \times 8) = 38.2\ \text{ft}(11.6\ \text{m})$. The travel time for a person moving with the flow is 38.2/105 = 0.36 min/floor.

5. Estimate building evacuation time.

   If all of the occupants in the building start evacuation at the same time, each stairway can discharge 48 persons/min. The population of 2400 persons above the first floor will require approximately 25 min to pass through both exits. An additional 0.36-min travel time is required for the movement from the second floor to the exit. (A more conservative estimate of the travel time might also include the time for the first person to move from within the second floor to the stair.) The total minimum evacuation time for the 2400 persons located on floors 2 through 9 is estimated at 25.4 min.

Solution B Second-Order Approximation.

1. Assumptions.

   The population will use all exit facilities optimally; all occupants start egress at the same time. All persons are assumed to start to evacuate at time zero.

2. Estimate flow density (D), speed (S), specific flow (F_s), effective width (W_e), and initial calculated flow (F_c) typical for each floor.

3. Divide each floor in half to produce two exit calculation zones, each 150 ft (45.7 m) long. To determine the density, D, and speed, S, if all occupants try to move through the corridor at the same time, that is, 150 persons moving through 150 ft of an 8-ft (2.4-m) wide corridor:

$$\begin{aligned} D &= 150\ \text{persons}/1200\ \text{ft}^2\text{corridor area} \\ &= 0.125\ \text{persons}/\text{ft}^2 \end{aligned}$$

From Equation 59.5, $S = \text{k} - \text{ak}D$.
From Table 59.2, k = 275.

$$\begin{aligned} S &= 275-(2.86 \times 275 \times 0.125) \\ &= 177\ \text{ft/min}\ (54\ \text{m/min}) \end{aligned}$$

From Equation 59.7, $Fs = (1-\text{a}D)\text{k}D$.

$\text{F}_\text{s} = [1-(2.86 \times 0.125)] \times 275 \times 0.125 = 22$ persons/min/ft(1.2 persons/s/m) effective width

From Table 59.5, F_s is less than the maximum specific flow, F_{sm}; therefore, F_s is used for the calculation of calculated flow.

From Table 59.1, the effective width of the corridor is

$$8 - (2 \times 0.5) = 7 \text{ ft}(2.13 \text{ m})$$

From Equation 59.9, calculated flow, $F_c = (1 - aD)kDW_e$.

$$F_c = [1 - (2.86 \times 0.125)] \times 275 \times 0.125 \times 7$$
$$= 154 \text{ persons/min}$$

At this stage in the calculation, calculated flow, F_c, is termed initial calculated flow for the exit route element (i.e., corridors) being evaluated. This term is used because the calculated flow rate can be sustained only if the discharge (transition point) from the route can also accommodate the indicated flow rate.

4. Estimate impact of stairway entry doors on exit flow.
   Each door has a 36-in. (0.91-m) clear width.
   From Table 59.1, effective width is

$$W_e = 36 - 12 = 24 \text{ in. } (2 \text{ ft})(0.61 \text{ m})$$

From Table 59.5, the maximum specific flow, F_{sm}, is 24 persons/min/ft effective width.

From Equation 59.12,

$$F_{s(\text{door})} = \left(F_{s(\text{corridor})} W_{s(\text{corridor})}\right) / W_{e(\text{door})}$$
$$= (22 \times 7)/2 = 77 \text{ persons/min/ft}$$
$$(4.2 \text{ persons/s/m}) \text{ effective width}$$

Since F_{sm} is less than the calculated F_s, the value of F_{sm} is used. Therefore, the effective value for specific flow is 24 p/min/ft.

From Equation 59.8, the initial calculated flow,

$$F_c = F_s W_e = 24 \times 2 = 48 \text{ persons/min}$$

through a 36-in. (0.91-m) door. Since F_c for the corridor is 154 p/min while F_c for the single exit door is 48 p/min, queuing is expected. The calculated rate of queue buildup will be

$$154 - 48 = 106 \text{ persons/min}$$

5. Estimate impact of stairway on exit flow.
   From Table 59.1, effective width, W_e, of the stairway is

$$44 - 12 = 32 \text{ in.}(2.66 \text{ ft}) \quad (0.81 \text{ m})$$

From Table 59.5, the maximum specific flow, F_{sm}, is 18.5 persons/min/ft (1.01 persons/s/m) effective width. From Equation 59.12, the specific flow for the stairway,

$$F_{s(\text{stairway})} = 24 \times 2/2.66 = 18.0 \text{ persons/min/ft}$$
$$(0.98 \text{ persons/s/m}) \text{effective width}$$

In this case, F_s is less than F_{sm} and F_s is used.

The value of 18.0 p/min/ft for F_s applies until the flow down the stairway merges with the flow entering from another floor.

Using Fig. 59.8 or Equation 59.7 and Table 59.2, the density of the initial stairway flow is approximately 0.146 persons/ft^2 (1.6 person/m^2) of stairway exit route. From Equation 59.5 the speed of movement during the initial stairway travel is

$$212 - (2.86 \times 212 \times 0.146)$$
$$= 123 \text{ ft/min}(0.628 \text{ m/s})$$

This value differs from that produced in the first-order, which is based on the maximum achievable density rather than a calculated density.

From the first-order solution, the floor-to-floor travel distance is 38.2 ft (11.6 m). The time required for the flow to travel one floor level is

$$38.2/123 = 0.31 \text{ min}(19 \text{ s})$$

Using Equation 59.8, the calculated flow is

$$F_c = 18.0 \times 2.66 = 48 \text{ persons/min}$$

After 0.31 min, 15 (i.e., 48 × 0.31) persons will be in the stairway from each floor feeding to it. If floors 2 through 9 exit all at once, there will be

$15 \times 8 = 120$ persons in the stairway

After this time the merging of flows between the flow in the stairway and the incoming flows at stairway entrances will control the rate of movement.

6. Estimate impact of merging of stairway flow and stairway entry flow on exit flow.
   From Equation 59.13,

$$
\begin{aligned}
F_{s(\text{out-stairway})} &= \left[\left(F_{s(\text{door})} \times W_{e(\text{door})}\right) + \left(F_{s(\text{in-stairway})} \times W_{e(\text{in-stairway})}\right)\right]/W_{e(\text{in-stairway})} \\
&= [(24 \times 2) + (18 \times 2.66)]/2.66 \\
&= 36 \ \text{persons/min/ft}(1.97 \ \text{prsons/s/m}) \\
&\quad \text{effective width}
\end{aligned}
$$

From Table 59.5, F_{sm} for the stairway is 18.5 persons/min/ft (1.01 persons/m/s) effective width. Since F_{sm} is less than the calculated F_s, the value of F_{sm} is used.

7. Track egress flow.
   Assume all persons start to evacuate at time zero. Initial flow speed is 177 ft/min (0.9 m/s). Assume that congested flow will reach the stairway in approximately 0.5 min. This conservative assumption is based on the population having to travel a distance of between 50 ft and 150 ft (15.2 m and 45.7 m) to the exit traveling at 177 ft/min (0.9 m/s); that is, the derived travel speed in the corridor. At 0.5 min, flow starts through stairway doors. F_c through doors is 48 persons/min for the next 19 s (0.31 min). At 49 s, 120 persons are in each stairway and 135 are waiting in a queue at each stairway entrance.
   How the evacuation progresses from this point on depends on which of the floors take precedence in entering the stairways. Any sequence of entry may occur [1]. To set a boundary, this example estimates the result of a situation where dominance proceeds from the highest to the lowest floor.
   The remaining 135 persons waiting at each stairway entrance on the ninth floor enter through the door at the rate of 48 persons/min. The rate of flow through the stairway is regulated by the 48 persons/min rate of flow of the discharge exit doors. The descent rate of the flow is 19 s/floor.

Therefore, referring to Equations 59.8, 59.10, and 59.11, at

$$(135/48) \times 60 + 49 = 218 \ \text{s}(3.6 \ \text{min})$$

all persons have evacuated the ninth floor.
At

$$[(135/48) \times 60 + 49] + 19 = 237 \text{ s } (4.0 \text{ min})$$

the end of the flow reaches the eighth floor.
At

$$237 + \{[(135/(2.66 \times 18.5)] \times 60\} \\ = 401 \ \text{s}(6.7 \ \text{min})$$

all persons have evacuated the eighth floor.
At

$$(401 + 19) = 420 \ \text{s } (7.0 \ \text{min})$$

the end of the flow reaches the seventh floor.
At

$$420 + \{[135/(2.66 \times 18.5)] \times 60\} \\ = 584 \ \text{s}(9.7 \ \text{min})$$

all persons have evacuated the seventh floor.

At 603 s (10.1 min)	The end of the flow reaches the 6th floor
At 767 s (12.8 min)	All persons have evacuated the 6th floor
At 786 s (13.1 min)	The end of the flow reaches the 5th floor
At 950 s (15.8 min)	All persons have evacuated the 5th floor
At 969 s (16.2 min)	The end of the flow reaches the 4th floor

(continued)

At 1133 s (18.9 min)	All persons have evacuated the 4th floor
At 1152 s (19.2 min)	The end of the flow reaches the 3rd floor
At 1316 s (21.9 min)	All persons have evacuated the 3rd floor
At 1335 s (22.3 min)	The end of the flow reaches the 2nd floor
At 1499 s (25.0 min)	All persons have evacuated the 2nd floor
At 1518 s (25.3 min)	All persons have evacuated the building

From this example it is clear that in some situations little difference exists in the results produced by the use of the two basic hydraulic models (first and second order). This may be expected in simple geometries and simple movement scenarios. However, as the scenarios and geometries become more complex, the results produced by the two versions of the model may differ significantly, especially if there are difficulties in establishing the controlling element in the first-order approximation.

The second-order hydraulic model produces a larger set of information (e.g., the time to clear components, the time to clear floors, the movement conditions between all structural components, etc.). However, it is sensitive to which of the components have precedence (e.g., in merging flows) and in the proportion of the population using particular routes. This may require several calculations to establish the most conservative result. The first-order hydraulic model produces only the overall evacuation time and the results relating to the constraining component. It should also be noted that in complex geometries identifying the constraining component is not a trivial task, and it can be extremely time consuming.

Given that an assessment of a structure is necessary, it is important to identify the scenarios involved in this assessment. It may not be possible to definitively establish the worst-case scenario prior to the calculation. It is therefore essential to examine several representative scenarios that form a set of predictions. This will offer insight into the scenarios examined and more reliably provide an estimate of the longest RSET value to be expected, as compared with the assessment of a single scenario.

Employing Extended Hydraulic Model to Calculate t_{esc}

Factors Influencing an Evacuation

The extended hydraulic model provides a foundation to evaluate evacuation performance, that is, escape time (t_{esc}) as opposed to evacuation movement time (t_e). Figure 59.3 indicates that there are more factors that actually influence an evacuation than can currently be modeled. The factors that can be included are dependent on our understanding of real-life phenomena, on the data available, and on the limitations of the model adopted. As has already been stated, the hydraulic model outlined here can be employed in the examination of different egress scenarios. This is critical in generating a robust and representative solution.

A number of behaviors can influence the performance of the population. It is possible to *implicitly* represent some of these behaviors (i.e., the consequences of these behaviors) by manipulating parameters associated with the hydraulic model and then examining a range of scenarios.

In order to increase the information obtained in any egress analysis and the confidence in this information, a representative set of egress scenarios could be examined. Producing one "definitive" result is insufficient, given the many scenarios that can actually develop and also given the limitations of the modeling approach. Presenting a single answer may produce overconfidence in the accuracy and validity of the result.

Basic Variables

Given the scope of the extended hydraulic approach, the scenarios that can be examined are limited and require the manipulation of a few basic variables:

- The routes available during the evacuation
- The evacuee's use of the routes available during the evacuation
- The movement attributes of the evacuating population and the presence of impairments and disabilities
- The time taken to respond to the call to evacuate—the pre-evacuation time (t_{p-e})

When using the extended hydraulic model, these variables can be manipulated to produce a number of different scenarios and therefore an envelope of results. By manipulating these variables, at least a small subset of the behaviors that might detract from egress performance can be accounted for, albeit in an implicit way. The manner in which this is performed will be dependent on the nature of the occupancy being examined and the scenarios that are considered as realistic. The scenarios examined (and omitted) by the engineer should be justified through a detailed explanation accompanying the reported results. In addition, the scope of the results can be extended to represent t_{esc} rather than just t_e.

Routes Available During the Evacuation In some scenarios it is possible that routes will be lost due to the nature of the incident or given the use of the space available; for example, a route might not be protected. This loss can be considered.

Some existing codes require such forms of analysis. For instance, in the British Standard BS5588 [44], the largest exit is discounted, assumed blocked by the incident. In NFPA *101* one scenario requires the evaluation of the impact of a fire located in the primary means of egress [41].

The hydraulic model can be manipulated to represent the loss of available egress routes. In the example shown in Fig. 59.12, an entire staircase could be presumed lost due to the nature of the incident. This would have a profound impact on the results produced. Instead of an overall evacuation time of 25.4 min, it instead required 50.4 min, when applying the first-order approximation. The calculation may also involve the loss of individual components, rather than the entire egress route.

Evacuee's Use of the Routes Available During the Evacuation In reality, egress routes are rarely used according to their design capacity (i.e., efficiently). Instead, routes are used according to occupant familiarity, visual access, the procedure in place, and the evolution of the incident itself. [4, 45] This reality can be represented within the hydraulic model by modifying the proportion of the population using a particular route. Although it might be difficult to gather accurate data on the use of the routes available, engineering judgment could still be used to assess the potential impact of the unbalanced use of the egress routes available. For instance, in the example shown in Fig. 59.12 it was assumed that the population used the egress routes in an optimal manner; that is, that they split evenly between the staircases. It may be the case that one route is more familiar to the population than another (through normal use, proximity to elevators, connectivity to nearby car park, etc.). This inefficient use can then be reflected in the calculations by more people using one of the routes available. If it is assumed that 75 % of the population make use of one of the staircases, then applying the first-order model produces an overall egress time of approximately 37.9 min (1800/48 + 0.36). As a consequence, the other staircase would clear more quickly.

Movement Attributes of the Evacuating Population The makeup of the population can vary over time. Variations in the population's capabilities can be represented through the modification of the maximum velocities that can be attained. The range of the population's capabilities can be extended to include the presence of the mobility impaired. Although the reduction of velocities represents only one aspect of impairment (e.g., it does not represent behavioral issues, pre-evacuation issues, the impact that the presence of the mobility impaired might have on population densities, etc.), it is still an important consideration. This may be of particular importance where the egress performance is not dominated by congestion and flow constraints, but by travel distances. Looking at the example presented above, in the first-order model, the presence of the impaired may increase the 0.36 min to travel between the floors on stairs. In the second-order model, it may have a more complex effect. It could also be taken into consideration when determining the t_{p-e} component, with a population with impairments extending the preparation required.

Time Taken to Respond Part of the RSET calculation (see Equation 59.1) requires the assessment of a pre-evacuation phase, t_{p-e}; this phase is the time between notification and the time for the population to evacuate. It can be varied given the scenario being represented, the notification system in place, the procedures employed, and so on. This time may then allow limited comparisons to be made between different procedural measures, notification systems, and the like. Pre-evacuation time may be particularly important where scenarios are not dominated by flow and the egress route capacities [1]. However, it should be recognized that the potential benefits of distributing the response of the population cannot be represented in the hydraulic approach given its fundamental assumptions.

In reality, the relationship between the pre-evacuation phase and the evacuation phase is complex. It is not simply a case of adding the times of the two phases together. Given the scenario, the extent of the pre-evacuation time distribution may increase or reduce the level of congestion produced. This complex relationship is difficult to represent unless the evacuees are simulated on an individual basis (see Chap. 60).

Data are required in order to include these factors in the calculation. These data, particularly regarding the pre-evacuation phase, are scarce and not always reliable (see Chap. 64). Although this limitation should be acknowledged, it does not preclude further engineering analysis. Even where engineering judgment is required, it is still critical to assess the robustness of the results by trying to account for these factors. Where it is not relevant or possible, then it should be clearly stated allowing the exclusion of the factors from the assessment to be judged.

Developing Escape Scenarios

As mentioned previously, when assessing the egress performance of a structure, it is vital to produce results that cover a range of scenarios. This process adds to the robustness of the results and the credibility; that is, it is not credible that the use of a hydraulic model (or any other model) would produce a definitive, single result. This is discussed in more detail in Chap. 57 and has been discussed and developed elsewhere (e.g. in PD 7975-6:2004) [46]. Ideally, a number of scenarios should be examined. A viable set of scenarios can be produced by varying factors within the hydraulic model (including those identified in the previous section) in a logical manner. Given that several factors are represented (e.g., speed, flow, route availability/usage, pre-evacuation times), each of these factors can be modified to implicitly represent different scenarios. Using this approach, a range of viable scenarios can be examined that produce different RSET values. Once complete, the longest RSET value generated would then be used for comparison against the ASET value produced.

Purser identified two base scenarios that can then be modified through the manipulation of model variables in order to produce sets of scenarios for analysis (Fig. 59.13) [1]. This is just one suggested approach at gaining a broader insight into the evacuation performance of a structure and establishing RSET using an engineering calculation; however, it is indicative of the different scenarios that can be examined.

Purser identified that in sparsely populated spaces, the overall egress time produced (t_{esc}) is more sensitive to the time taken to traverse the distance to a place of safety and the time taken to respond, than to the time for congestion to evaporate. In such situations, it is unlikely that egress

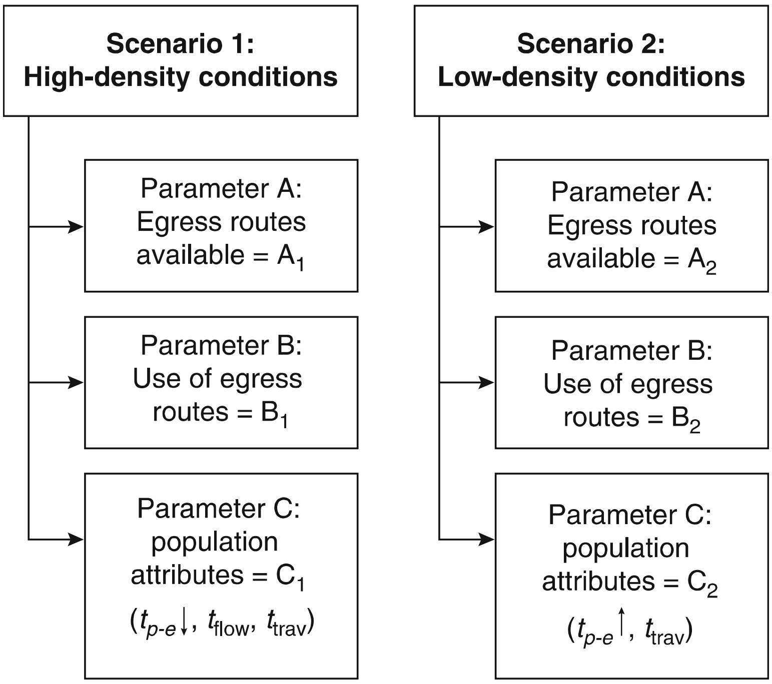


Fig. 59.13 Generation of scenarios by manipulating parameters

components will be overloaded and generate queues that dominate the egress performance.

In densely populated spaces, Purser identified that it is more likely that congestion will be produced. In such situations, the response of individuals may be influenced by observing the activities of other evacuees [45, 47]. This is likely to reduce the distribution of pre-evacuation times produced. This implies that the population will arrive at structural components within a smaller range of times. Therefore, the time to reach a point of safety is likely to be highly sensitive to the clearance of congestion along the egress routes.

When applying a sophisticated simulation model, the factors that determine the outcome of a scenario (e.g., whether it is determined by flow, travel, etc.) will be a *result* of the analysis (see Chap. 60). Given the limitations of the hydraulic model, the engineer has to *impose* these conditions prior to the calculation being conducted (e.g., whether congestion or travel distance determines the time to reach safety) and then assess their impact; the critical behavioral/movement components are determined prior to the calculations being made. The Purser approach can be applied in order to establish what underlying factors determine the overall evacuation time, by examining scenarios where the results are determined by different factors; for example, flow and/or travel and response. For a single structure the impact of these different scenarios can be assessed to establish which of them produces the most prolonged egress time.

When using the Purser approach to establish the evacuation time from a particular structure, it is assumed that the engineer cannot be sure which of these scenarios will produce the longer escape time, prior to the calculation being conducted. Both scenarios are therefore examined. Each of the scenarios includes an assessment of the population movement (i.e., t_e) and the pre-evacuation phase (i.e., t_{p-e}). The combined result of these two phases is termed t_{esc} (see Equation 59.2). Where other new terms are used below, they are described.

Purser identified two situations (labeled Scenarios 1 and 2 in Fig. 59.13). In Scenario 1 it is assumed that congestion dominates the results produced (t_{flow}). In such situations the time required for the evacuation of an enclosure depends on the pre-evacuation time and unrestricted walking time of the first few occupants to start to leave; these determine the time for congestion to develop. Once queues have formed at the “constraining” component, the time to clear the building becomes a function of the number of occupants and the evacuation flow rate capacity of these components. The evacuation time for an enclosure is estimated to be

$$t_{\mathrm{esc}} = t_{p-e1} + t_{\mathrm{trav}} + t_{\mathrm{flow}} \tag{59.15}$$

where t_{p-e1} is the pre-evacuation time associated with the first people to respond. Purser uses the first percentile of a representative pre-evacuation distribution to estimate this value [1]. If this is not available, then the average pre-evacuation time associated with the occupancy (which is more likely to be available; see Chap. 64) should be used as a conservative estimate. t_{flow} is the time of total occupant population to flow through the most restrictive components. t_{trav} is the time taken to traverse the average distance to a place of safety. (The maximum distance should be employed in this calculation for a more conservative approach.)

It is apparent that either the first- or second-order hydraulic model can be used to generate t_{flow} and t_{trav}; indeed the combination of these two parameters approximates the t_e term previously described (see Equation 59.4).

In Scenario 2 it is assumed that congestion does not dominate the results; the results are primarily influenced by the time taken to reach safety (t_{trav}) and the time to respond (t_{p-e}). This scenario is not necessarily based on the assumption that congestion does not develop; only that the impact of the congestion is dominated by the extensive pre-evacuation phase and the distances that need to be traversed, and is not a factor in the calculation. The egress time for an enclosure is given by

$$t_{\mathrm{esc}} = t_{p-e1} + t_{p-e99} + t_{\mathrm{trav}} \tag{59.16}$$

where t_{p-e99} is the pre-evacuation time for the last few occupants to respond (i.e. the 99th percentile). Purser uses the 99th percentile of a representative pre-evacuation distribution to estimate this value [1]. If this is not available, then a multiple of the mean pre-evacuation time should be employed; it is not appropriate to use the average pre-evacuation time. The pre-evacuation times usually form a log-normal distribution [1, 47]. Given the limited data currently available it appears that the 99th percentile can be reasonably approximated by a value of four to five times the mean pre-evacuation time [25, 30, 47–50].

Again the example shown in Fig. 59.12 can be used to illustrate the two different scenarios. Let us assume that the structure represents an office space as indicated. In the first analysis, it is assumed that the evacuation is dependent on flow characteristics (i.e., Purser's Scenario 1) and will therefore make use of the flow calculations already made. In addition, pre-evacuation times will be extracted from the work conducted by Fahy and Proulx to support these calculations [25]. Given that it is an office space, pre-evacuation times ranging from 1 to 6 min will be assumed. These times are employed as conservative estimates of the 1st and 99th percentiles.

Given the results already produced, the evacuation time for Scenario 1 can be estimated as being

$$t_{\mathrm{esc}} = 1 + 25.3 = 26.3\ \mathrm{min}$$

This time is based on the assumption that t_{trav} and t_{flow} is approximated by the results produced in the second-order model.

If instead it is assumed that, for some reason, this scenario was not determined by flow (i.e., Purser's Scenario 2), then the following calculation can be made:

$$\begin{aligned} t_{\mathrm{esc}} &= 1 + 6 + (0.5) + (8 \times 38.2)/187 \\ &= 9.2\ \mathrm{min} \end{aligned}$$

Here, t_{p-e1} is again assumed to be 1 min, while t_{p-e99} is assumed to be 6 min, with both values being derived from Fahy and Proulx [25]. The distance calculations generated by the first-order model are used here. In this case Scenario 1 produces the most prolonged evacuation times and would therefore be used in the estimation of the RSET value.

If it is now assumed that the space is instead a mid-rise apartment building, rather than an office space, then different pre-evacuation times are suggested by the data [25]. In this case, pre-evacuation values of 1–24 min are used (again derived from Fahy and Proulx [25]). In this case the calculations become

$$\text{Scenario } 1: t_{\text{esc}} = 1 + 25.3 = 26.3 \text{ min}$$

and

$$\begin{aligned}\text{Scenario } 2: t_{\text{esc}} &= 1 + 24 + (0.5) + (8 \times 38.2)/187 \\ &= 27.1 \text{ min}\end{aligned}$$

Once the set of scenarios have been examined, the longest t_{esc} value produced should then be employed to generate the RSET calculation. In this case Scenario 2 produces the most extended evacuation time and would therefore be used in any RSET calculations.

This is certainly not the only approach for producing a range of scenarios (or at understanding what factors should be taken into consideration [51]). However, it does demonstrate how several different scenarios can be considered using the hydraulic approach allowing comparisons to be made between the results produced. This approach can be taken further by incorporating the other parameters deemed to be amenable to the hydraulic approach; for example, manipulating the routes available, familiarity, mobility impairments, and so on.

The results will always be limited by the sophistication and fidelity of the model employed. However, the examination of different scenarios is critical in providing a reasonable understanding of the conditions that might arise. Inevitably, there may be cases where data are not available to support these calculations. These situations will require engineering judgment. These cases should be documented and based on the most reliable and appropriate information available.

Addressing Modeling Error

The hydraulic model, whether it is the standard or extended version, produces only *modeled* predictions. The actual egress time will exceed the modeled time by an unknown amount. This is due to the exclusion from the model of many of the factors that might inhibit evacuation performance (e.g., t_{n-e}) and also to limitations in the data available (see Chap. 60). The difference between modeled evacuation movement time and actual evacuation movement time can be expressed in the following terms:

$$t_e^{\text{act}} = t_e^{\text{mod}} e \tag{59.17}$$

where

t_e^{act} = Actual time from when purposive evacuation movement commenced to when safety was reached

t_e^{mod} = Modeled estimate from when purposive evacuation movement commenced to when safety was reached

e = Modeling error

It is assumed here that the relationship is multiplicative; however, the relationship could also be additive.

The modeling error, e, is a function of elements that interfere with the model prediction. In the case of a hydraulic model, this includes

- Delays caused by the egress management activities of wardens or others directing the evacuation
- Time delays involved in the stopping and restarting of flows at merging points and conflicting flows
- Evacuee behaviors that detract from their movement to safety

Similar inaccuracies exist in the modeled pre-evacuation phase.

From Fig. 59.2 there are many factors that can interfere with an evacuation, but that cannot be explicitly represented by a hydraulic model. It should be noted that many of these factors are also beyond the most sophisticated simulation models currently available (see Chap. 60).

All of these factors can increase the discrepancy between the modeled and actual results. The first step in appraising emergency movement is usually to calculate the modeled evacuation time, t_e^{mod}. The use of model calculations provides a reproducible base of reference in appraising the impact of overall systems, individual components, or changes in systems. If, however, the results of the modeled evacuation time are to represent a realistic evacuation time (or are to be compared against expected fire development), then the engineer should understand that the modeled movement time is seldom achieved in reality; that is, that e is greater than 1 in Equation 59.17. A conservative estimate of the movement time requires the modeled time and an appraisal of modeling error (see Equation 59.17). This will allow t_e^{act} to be approximated (or at least surpassed) by the modeled time, which is achieved through the application of a safety factor. The employment of a safety factor is a recognition that the hydraulic model omits some factors that may prolong the time to reach safety and/or represents other factors in a simplistic manner.

For the design of a structure to be acceptable, a sufficient margin of safety is required between ASET and RSET. In order for the engineer to have confidence in the RSET calculations, a safety factor, e', is employed that approximates e (i.e., the discrepancy between the modeled and actual movement time):

$$\text{Safety margin} = \text{ASET} - \left[t_d + t_a + t_{p-e} + e'\left(t_e^{\text{mod}}\right)\right] \tag{59.18}$$

The application of the safety factor described in Equation 59.18 is based on the assumption that the inaccuracies are found in the evacuation movement component and that these inaccuracies need to be addressed (see Chap. 64 and the SFPE Task Group document [43]). In this case, the engineer would need to be confident in the accuracy of the other components in the calculation. A more conservative estimate would be to apply the safety factor, e', to all of the behavioral components (i.e., both the pre-evacuation and evacuation phases):

$$\text{Safety margin} = \text{ASET} - \left[t_d + t_a + e'\left(t_{p-e} + t_e^{\text{mod}}\right)\right] \tag{59.19}$$

Although this is more conservative, it does require the assumption that the error levels in the pre-evacuation and evacuation movement components are comparable and can be addressed by the same safety factor.

The most conservative approach requires the application of the safety factor to the entire RSET calculation:

$$\text{Safety margin} = \text{ASET} - \left[e'\left(t_d + t_a + t_{p-e} + t_e^{\text{mod}}\right)\right] \tag{59.20}$$

This is the approach adopted by Tubbs and Meacham [29]. If the same values are assumed throughout, this approach will generate the largest RSET value of the three methods (shown in Equations 59.18 through 59.20). This approach does assume that the errors that exist are comparable between the behavioral and technical components. Alternatively, separate error factors might be applied to these components, such that

$$\text{Safety margin} = \text{ASET} - \left[e_1'(t_d + t_a) + e_2'\left(t_{p-e} + t_e^{\text{mod}}\right)\right] \tag{59.21}$$

where e_1' may be based on information provided by the manufacturer of the technology involved; and e_2' is based on the research literature available. Given the method adopted, the safety margin needs to be acceptable, even after the RSET value has had a safety factor applied. Guidance on the values to employ in order to estimate the modeling error (particularly relating to the behavioral components) can be established (see Chap. 64). The basis for the safety factors employed should be clearly stated and supported.

Using the Hydraulic Model in Conjunction with Other Models

The hydraulic model can be used in a number of different ways, depending on the resources and expertise available. Currently the expertise in the use of hydraulic models far outweighs the expertise in applying simulation models, that is, computer-based models that attempt to represent the evacuation by simulating the activities of individual agents. However, it is anticipated that this will change in the coming years especially as larger and more complex spaces are examined. Indeed, the hydraulic model is often calculated using a computer. It should also be

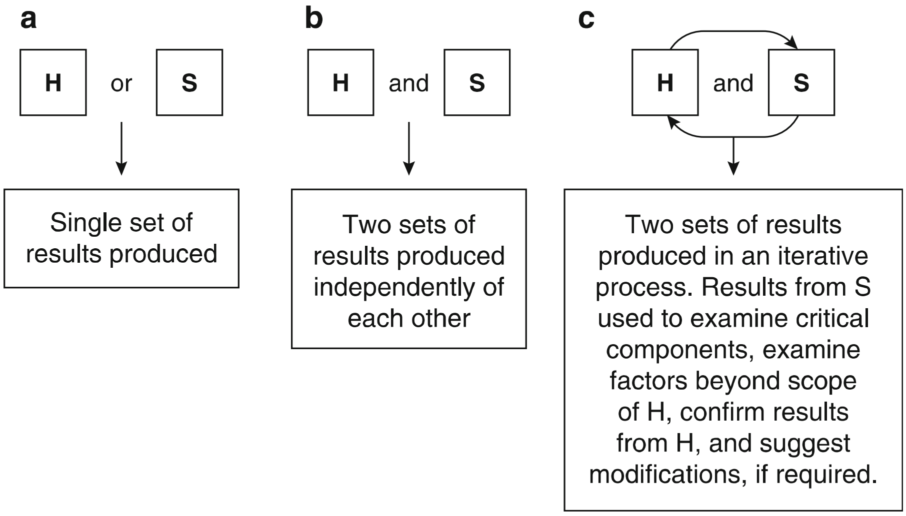


Fig. 59.14 The three uses of the hydraulic and simulation models (**a**) Used on their own; (**b**) used in parallel; (**c**) used in conjunction with each other [1]

recognized that several current computer models are little more than the hydraulic model coded into computer software (see Chap. 60). Therefore, as engineers become more familiar with the computer models available and the results that they can produce, the following points will become increasingly apparent:

- Engineers will gain expertise in a number of modeling approaches.
- Engineers will become more familiar with the capabilities of a number of different modeling approaches.
- Several models will be applied to the same problem.

These points will have an impact not only on how hydraulic models are used but also on the nature of the hydraulic analysis and the expectations of the results produced. Any discrepancy between the results produced by simulation and hydraulic models (in their format and their content) will therefore become more apparent to the engineer. Therefore, when the hydraulic model is applied:

- A number of scenarios should be examined.
- The assumptions and limitations should be identified.
- A detailed set of results should be presented.

The difference between the typical results produced when employing simulation and hydraulic models becomes all the more evident if these models are used together on the same project. It is suggested that the hydraulic model can be employed in three distinct ways (Fig. 59.14) [1]. The manner in which it is employed will be dependent on a number of factors including the expertise and the resources available.

The hydraulic model (identified as H in Fig. 59.14a) is commonly used on its own to determine the evacuation time. Computer simulation models (indicated as S in Fig. 59.14a) are also now routinely employed on their own. Alternatively, more than one model can be employed (Fig. 59.14b). The hydraulic and simulation models may be employed independently of each other and then the final results compared. This would allow comparisons to be made between the results, the strengths of the different models to be exploited, and the level of confidence in the findings to be increased.

The application of more than one model provides benefit but also results in additional efforts since results have to be calculated more than once requiring additional time, expertise and analysis. However, using multiple models may provide some engineering benefits (see Table 59.6). A typical analysis may include both a simple, computationally inexpensive model (e.g., hydraulic approach) and a more refined representation of evacuee response (e.g., simulation tool). This then allows some additional confidence in the overall results produced.

Table 59.6 Engineering benefits of the use of multiple models

Benefit	Description
Triangulation	Given that there is no absolute confidence in any one model being employed, the results of several models may be compared to determine whether the conclusions reached are consistent between different approaches.
Refinement	The scenario may require examination of elements of the evacuation process not represented in the underlying model employed.
Scope	The project may be of such a scale (e.g. WTC) that the most refined models cannot be employed to the whole task. In such projects it may pay for the engineer to employ the most refined models in critical areas, which have the greatest influence over the conclusions drawn. These would then be used in conjunction with the underlying model to assess performance at key spatial or temporal locations.

This would allow comparisons to be made between the results, the strengths of the different models to be exploited, and the level of confidence in the findings to be increased based on the assumption that consistent model results improve confidence.

Finally, models can be run in an iterative manner (or even in a coupled manner), with the results of one influencing the scenarios examined by another. For instance, in a project involving extremely large structures, the hydraulic model can be employed to provide an overview of the results produced, possibly suggesting areas for further analysis (Fig. 59.14c). A more "sophisticated" simulation model could then be used to confirm the key assumptions and findings produced by the hydraulic model (e.g., areas of congestion) and suggest remedies. The simulation tool can confirm the results by examining sections of the structure or events of particular interest to provide detailed analysis. By using the simulation model in a more focused way, fewer computational resources will be required and the results produced by the hydraulic model, especially in critical locations, can be validated (Fig. 59.15). A hybrid approach of hydraulic and simulation analysis may allow for detailed analysis to be conducted, where previously the cost of a full-scale computational analysis was prohibitive. This hybrid approach may also be useful when resources are scarce or the scale of the project is beyond the capabilities of a sophisticated model; for instance, where an evacuation involves a business district or complex, rather than a single building.

Some simulation tools are currently under development that would allow such coupling of simple and more complex tools within the same environment. In this instance, the computational resources available could be targeted at the areas deemed to be most critical within the same computational environment [52]. Currently, users need to define in advance which areas of the geometry are represented in a refined manner, while others are represented in a cruder manner. This distinction requires an understanding of the importance of particular routes, the computational impact of design decisions and the impact that these decisions might have on the results produced. In the future, these decisions may be conducted dynamically, where the models allocate locations to one or other of the various levels of representation, precluding the need for the user to make this judgment in advance.

Impact of Tenability on ASET and RSET

As part of a performance-based assessment, a decision has to be made regarding tenability; that is, the point at which the conditions preclude the evacuation to "safely" continue [3]. The tenability limits will then be used to determine the ASET value: calculations are made to determine when the environmental conditions reach the tenability criteria stated. The ASET value produced will then be the benchmark against which the RSET results will be compared.

In reality, environmental conditions can have a behavioral and a physical (physiological)

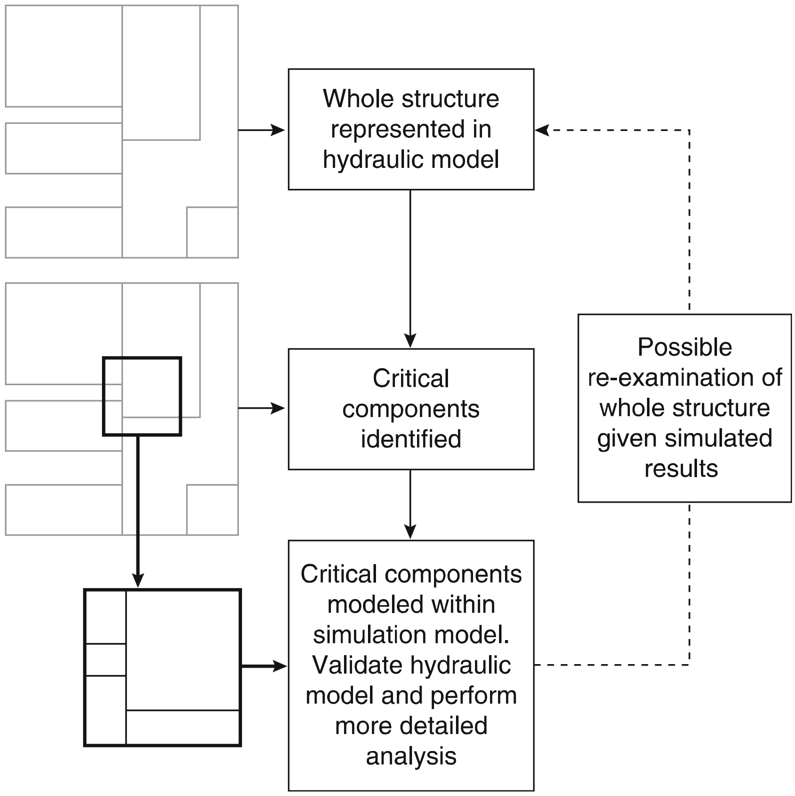


Fig. 59.15 Example application of both hydraulic and simulation models

impact on the performance of the evacuating population (see Chaps. 58, 61, and 63). Ideally, the impact of the tenability criteria should be reflected in the model scenarios employed; that is, if the environmental conditions reach a point at which they are expected to influence physical or behavioral performance, then this should be reflected in the model employed. The assumed occupant performance will have an impact on the validity of tenability criteria selected and on the credibility of the results produced.

There may be a temptation for engineers to select tenability criteria that artificially prolong the ASET time; that is, that the environmental conditions are allowed to develop to a relatively severe level before the tenability limits are reached, allowing a longer RSET calculation to be acceptable. This situation might include severely reduced visibility, elevated temperatures, and smoke layers descending close to the floor. By coupling the assumed tenability limits with the movement calculations made, there will at least be some counterbalance to these assumptions (Fig. 59.16), possibly encouraging a more conservative approach to be adopted throughout. *The adoption of tenability criteria that represent severe environmental conditions will then have a direct impact on the modeled performance of the evacuees.*

Suggested values are available for tenability limits (refer to Chaps. 61 and 63). These values, or similarly derived empirical values, should be used to inform the selection of reasonable and informed tenability criteria. This critical component in the performance-based assessment should be clearly supported in any results reported; effectively these values determine the amount of time available to complete the evacuation.

Given that these tenability criteria are established, their impact can be reflected within the hydraulic model. Some data (albeit, in some instances, supported by engineering judgment) are available to reflect the impact that a deteriorating environment can have upon egress performance (see Chaps. 58, 61, and 63). Data relating to physical performance are provided by Jin, who indicates the possible effect that deteriorating visibility has on travel speeds (see Chap. 61), specifically in relation to smoke. Other physical and behavioral data are also available (see Chaps. 58 and 63). Data on the impact of smoke are particularly important given that in

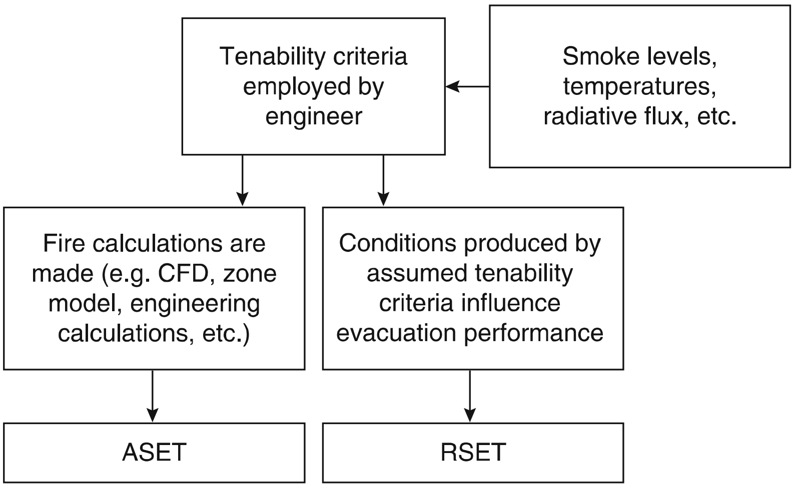


Fig. 59.16 Coupling tenability criteria to egress performance

many instances evacuees will be more likely to interact with smoke than with the fire itself.

Although there may be many ways in which the environment influences evacuee performance, it can be simplified especially given that the evacuating population is typically moving to minimize their exposure. This will produce several scenarios to be considered (in addition to those mentioned in the previous sections) when the hydraulic model is employed. These scenarios relate to the attainable travel speeds and the routes available.

The conditions produced (e.g., specific smoke visibility levels are reached, see Chap. 63) might block off certain routes. For instance, it could be assumed that when smoke reaches a certain level, a proportion of the population might not proceed through the smoke. The tenability criteria reached (e.g., smoke level) could also be deemed to influence attainable travel speeds in the affected areas. This can be modeled by reducing the maximum achievable travel speed; for instance, in Chap. 61 data are provided relating smoke level to visibility and travel speed. A conservative approach might be to assume the impact at the level of the tenability criteria in the affected spaces (i.e., where the environment is deteriorating) throughout the entire evacuation; that is, that whenever tenability criteria are reached the related impact on travel speed is assumed to be present throughout the evacuation. An example of the way in which the two effects of smoke can be included into the hydraulic model is shown in Fig. 59.17.

In Fig. 59.17a, route selection is not influenced by the presence of smoke. Within the hydraulic model the maximum travel speed within this component can be reduced to simulate the impact on the evacuees traveling through this component when filled with smoke (e.g. at or below the tenability threshold). In Fig. 59.17b, it is assumed that the smoke-filled corridor is not used; this is reflected in the hydraulic model by assuming that a larger population uses the East corridor. The potential impact of the two different behavioral scenarios can then be compared.

Attempting to match the development of the fire with the progress of the population in the hydraulic approach is cumbersome and would require numerous additional assumptions. To assess the maximum impact, a scenario could be examined where the entire population refused to pass through the smoke; similarly a scenario could be examined where the entire population is assumed to pass through the affected area at reduced speeds.

It may be impractical to employ these factors within all egress calculations. There is certainly a lack of supporting data. However, even if these additional scenarios are not considered, the impact that the deteriorating environment can have on egress performance should at least be acknowledged and explained in the presentation of any results. Otherwise, it is assumed that the

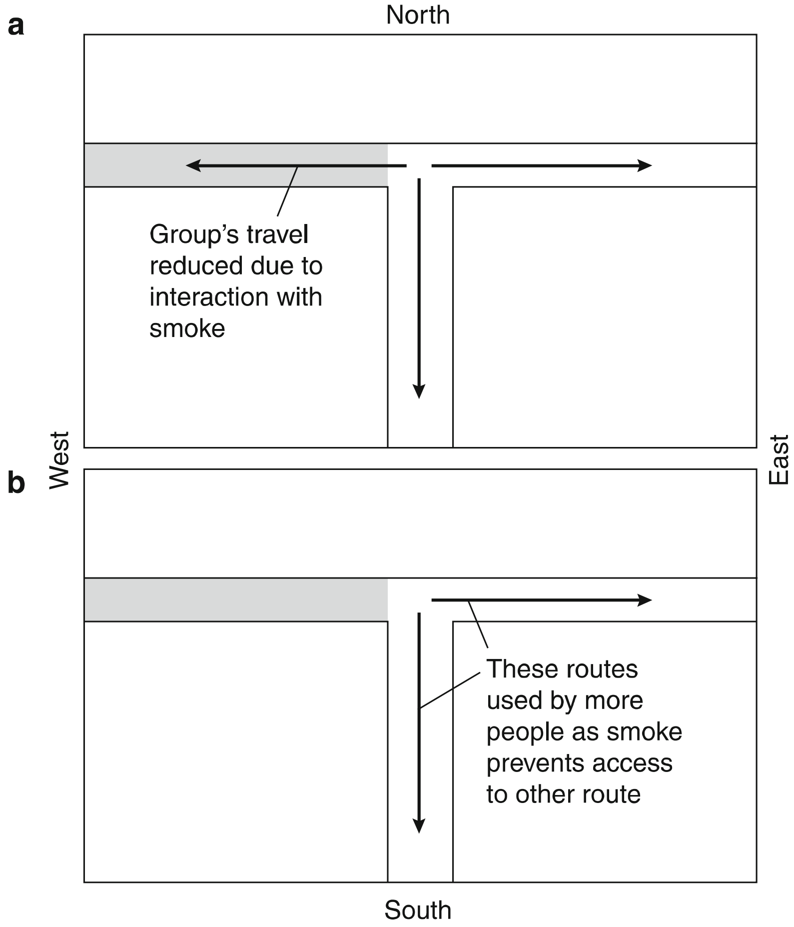


Fig. 59.17 Example of the impact of smoke on the hydraulic model

environmental conditions have no impact upon the performance of the evacuating population prior to tenability conditions being reached. This may be credible; however, it should be acknowledged.

In most designs, there would ideally be no physical interaction at all between the evacuating population and the deteriorating environmental conditions. That does not preclude the population seeing the developing conditions, which might influence their behavior. Even here the untenable conditions could be modeled in the hydraulic model through the loss of available egress routes.

Summary

This chapter described the application of the hydraulic model and its capabilities in assessing emergency movement. The model is able to provide a reliable means of assessing RSET and therefore in conducting performance-based analyses. When employing the model, it should be remembered that the results produced will be optimistic, and therefore remedial measures should be employed to compensate for this.

The limitations associated with the model do not prevent its being used to examine different egress scenarios; neither do they excuse the over-simplistic use of this model or presentation of the results. Those employing this model need to provide sufficient information on the approach adopted, the assumptions made, the scenarios examined, and the results produced.

When using the hydraulic model, it is still possible to examine a number of evacuation scenarios and incorporate the effect of various factors on the performance achieved. Given the potential for hydraulic and simulation models to be employed together, it becomes even more important to provide comparable levels of detail and confidence in the results produced.

Acknowledgment The authors acknowledge that this work includes substantial sections from the original chapter written by Harold "Bud" Nelson in partnership with Hamish MacLennan and then Fred Mowrer.

Nomenclature

ASET	Available safe egress time
RSET	Required safe egress time
t_d	Time from fire ignition to detection
t_n	Time from detection to notification of occupants of a fire emergency
t_{p-e}	Time from notification (or receipt of cues) until evacuation commences
t_e	Time from start of purposive evacuation movement until safety is reached
t_{esc}	Escape phase, being the sum of the pre-evacuation ($t_{p\text{-}e}$) and evacuation (t_e) phases
t_{trav}	Time spent moving toward a place of safety
t_{flow}	Time spent in congestion controlled by flow characteristics
t_{n-e}	Time spent in nonevacuation activities that do not directly contribute to the population moving to a place of safety
W_e	Effective width
D	Population density
S	Travel speed
k	Constant used to calculate travel speed
a	Constant used to calculate travel speed
F_s	Specific flow
F_{sm}	Maximum specific flow
F_c	Calculation flow through a component
t_p	Time for a group of persons to pass a point in an exit route
P	Population size in persons
$F_{s()}$	Specific flow and associated direction of movement
$W_{e()}$	Effective width of a particular component given its location
t_{p-e1}	Pre-evacuation time of the first people to respond
$t_{\text{p}-\text{e}99}$	Pre-evacuation time of the last people to respond
t_e^{act}	Actual time from when purposive evacuation movement commenced to when safety was reached
t_e^{mod}	Modeled estimate from when purposive evacuation movement to when safety was reached
e	Modeling error
e'	Approximation of e employed within calculation

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Computer Evacuation Models for Buildings

60

Erica D. Kuligowski

Introduction

With the rapid increase in computer capability and the increase in egress model development, there is a need for guidance on evacuation modeling, specifically the process involved and the models available. This chapter provides general guidance to users on the first three steps of the evacuation modeling process, namely, (1) identifying project requirements, (2) selecting the appropriate model (including a review of 26 current building evacuation models), and (3) configuring the model scenarios. In addition, an example of evacuation modeling configuration is provided to identify the factors to consider when configuring the building, the population, and the procedures. The chapter briefly reviews the final three steps of the evacuation modeling process, which are applying the model, obtaining output, and analyzing results. These final steps are important but only briefly mentioned due to the fact that these are often specific to the evacuation model chosen and the goals of the project. Overall, this chapter aims to provide necessary guidance that is general enough to be model independent and specific enough to be valuable to the model user.

Overview of Computer Evacuation Models

The rapid increase in computer capability and decrease in cost have expanded the use of computer models in all fields of engineering, particularly for evacuation models. This chapter introduces a framework for deciding which model or models are appropriate for a particular life safety analysis, presents a review of 26 current evacuation models, and provides an example of an evacuation model configuration that identifies important factors to consider involving the building, population, and procedures.

An engineer performing a life safety analysis on a structure is presented with a number of alternative tools from which to choose to complete this task. Depending on the type of building and the time allotted for the analysis, the engineer may choose to employ a variety of techniques, including empirical calculations [1], manual engineering calculations [2], and/or evacuation modeling.

The empirical engineering approach compares the structure in question to data collected from a comparable structure. The user can then extrapolate from those data in order to make a

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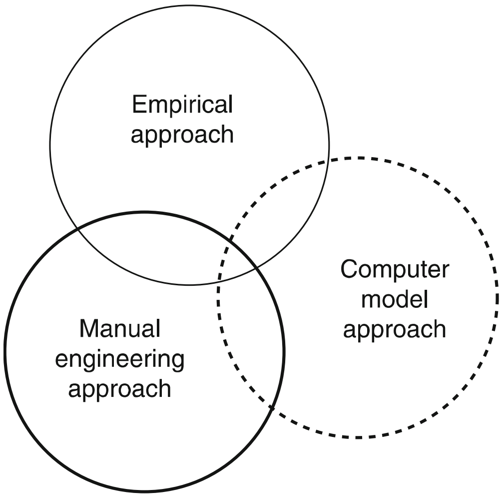


Fig. 60.1 Overlap between computational, empirical, and manual approaches to modeling

prediction of the egress performance of the structure [1]. The manual engineering approach applies empirical data at the component level (doorways, stairs, etc.) in order to ascertain the egress performance across the structure. This is done by predicting the performance of the evacuees on the components in question along predefined routes within the structure [2]. Finally, computer evacuation models represent a diverse set of methods and sophistication, ranging from a relatively crude account of homogeneous occupant flow to autonomous agents moving throughout three-dimensional space. The diversity of this sophistication is such that some models simply incorporate the methods of the empirical and manual engineering approaches (Fig. 60.1), effectively automating the process. Since the *SFPE Handbook of Fire Protection Engineering* [1, 2] describes a life safety analysis using both empirical and manual engineering approaches, this chapter will focus on the use of evacuation models.

In the recent past, both computer evacuation model development and use have expanded due to technological developments as well as the demand for flexible techniques that can cope with complex designs. In addition, the needs of the fire protection community to address problems other than building fires have been apparent. Computer evacuation models can evaluate evacuation results from a variety of structures, such as marine vessels, aircraft, buildings, and cities. In addition to diversity in structure, evacuation models can be used to simulate different types of scenarios, such as evacuation from fires, bomb threats, terrorist events, weather, riots, and even relocation (instead of evacuation) within the building. Acknowledging the different types of computer models and emergency events, this chapter will focus on computer evacuation modeling of fire emergencies in buildings, specifically the process of evacuation modeling.

Figure 60.2 displays a simplified version of the egress modeling process. The steps of the process are the following: [3]

1. Project requirements are provided to the user.
2. The user selects a model based on the project and other requirements.
3. The user constructs detailed model scenarios, which involves obtaining data and configuring the model.
4. The user applies the model.
5. The user obtains outputs from the application.
6. The user analyzes results and formats these results for the client.

The rest of this chapter focuses on providing guidance for Steps 1–3 of the modeling process displayed in Fig. 60.2: obtaining project requirements, selecting a model, and constructing model scenarios. The chapter begins by describing the project requirements that help guide model selection. Next, the features of evacuation models will be described to aid the user in model selection. The features of 26 evacuation models will be presented for comparison. Finally, the chapter will focus on model scenarios and provide an example to illustrate the issues that may arise in model configuration. Although Steps 4–6 are also important to the modeling process, these are often specific to the evacuation model chosen for the project (see Kuligowski and Milke [4] as an example).

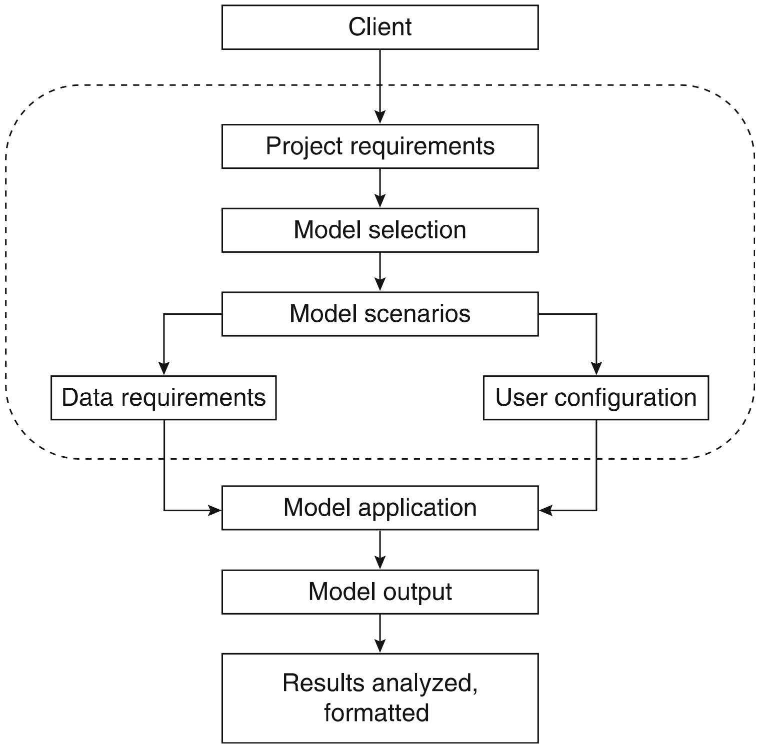


Fig. 60.2 The computer modeling process

Step 1: Project Requirements

Before selecting a model, the user should consider the following key questions relating the suitability of the model to the specific project [3]:

- What information is needed within the project to frame the egress analysis and configure the computer model?
  - What information is available?
- How much time and funding are available to complete the project?
  - What effort is required to configure and execute the model?
- What is the nature and scope of the project?
  - What are the technical resources required?
  - What additional human resources (training, expertise, etc.) are required?
  - What are the conditions that need to be represented?
- What are the deliverables of the project?
  - What output needs to be produced by the model?

This list is not an exhaustive list of the questions that need to be asked, nor are the questions necessarily mutually exclusive; however, by answering these four questions, the user should be able to ascertain whether the model is able to support the project requirements and whether it is appropriate to be used for the project at all.

Project Information Availability

The amount of project information available to the user may influence the model selection. The model may require a number of inputs in order to take advantage of its functionality or to function at all. However, the information that the user has during the project may be limited (e.g., a vague description of the building floor plan rather than a detailed architectural diagram, limited information on the population distribution, etc.). In some instances, this information may be collected/acquired during the life-time of the project. However, typically this will not be the case. If the required information is not available, the user may select a less sophisticated model with a limited number of inputs; i.e., the functionality of a sophisticated model cannot be employed given gaps in the data available.

Nature and Scope of the Project

It is important to examine the nature and scope of the project in order to determine whether the model is able to cope with the requirements of that particular application area. The user may need to establish whether certain factors are represented at all or, if they are, whether they are represented in a sufficiently refined way. For instance, if modeling a building evacuation, the user may need to represent stair movement. However, given the procedure, the user may also require stair counter-flow to be represented—i.e., people simultaneously moving up and down a stairway. The user should then ask whether stair movement is represented, and, if so, whether this representation is sophisticated enough to answer the counter-flow questions being posed within the project.

Deliverables of the Project

Typically, model output can be produced in a number of forms (e.g., numerical, tabular, plot, 2D, 3D, animated, or descriptive) and may represent different levels of refinement (e.g., individual object/agent, a specified set of objects/agents, or the entire collection of objects/agents). Depending on the combination of form and refinement, the user will be able to deduce different information from the results generated— ranging from understanding possible causal factors to examining the conditions that were produced.

The completion of any project involving modeling will require the production of a set of deliverables that will support the desired outcomes. The user should be aware of both the model output that can be produced and whether it provides sufficient detail to satisfy the project deliverables. It may not be feasible to make use of a model when, for instance, a detailed understanding of the experiences of the simulated evacuees is required but only the final arrival time can be produced by the model. In addition, the techniques used within the model (e.g., artificial intelligence techniques, flow calculations, cognitive models, etc.) may not be capable of producing the output required by the project. For instance, a cognitive model may provide information on the decision-making process; however, it might not be able to provide a quantitative assessment of the overall evacuation time.

Project Timing and Funding

Finally, it is important for the user to understand the amount of time and funding allocated to the egress analysis of the project that may influence the selection of the model, potentially precluding those models from selection that are financially and/or computationally expensive and that then cannot be employed given the resources available.

Step 2: Model Selection

The next step in the modeling process, as identified in Fig. 60.2, is model selection. This section will highlight the key factors involved in choosing an appropriate computer evacuation model [3]. This task is often governed by matters of availability, expediency, and economics rather than based on selecting the model best suited for the task at hand. Of primary importance in the selection process is an understanding of the background of the models and their current characteristics (capabilities and limitations). By understanding these aspects of the model, the user can differentiate among the models available and make a more educated choice.

Background Research on Origin of Model

Understanding the background of the model is important in the selection process because it establishes the model development and model validation criteria.

Model Development The user should be aware of the group or individual who developed the model. For many models, information can be found on the developer/developing institution from the model users' guide. The background of the development team may affect the abilities of the model to capture some of the more complex behaviors or actions of the occupants during an evacuation.

Model Validation An important aspect of model selection is determining the level to which the model has been subjected to validation. It is vital that the user obtain documentation from the developer and other agencies that have performed any type of validation to make his or her own judgments on the validity of the results produced and whether the validation is sufficiently detailed, reliable, and in an area comparable to that involved in the project. For instance, if the model has been validated using scenarios and/or data extracted from a small-scale building, would the validation performed be sufficient to warrant the use of the model in a tall building application? Validation studies help to identify the capabilities of the model as well as its limitations. These validation studies can investigate a number of different aspects of the model: quantitative performance, qualitative performance, functional performance, component-based performance, efficiency, speed, and scope [5]. The availability of the supporting data required to perform such comparisons can limit these vital evaluations. The user should develop his/her own suite of tests to provide a level of confidence in the validation process and an understanding of the use of the model.

Current computer evacuation models are validated using a variety of techniques including validation against code requirements, validation against fire drills or other people movement experiments/trials, validation against literature on past evacuation experiments (flow rates, etc.), validation against other models (see Weckman et al. [6] and Lord et al. [7]), and third-party validation. However, some current computer evacuation models provide no indication of validation of the model in the references available. It should also be recognized that validation is a challenging process constrained by the data available, and the complexity of the processes represented. It is critically important for users that validation efforts are documented in detail allowing them to make an informed choice; understanding (amongst other things),

- What validation activities have been undertaken?
- How these activities have been conducted?
- What aspects of the model have been validated?
- How relevant the validation is to the project at hand?

Model Characteristics

In addition to assessing the project requirements and model's developmental background, it is important to understand the current modeling capabilities and characteristics, thus enabling a comparison between the models currently available. By identifying and understanding the key capabilities and characteristics of the current evacuation models, the user will be able to make a more informed choice of the most appropriate model for the specific project. The key characteristics deemed to define the current evacuation models are displayed in Fig. 60.3.

Modeling Method The modeling method [8] is a feature of computer evacuation models that describes the level of sophistication used to calculate evacuation times for buildings. The modeling method can be broadly categorized as one of the following:

- *Movement models*. Those models that concentrate on the simulation of occupant movement and that do not have a behavioral component. These models demonstrate congestion areas, queuing, or bottlenecks within the simulated building. Also, within the movement category, there are some models that are specifically optimization models, meaning that they aim to optimize time in an evacuation through the exclusion of nonoptimal behaviors.
- *Partial behavior models*. Those models that primarily calculate occupant movement but also simulate evacuee behavior to some degree. Possible behaviors could be implicitly

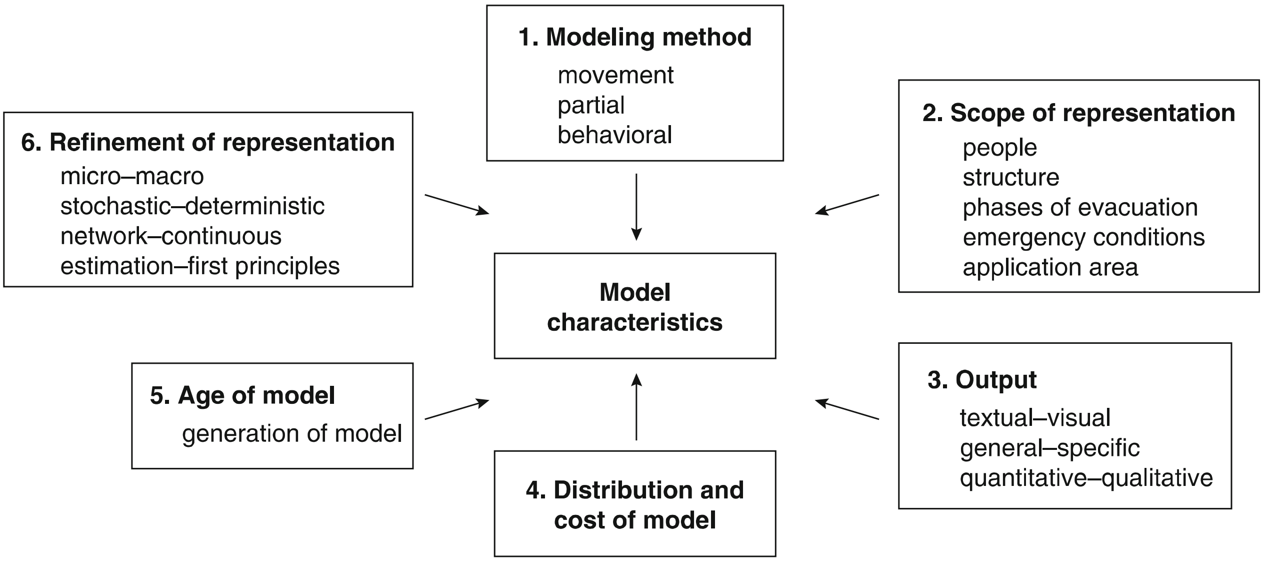


Fig. 60.3 Current characteristics of evacuation models [3]

represented by pre-evacuation time distributions among the occupants, unique occupant characteristics, overtaking behavior, and the introduction of smoke and its effects on the occupants.

- *Behavioral models*. Those models that incorporate occupants performing actions in addition to movement toward a specified goal (exit). These models can also incorporate decision making by occupants and/or actions that are performed due to conditions in the building. The behaviors simulated may detract from the evacuation performance of the individual or the population as a whole. Within this category, there are some models that have the capability of performing a risk assessment of the evacuation.

Scope of Representation Users should also be familiar with the differences in the scope or flexibility of how the models represent aspects of the evacuation, including the occupants, the structure, emergency conditions, the expected evacuee behavior, the procedures present (e.g., whether there are safety, operational and security procedures in place that may affect each other), and so on. Examples of the scope of representation include the simulation of the impact of occupants with disabilities, the inclusion of certain aspects of the structure (e.g., doorways, signage) via engineering plans, the number of phases of the event simulated (e.g., whether ingress, circulation and egress need to be considered), the procedural elements included (e.g., security, operational, safety, etc.) and the simulation of fire conditions and their impact on evacuees against their performance under non-emergency conditions. It is important to understand how a particular model represents/simulates certain aspects of an evacuation, especially if they are a key component of the scenarios required for the project in question. For example, if the project requires the simulation of a population that includes people with differences in age, gender, mobility impairments, and size, the user should ensure that the model has this capability.

Output The output is an important characteristic to consider when selecting a model. Many times, the interested parties will require more information from the simulation than simply the total evacuation time. Current models can provide a variety of output, including textual output (qualitative and quantitative), two-dimensional graphical output, and three dimensional/virtual reality interface. In addition, several models are able to have the nature of their output modified in order to fit the project requirements. Data formats are briefly discussed in Chap. 64.

Distribution and Cost of Model Model availability and cost are considered to be of primary importance, as the initial concern of the users will be to gain access to the model. Some models are distributed for local application, whereas other models are employed by their developers centrally with the results then distributed. In the former case, the model user is actually developing the input, running the simulations, and then analyzing the output; and in the latter, the user is working with the developing company and will have access to the output only. In reality, the model may be distributed in a number of different ways: the software is free of charge; available on a consultative basis; available via a flat rate fee; available under license control, or some combination of these methods.

Age and Generation of the Model In addition to availability, it is important for the model user to be aware of the age of the model and the developments/advancements since its release. In some cases, older models become dated, cease to advance in accordance with technology progress, and therefore become obsolete. Conversely, if it is seen that the developing organization of an older model continually updates and maintains the software, the user may be interested in using a more established model that has been continuously developed and has been involved in a variety of projects over the years. In the case of newly developed models, the user should be cognizant of its validation efforts, specifically if the model has been used for practical purposes and projects since its release.

Level of Refinement The level of refinement of an evacuation model describes to what level of detail the aspects of an evacuation, such as the population and structure, are simulated. The refinement of a structure reflects the method employed to represent the configuration of the building within the model and will also have an impact on how the movement of the occupant is represented. The user should be aware that an increase in refinement may require an increase in the effort needed of the user and an increase in the computer time needed to run the simulation. Computer evacuation models can differ regarding the refinement of the structure, the population, and the behavior of the occupants (if behavior is simulated at all).

The refinement of a structure can be categorized in the following way: a coarse network, a fine network, and a continuous network. A defining attribute of a coarse network is that the nodes do not need to be uniform, representing the actual shapes and sizes of rooms in a building. A coarse network divides the floor plan into rooms, corridors, stair sections, and so on, and the occupants move from one structural component to another (e.g., room to corridor). The fine network, on the other hand, produces a series of small, uniform nodes (in both shape and size). Each can be occupied typically by one person at a time. A fine network divides a floor plan into a number of small grid cells between which the occupants move. The defining attribute of a continuous network is that, instead of nodes, the structure is overlaid with *x*-*y* coordinate points, allowing occupants to travel through all possible space in a building. The continuous network applies a two-dimensional (continuous) space to the floor plans of the structure, allowing the occupants to walk from one coordinate to another throughout the building. Fine and continuous networks have the ability to simulate the presence of obstacles and barriers in building spaces that influence individual path route choice, whereas the coarse networks "move" occupants only from one portion of a building to another.

The refinement of a population refers to the method employed by the model to represent the population as either individuals (a microscopic level) or a homogeneous population (a macroscopic level). The refinement of behaviors refers to the method employed by the model to simulate behaviors of the occupants during an evacuation. These behaviors can be defined by the user or model (deterministic) or based on probabilities specified by the user (stochastic).

Given the rapid development of current computer evacuation models, any review attempting to categorize the models currently available may present data that are out-of-date. The categorization presented in the next section attempts to avoid this problem by limiting itself to the fundamental aspects of the models.

Review of Current Computer Evacuation Models

Currently, several evacuation model reviews exist [8–21] that attempt to explain and categorize the computer evacuation models. This section briefly reviews each computer evacuation model,[1] identifying fundamental characteristics of the models currently available. For a more detailed analysis of the models, the reader should refer to the reviews referenced above.

This section covers a total of 26 computer models that simulate emergency egress within the built environment, categorized by the model features outlined in the previous section [16]. Many of the models reviewed can also simulate evacuation from other types of structures; however, evacuation from buildings is the main focus of this review. The model features that will be highlighted involve the model's background and characteristics including the following categories:

- Developer information
- Validation
- Availability
- Modeling method
- Refinement of the population
- Refinement of the structure
- Refinement of the behavior (where behavior is simulated)
- Output

Specific information on each of the 26 models is provided in Table **60.1**. Accompanying references and links for each model can be found in the following references: Kuligowski and Peacock 2010 [16] and the Evacmod.net website [22]. To clarify the abbreviations provided in Table **60.1**, a key is provided.

[1] Certain commercial entities, equipment, or materials may be identified in this document in order to describe an experimental procedure or concept adequately. Such identification is not intended to imply recommendation or endorsement by the National Institute of Standards and Technology, nor is it intended to imply that the entities, materials, or equipment are necessarily the best available for the purpose.

Once a computer evacuation model is chosen, it is often the case that the user has little guidance on possible model scenarios. Even the referenced material may omit information on how the model was configured and simply discuss in detail the results of the particular study. The next section is written from a user's perspective in order to present the key considerations in the creation of model scenarios, specifically focusing on the building, the population, and the procedures during an evacuation [9].

Step 3: Model Scenarios

Once the user is familiar with the project specifications, model features, and specifics on current models, the user should begin developing possible scenarios for model configuration. The purpose of this section is to outline the choices a user will have to consider and offer guidance on how to make the decisions that will eventually lead to application of the model.

In the following sections, the four aspects of scenario configuration will be introduced: the building, the population, the procedures, and environmental conditions. Within each category, the model user will be provided with descriptions of different methods of configuration within the scenario(s) for a project. Following this section on scenarios, the methods within each category will be displayed in an example.

Building Configuration

When using a computer evacuation model, it is up to the user to describe the building characteristics in a manner consistent with the method used by the model to represent the geometry of the building. This description includes the location of open spaces and walls, information on the stairs, and the location of the final destination of safety. The user may be required to provide these data in a number of different ways, according to the model features available. As described previously, the modeling method being employed to represent the structure will

Table 60.1 Model features

	Background of model		Model characteristics					
Model	Developer/institution	Validation	Availability	Modeling method	Refinement of population	Refinement of structure	Refinement of behavior	Output
EVACNET4	Kisko, Francis, and Nobel/Univ. of FL, U.S.	FD	Y	M-O	Ma	C	N/A	T
WAYOUT	Shestopal/Fire Modelling & Computing, AU	FD	Y	M	Ma	C	N/A	V
STEPS	Mott MacDonald, U.K.	C, FD, PE	Y	M/PB	Mi	F	D	V
PedGo	TraffGo, Germany	FD, PE, OM, 3P	Y	PB/B	Mi	F	S	V
PEDROUTE	Halcrow Fox Associates, U.K.	N	Y/N3	PB	Ma	C	D	V
Simulex	Thompson/IES, U.K.	FD, PE, OM, 3P	Y	PB	Mi	Co	D	V
GridFlow	Purser and Bensilum/BRE, U.K.	FD, PE	Y	PB	Mi	Co	D	V
ASERI	Schneider/I.S.T. GmbH, Germany	FD, PE	Y	B-RA	Mi	Co	S	V
BldEXODUS	Galea and FSEG/University of Greenwich, U. K.	FD, PE, OM, 3P	Y	B	Mi	F	S	V
Legion	Legion International, Ltd., U.K.	C, FD, PE, 3P	Y	B	Mi	Co	S	V
FDS + Evac	VTT, NIST, Helsinki Univ of Tech	FD, PE, OM	Y	PB	Mi	Co	S	V
PathFinder 2009	Thunderhead Engineering	C, FD, PE, OM	Y	PB	Mi	Co	D	V
SimWalk	Savannah Simulations AG	FD, PE, 3P	Y	PB	Mi	Co	S	V
PEDFLOW	Edinburgh Napier University, Transport Research Institute	PE	Y	B	Mi	Co	S	V
SpaceSensor	Sun/de Vries	FD, OM	Y	B	Mi	Co	S	V
EPT	Regal Decision Systems, Inc.	FD	Y, N1	B	Mi	C, F, Co	AI	V
MassMotion	Arup	C, FD, PE, OM	Y, N1	B	Mi	Co	AI, S	V
Myriad II	Keith Still	PE, 3P	Y, N1	B	Mi	C, F, Co	AI	V
Pathfinder	Rolf Jensen and Associates, Inc.	N	N1	M	Mi	F	N/A	V
ALLSAFE	InterConsult Group ASA, Norway	OM	N1	PB	Ma	C	D	V
CRISP	Fraser-Mitchell/BRE, U.K.	FD	N1	B-RA	Mi	F	S	V
EGRESS 2002	Ketchell/AEA Technology, U.K.	FD	N1	B	Mi	F	S	V
SGEM	Lo/University in Hong Kong	FD, OM	N1	PB	Mi	Co	D	V
EXIT89	Fahy/NFPA, U.S.	FD, OM	N2	PB	Mi	C	D	T
MASSEgress	Stanford University (Civil and Env Engineering)	PE, OM	N2	B	Mi	Co	S	V
EvacuatioNZ	Spearpoint/Univ of Canterbury, NZ	FD, PE, OM	N2	B	Mi	C	S	V

Key to reading the table:

Validation:

C Validation against codes
FD Validation against fire drills or other people movement experiments/trials
PE Validation against literature on past experiments (flow rates, etc.)
OM Validation against other models
3P Third-party validation
N No validation work could be found on the model

Availability to the Public:

Y The model is available to the public for free or a fee
N1 The company uses the model for the client on a consultancy basis
N2 The model has not yet been released
N3 The model is no longer in use
U Unknown

Modeling Method:

M Movement model
M-O Movement/optimization models
PB Partial behavioral model
B Behavioral model
B-RA Behavioral model with risk assessment capabilities
B-AI Behavioral model with artificial intelligence capabilities

Refinement of the Population:

Ma Macroscopic
Mi Microscopic

Refinement of Structure:

C Coarse network
F Fine network
Co Continuous

Refinement of the Behavior:

D Deterministic
S Stochastic

Output:

T Textual output
V Visual output

directly influence the results produced; therefore, the user should seek information within the user's guide and additional model reviews relating to the specific method being applied. The following sections describe the methods used in current models to configure the building:

- Structure generation
- Structure representation
- Additional building information

Structure Generation The first stage in this process is for the user to determine the format for incorporating the building geometry (known as grid or structure) into the model, which is dependent on the assumptions of the model. Broadly speaking there are three means by which a user can generate the structure and three means by which the models represent the geometry of the building.

There are three main ways that the user can generate the structure within the model. These ways are through computer-aided design (CAD) drawings, manual drawings, and text files. Although these methods can produce an accurate depiction of the structure, it is by no means a trivial activity; indeed the preparation of the engineering diagram can represent a significant proportion of the modeling process when dealing with complex structures. In addition, methods are now becoming available that reflect additional aspects of the building (e.g., BIM), the building as a three dimensional structure (e.g., Google Sketch-Up) and/or other aspects of the structure that might influence evacuee performance.

Alternatively, if an engineering diagram cannot be directly imported, the user is required to manually specify the building geometry, either by drawing it within the model or importing a text file that links building segmented areas to other areas on a floor plan. Several models provide users with the ability to select exactly how they wish to re-create the geometry of the structure within the model.

Structure Representation Irrespective of the means by which the user generates the structure within the model, there are methods by which the model represents the structure. If a coarse network is employed within the model, the model represents the floor plans of the structure as a segmented version of the building. This will normally relate to the connectedness and capacity of each of the structural components (i.e., rooms, corridors, hallways, and stairs) without specifying a detailed geometrical representation of the structure. This segmented version of the building would usually be in the form of a text file, manually or automatically produced from the architectural diagrams. This file identifies certain areas of the building and describes how they are linked together within the building. Many models that use a coarse grid structure do not accept CAD drawings and do not have a visual representation of the structure. This is an important consideration as it usually implies that the user will be expected to manually reproduce the geometry of the structure in some form without making reference to a visual representation of the geometry. Given the sensitivity of the results to this structure, the level of work required here and the likelihood of error in this process should be recognized.

When employing a fine grid structure, the model (via the user) overlays a mesh of small nodes throughout the occupiable space within the entire floor area. These nodes connect to each other to form the paths that occupants might use to travel between and within the structural components. The fine nodes are usually given a uniform default area that corresponds to the space normally occupied by one individual, unlike the coarse representation where the area of the nodes is governed by the configuration and by the user. Many of these models allow the importation of CAD drawings to make this procedure easier. The majority of the models that employ a fine node network are then based on the assumption that a node will only be occupied by one person at a time. Nodes are then generated automatically or manually to cover the occupiable space within the plan. These nodes are generally square, although other shapes have been used (e.g., hexagons). The choice of node size may affect the final evacuation time significantly, especially in the cases where an occupant can occupy only one node at a time. The user needs to understand how varying the node size impacts the results from a particular model [7].

Finally, there are several models that are categorized as continuous models. These incorporate the engineering (e.g., CAD) diagrams of the building and produce a continuous plane to represent both the occupiable space and the potential movement of the simulated occupants using a coordinate-based system. Consequently, simulated occupants move from coordinate to coordinate within the continuous space. Theoretically, this method should involve the least amount of user judgment and adaptation of the building representation.

Additional Building Information In addition to providing network linkages throughout the building, the user is sometimes required to enter additional building information into the model for each scenario. This information consists of areas, lengths, and widths of certain spaces (specifically with the coarse network models) and information about the stairs connecting floors. The stair information is not usually imported with the CAD drawing, since stairs are not strictly part of one floor plan, but rather a linkage between floors. Depending on the sophistication of the building representation, the model user may have to supply the following information: stair width, diagonal length between stories (discussed later in the chapter), riser and tread dimensions, and handrail information.

Summary of User Configuration of the Building When using a computer evacuation model, it is up to the user to describe the building characteristics in a manner consistent with the scenario and the methods used by the model to represent the building. This includes the location of open spaces and walls, information about the stairs, and the location of the final destination of safety. Each provides a different level of time and effort from the user, and the decisions made by the user affect the results produced by the model. Irrespective of the approach adopted, great care has to be shown to ensure that any simplifications made relating to the spatial representation are justified (and justifiable) and that the geometry modeled actually reflects these simplifications as stated.

Population Configuration

Once the structure has been produced, it needs to be populated before the simulation can proceed. In order to do this, the following information from the scenario needs to be supplied to the model:

- The number of occupants and their distribution throughout the building
- Occupant characteristics (e.g., age, gender, knowledge level, impairment, etc.)
- Movement data (e.g. achievable speeds, flow/density relationship, etc.)
- Pre-evacuation delays
- Specified behaviors and associated delays

It should be noted that within the model, the impact of these factors might not be completely independent of each other. For instance, occupant characteristics and pre-evacuation time might influence the time for an evacuee to commence movement; movement data and specified behaviors might influence the time to reach safety, etc.

As the model's sophistication increases, so the number of behavioral variables considered may also increase, potentially increasing the number of possible input parameters. It is then up to the user to select input parameters that specify the entire population, subpopulations, or individuals throughout the building. Often the models provide default values; however, the user should be informed about these defaults and make decisions about whether they pertain to the population involved in the project at hand. Default data sets are not necessarily appropriate for a particular scenario and it is not safe to assume that they necessarily are so.

As discussed earlier in the chapter, there are two fundamental methods to represent the evacuating population within the structure during the simulation. The simulated population can be represented at the micro level as individuals (shown by multiple arrows in Fig. 60.4) or at the macro level, as a homogeneous group given population-wide characteristics (as shown by one large arrow in Fig. 60.5). The method used by the model affects the decisions made by the user when implementing a specific scenario. For

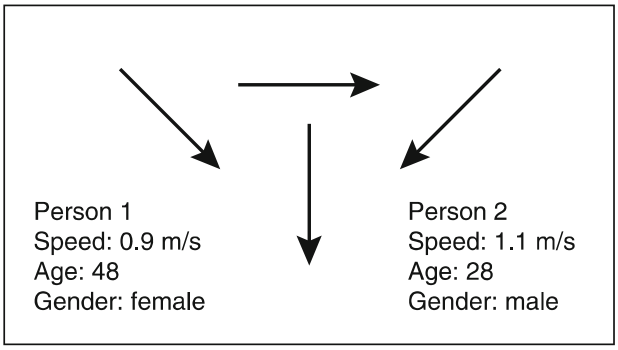


Fig. 60.4 The population represented at the micro level

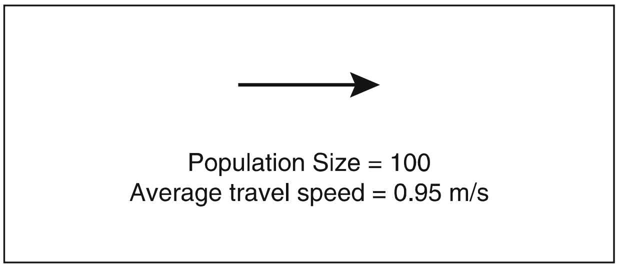


Fig. 60.5 The population represented at the macro level

instance, when the individual evacuee is modeled, there is the potential to simulate a range of personal characteristics for that individual. At the population level, the same attributes may also be included; however, these are assigned to the entire population as a whole.

Number of Occupants in the Building The first thing that a user will have to specify about the population inside the building is the number of occupants and their distribution throughout the structure. This calculation can depend on a variety of factors within a scenario, such as the building type, the locations of facilities/services located inside and outside of the structure, the floor space within the structure devoted to occupants, the date, and the time of day. Depending on the building type and simulation scenario, a particular season of the year and especially a particular day and time of day may warrant more occupants than another season, day, or time of day. For example, if a university building is being simulated, the number of people in the building increases during the months when school is in session and typically peaks between 9:00 a.m. and 3:00 p.m. on school days. The number of occupants influences the interaction between occupants, which therefore directly influences the following performance elements.

Occupant Characteristics Many factors need to be considered when choosing movement data because, in much of the existing evidence available, unimpeded speeds are influenced by gender, age, ability, and other occupant characteristics. If the model represented the population as homogeneous (on a macro level), the user would then need to provide the model with a higher-level representation of data (e.g., an average initial unimpeded movement speed for the occupants of the building) rather than including the details. Resources for movement data can be found in Chap. 64.

It should be noted that there is no correlation between increased sophistication in the refinement of the representation and accuracy. A high modeling sophistication does not necessarily indicate that the evacuation model uses and/or provides the appropriate data to model such behaviors. The user should be aware of the validation methods and associated limitations of each model used.

In addition to physical characteristics, some models allow for the knowledge levels of evacuees and other non-physical factors to be set; e.g., exit awareness, level of motivation, etc. These may influence the actions performed and the manner in which they are performed, depending on the model in question.

Pre-evacuation Times In addition to movement data, the user is confronted with the decision of selecting and applying a pre-evacuation time (i.e., the time between ignition and purposive response safety) for either the entire population or subpopulation (macro level) or for individual occupants throughout the building (micro level). The user will be faced with the following choices:

- No pre-evacuation times (i.e., no delay), where the pre-evacuation component is not modeled or the response is assumed to be instantaneous (i.e., a best-case scenario)

- A specific time delay that is applied to the entire population
- A specific time delay for particular individuals throughout the building (for instance, with a particular trait or at a specific location)
- A distribution over the population of pre-evacuation times

Enormous care should be taken when importing pre-evacuation times into the model. The results produced and conditions within the scenario are likely to be sensitive to the extent and range of the pre-evacuation times provided. The pre-evacuation phase is often the most extensive phase of the evacuation and is always critical [1].

The nature of the pre-evacuation times employed will depend on a number of factors including the time of day of the event (e.g., was it nighttime when the evacuees initially would be asleep?), the type of alarm system in the building (e.g., was there a traditional bell alarm system or were more advanced techniques employed?), the expected exposure of the individuals to external social/physical cues, the activities of the occupants in the building (e.g., were they committed to an activity?), and the presence of staff. Although these factors should be considered, it is not suggested that the models currently available could explicitly simulate these factors. These factors may need to be implicitly simulated through the provision of suitable data to the model, placing a greater onus on the user.

Movement of Occupants Depending on the level of refinement utilized by the model, the user will need to make certain decisions regarding the movement data supplied for the simulated occupants. For the majority of evacuation models, the user is tasked with providing initial unimpeded movement speeds for the entire population. This may be a single value or be selected from a distribution of values.

The initial travel speed attribute is usually then modified according to the density of the surrounding population. The effect of speed versus density is usually either derived directly from the available density correlations (see Gwynne and Rosenbaum [2], Fruin [23], and Predtechenskii and Milinskii [24]) or calculated according to the position, route choices, trajectory, and/or separation distances of those around the individual in question. However, in some models, the user must provide the model with speed, flow, and density values for each space within the building. Again, whether the evacuees are represented as individuals or as a uniform entity will influence the detail in which the user may have to provide the data. At the individual level, movement speeds might take into consideration the range of abilities and mobility within a population and how these may interact, whereas at the population level, this effect would be averaged out across the population in question.

Behavioral Actions of Occupants In most real situations, there is a diverse set of actions that would be expected of the occupants in response to the incident. Similarly, there is a range of methods employed to simulate these actions—in terms of their nature, their impact and any associated delays that might be incurred when they are performed. In turn, the number of assumptions and the amount of data required by the models will vary greatly.

In order to represent the specific behavioral response of a population, the user may have to select and apply an expected behavioral response for a section of the population. In doing so, the user needs to understand the expected behavior of the population in the scenario, when and where this behavior occurs, and the expected consequences. An example might be that the user is aware of a daycare center in the middle of an office building. Given that this facility is provided to cater for the children of staff, the user might wish to simulate some office workers first traveling to the daycare before evacuating the building. (Refer to the case of the Summerland incident, where just such behavior was evident [25, 26].) As with the previous considerations, the level of refinement of the behavior is dependent on the representation of the population (e.g., can the performance of individuals be tracked?) and the detail to which their movement is simulated (e.g., can the model assign itineraries?). This is just one example of a possible decision that the user may want to simulate involving behavior.

Models simulate behavior in different ways, including the following methods:

- Neglect to simulate behavior at all (response is then imposed and constant through the population)
- Simulate only occupant characteristics that affect movement
- Simulate behavior conditionally (individuals are affected by conditions within the building)
- Allow behavior to emerge adaptively such that behaviors are constructed according the conditions faced, the internal information available and some analysis of the situational picture available (attempting to simulate the decision-making process)

It is relatively common within those models that include a conditional representation that the user can specify certain behavioral actions for individuals or sometimes distribute certain probabilities of behaviors over a segment of the population. In such circumstances, the user is directly determining the actions performed by the evacuees. Therefore, the conditions under which the actions are performed, the likelihood of their performance (potentially 100 %) and the consequences of their performance (e.g., a delay of between 20 and 60 s or a change in the state of an object or person) should be based on empirical data and guidance wherever possible. Unfortunately, there is not a great deal of information or data on occupant behaviors during evacuations that can then be categorized according to the nature of the structure.

Summary of User Configuration of Resident Population Once the structure has been configured, information needs to be supplied to the model by the user including the number of occupants in the building, movement data, personal characteristics (e.g., age), pre-evacuation delays, and even specified behaviors. The level of detail and sophistication of the resident population simulated depends on the type of evacuation model chosen. See Chap. 57 for additional information on the design of occupant scenarios.

Procedural Configuration

The third area of the evacuation simulation that would need to be addressed is the procedures that are expected to be applied during an evacuation. These relate to credible situations within the scope of the project at hand to be simulated within the model. These may have been defined and presented to the user or arrived at by the user alone.

As the scenarios vary for the building, the user has to make a variety of choices on whether to include certain evacuation procedures and situations (assuming that the model is capable of representing the scenario in question). Considerations involving the configuration of the procedures include the following:

- The route choice of the occupants
- The existence of counterflow (i.e., the occupants and/or fire fighters)
- The inclusion and activity of human and technological resources

Many of these features are only included in the more sophisticated models. Also, since many of these features are specific to the evacuation models themselves, the user should consult model references and/or evacuation model reviews to find out the current information on the procedural capabilities.

Route Choice When simulating fire evacuation scenarios, a user should be cognizant of the occupant route choice. Several evacuation models offer choices as to the route that the population or portion of the population would adopt when evacuating the building. These choices might include the evacuees adopting the shortest route, optimally using exits according to their familiarity and experience, being assigned a predefined route, or configuring a conditional route. Many times, the default choice for the model will be the shortest route available; however, the user should be aware that this choice may not always represent the paths that occupants will *actually* choose in a fire evacuation. A few models also provide the option of evacuating occupants via elevators and stairs. The route selection of the individual evacuees (if they are simulated individually within the model) will not only directly influence the outcome for the individual but will also influence the overall outcome for the structure. As such, this is a key component of the configuration process.

Representing Emergency Responders Another consideration for alternative evacuation scenarios is the presence of emergency responders in the building. This is primarily of interest in the interaction that they might have with the evacuees and the changes that they may bring to the availability of routes and the environmental conditions. Some of these aspects would be beyond the models currently available and would, therefore, require implicit modeling.

If the user is interested in simulating this type of counterflow situation, then there are several models that have this capability, which is achieved in a variety of different ways. For instance, it might require the provision of the percentage of stair space taken up by the counterflow at certain times, providing a general delay caused by counterflow (i.e., implicitly representing the counterflow) or assigning an itinerary to a group of occupants (e.g., the fire department), so that the group travels to a designated area of the building that causes them to interact with the evacuees (i.e., explicitly modeling the counterflow generated). This would depend on having a relatively detailed understanding of the procedures employed by the fire department and might be sensitive to a range of issues including the body size of this emergency group.

Representing Human and Technological Resources The simulation of a scenario with the explicit inclusion of a human or technological procedural measure that directly affects evacuee performance (e.g., the impact of alarm type or the presence of staff on pre-evacuation time) is a relatively rare capability in the existing set of evacuation models. Most of the models currently available do not have the capability of explicitly simulating this effect. Instead, the impact is more typically represented indirectly or implicitly with numerical values (i.e., timing) assigned to represent the impact [9].

Summary of User Configuration of Procedural Actions The third area of the evacuation simulation involves the procedures that are expected to develop during an evacuation. These relate to credible situations within the structure that need to be addressed within the scope of the project and simulated within the model. These may have been defined and presented to the user or arrived at by the user alone. Specific examples of the decisions made by the user include the route choice of the occupants, the provision of countermeasures (i.e., the counterflow of occupants and/or fire fighters), and the inclusion and activity of staff.

Incident information

When modeling a fire event, the user has to consider the initial location(s) of the fire, depending upon the number of different scenarios simulated. Along with this decision, the user should decide how to coordinate any information about the fire event with the simulation of the occupants in the building (i.e., how closely coupled is the simulation process with the development of the fire?). Depending on the nature of the model, the effect of the fire might be supplied by the user or represented within the simulated environment.

Evacuation models have different means of incorporating fire information with the evacuation process, including no fire representation, input of fire information manually, importation of calculated fire information, and coupling with a fire model. Several models have no representation of the fire conditions. Within these models, the user would have to manually determine when the conditions reached a level that would influence the behavior and well-being of the evacuees. This would require assumptions to be made on behalf of the user that would directly influence the results produced. Some models allow the user to input fire information manually, requiring the user to either derive a description of a fire suitable for the scenario in question or apply empirical data. Other evacuation models allow fire model results to be imported in order to inform the calculations of how the environmental conditions change during the simulation. In this case, the user would need to be able to configure the fire model appropriately and ensure that the conditions produced within the fire model reflected the same scenario conditions that were being represented within the evacuation model (e.g., position and status of doors). A few of the evacuation models have a fire model built into the program. It is up to the user to decide which method is best to use for the specific project.

Summary of User Configuration of Incident Information The fourth area of the evacuation simulation involves the location and impact of the incident. Examples include the location of the fire and the inclusion of toxicity or fire data.

Summary of Model Scenarios

The examples presented in this section are meant to provide users with guidance when examining and designing scenarios for a project. This section has been designed to provide guidance on the factors that should be considered when using an evacuation model.

Grid size, as well as other user inputs that are occupant-focused (e.g., occupant numbers, occupant size, and occupant speed) may affect the results of the evacuation model. For more information on how inputs can affect evacuation model results, see Lord et al. [7].

Example of Evacuation Model Scenario Configuration

The total evacuation from a high-rise building will illustrate the types of concerns relating to the use and configuration of an evacuation model. This will provide the user with an example of the configuration process to use as a reference. (See Chap. 57 for additional information on the design of occupant scenario's for life safety analyses.) The following paragraphs will describe the building and the scenario.

Although this example does not incorporate results from any specific model, research has been done to highlight differences in results when multiple models are used on the same building [4, 6, 7, 27–29].

Scenario Information

Only one scenario will be discussed in this section to provide an example of the kinds of decisions that users will make when configuring an evacuation model. In this scenario, a fire initiates in a guest room on the 5th floor at 2 a.m. The reason for choosing a fire initiating at 2 a.m. is to provide an example of a worst-case scenario for a hotel building due to the fact that most guests will be in their rooms sleeping. In this scenario, the fire event will trigger a full-building evacuation.

As mentioned previously, the user is faced with decisions on how to configure the building, the population, and the environment. The following discussion provides examples of decisions made for this specific scenario in each category of configuration.

The building used for the example is a hypothetical office/hotel building. The office/hotel building has 20 stories, with each floor occupying an area of approximately 1200 m^2. The distance measured between floors (floor height) is approximately 3 m. The first 10 floors (floors 1–10) consist of a segmented floor plan typical of hotel rooms and the top portion of the building (floors 11–20) consists of an open floor plan used for office space. There are two 1.11 m (44 in.) stairs located on either side of the floor plan that serve all floors in the office/hotel building. It is assumed that the user has been given this design to evaluate for life safety purposes. In reality, the design may be far more complex. However, this design should be sufficient to illustrate the processes at hand.

The following additional information is provided to the user for this scenario:

- The hotel portion of the building is occupied by people on business and leisure travel.
- The hotel has a limited 24-h staff.
- The fire department is located across the street from the hotel.
- Once an alarm sounds in an area of the building, a staff member will investigate. The staff member then decides whether to sound the main building alarm.

The plans for the hotel space on each of the 10 floors (floors 1–10) are identical and the floor plans for the office spaces (floors 11–20) are assumed to also be identical. The floor plans for floors 1–10 and 11–20 are displayed in Figs. 60.6 and 60.7, respectively. In this example, the ground floor is not considered. Therefore, in order to reach an area of safety as part of this life safety analysis, all occupants in the building will move past floor 1, down two flights of steps, and out the final exit.

Building Configuration

The model user is faced with a variety of decisions when configuring the building. Depending on the type of grid/structure method employed by the model, the user will have to construct a coarse network, fine network, or continuous network within the floor plan of the building. Examples are provided here for each type of network. In addition, the user must also make decisions about adding extraneous building information, such as stairs and exits.

Coarse Network When using a coarse network, the network does not explicitly represent all of the occupiable space. Therefore, the user is required to artificially segment the structure in order to produce components that will appear in the network. It is not always apparent how best to segregate the structure and, therefore, represent the structure within a coarse network model.

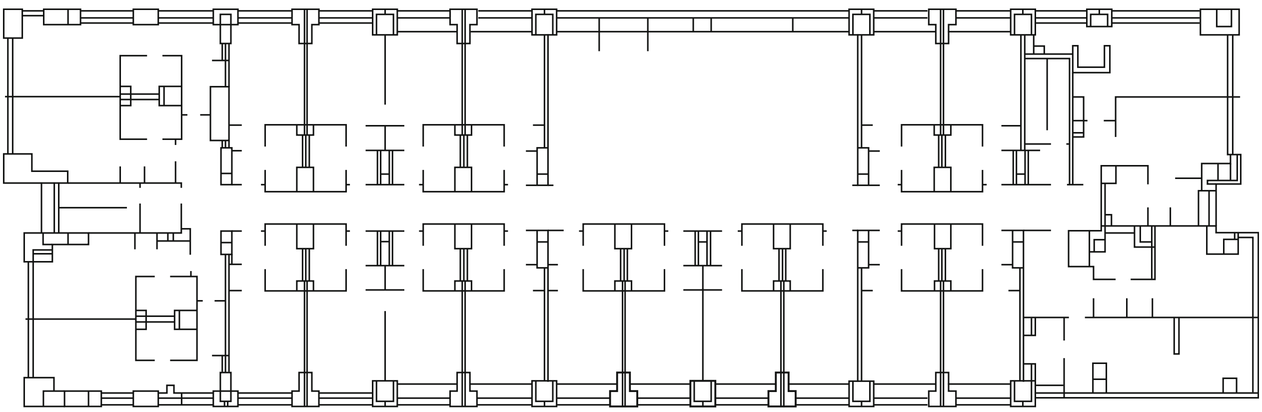


Fig. 60.6 Floor plan of floors 1–10 (the hotel space)

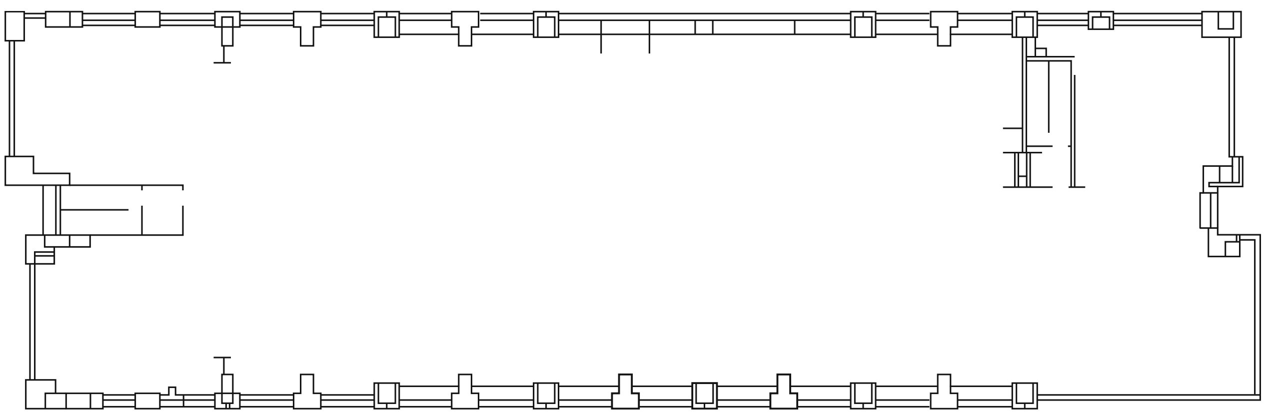


Fig. 60.7 Floor plan of floors 11–20 (the office space)

As mentioned previously, this segmentation will have a direct impact on the results produced. Figures 60.8 and 60.9 are used to demonstrate the different (and equally viable) ways to segment the building for a coarse network. Figure 60.8 shows the open office floor plan that is divided into 12 "user-derived" sections (derived in that they are not immediately apparent from the architectural description of the structure) with each connecting arc. This derived design leaves a longer rectangular box for the hallways and finally two sections for the stairs on either side of the floor plan. In a coarse network, the model simulates that the occupants will move from the middle of one segmented area to the middle of another (with which it is linked). The segmentation of the structure will, therefore, directly influence the movement of the occupants and the routes that may be adopted. Often open floor plans are difficult to segment because users are not privy to the eventual segmentation that each company will employ when the building is in use. Therefore, it is up to the user to provide segmented areas that are representative of how occupants might move throughout this space to safety as shown in Fig. 60.8.

In contrast, Fig. 60.9 provides a different example of larger segmented spaces of the same structure. This space is segmented into fewer office sections than in Fig. 60.8 (eight in total) and two staircase sections. Although this example requires less time to produce, it might not accurately represent occupant movement through this space. When segmenting out any space in a building, the user might want to run sample simulations of each floor plan to analyze the simulated occupant movement to determine whether the movement path and times are representative.

Figure 60.10 shows a segmentation of one of the hotel floors of the example building. The majority of the segmented areas relate to the hotel guest rooms. Therefore, there is less scope for flexibility in the association of nodes

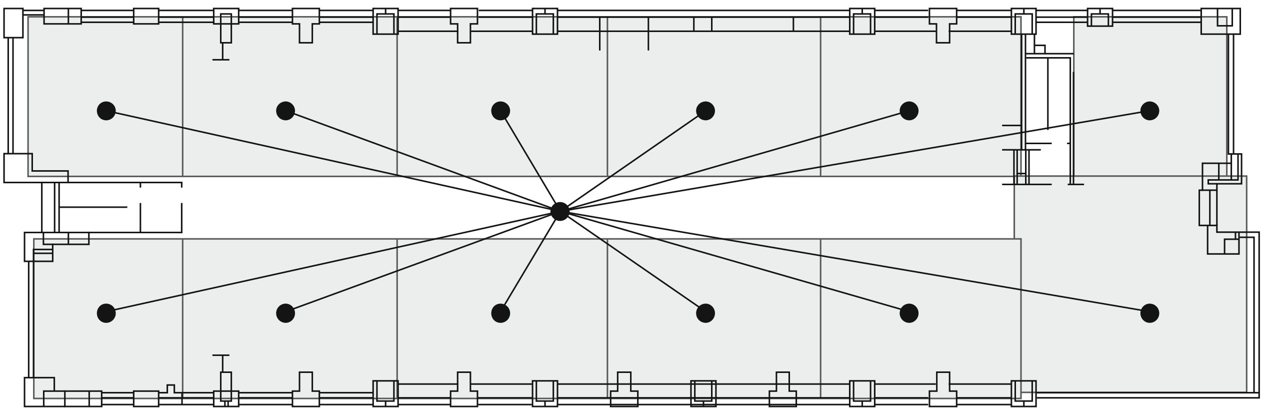


Fig. 60.8 First example of the segmented office floor plan

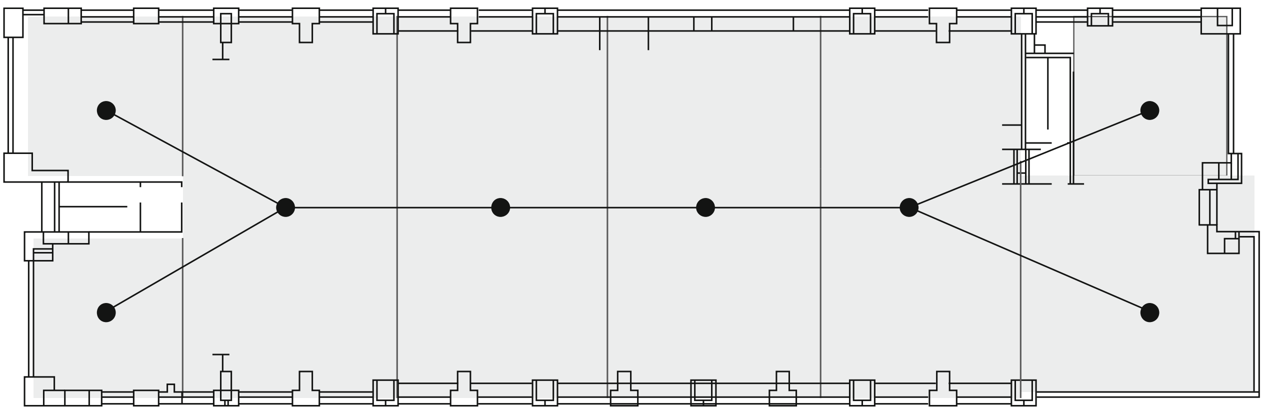


Fig. 60.9 Second example of the segmented office floor plan

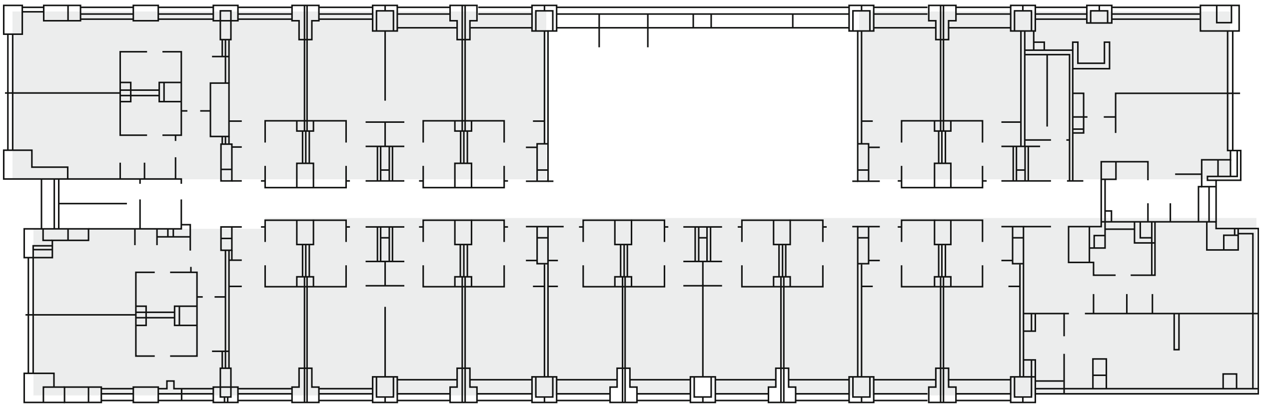


Fig. 60.10 Physical segmentation of hotel design providing a more apparent coarse node network

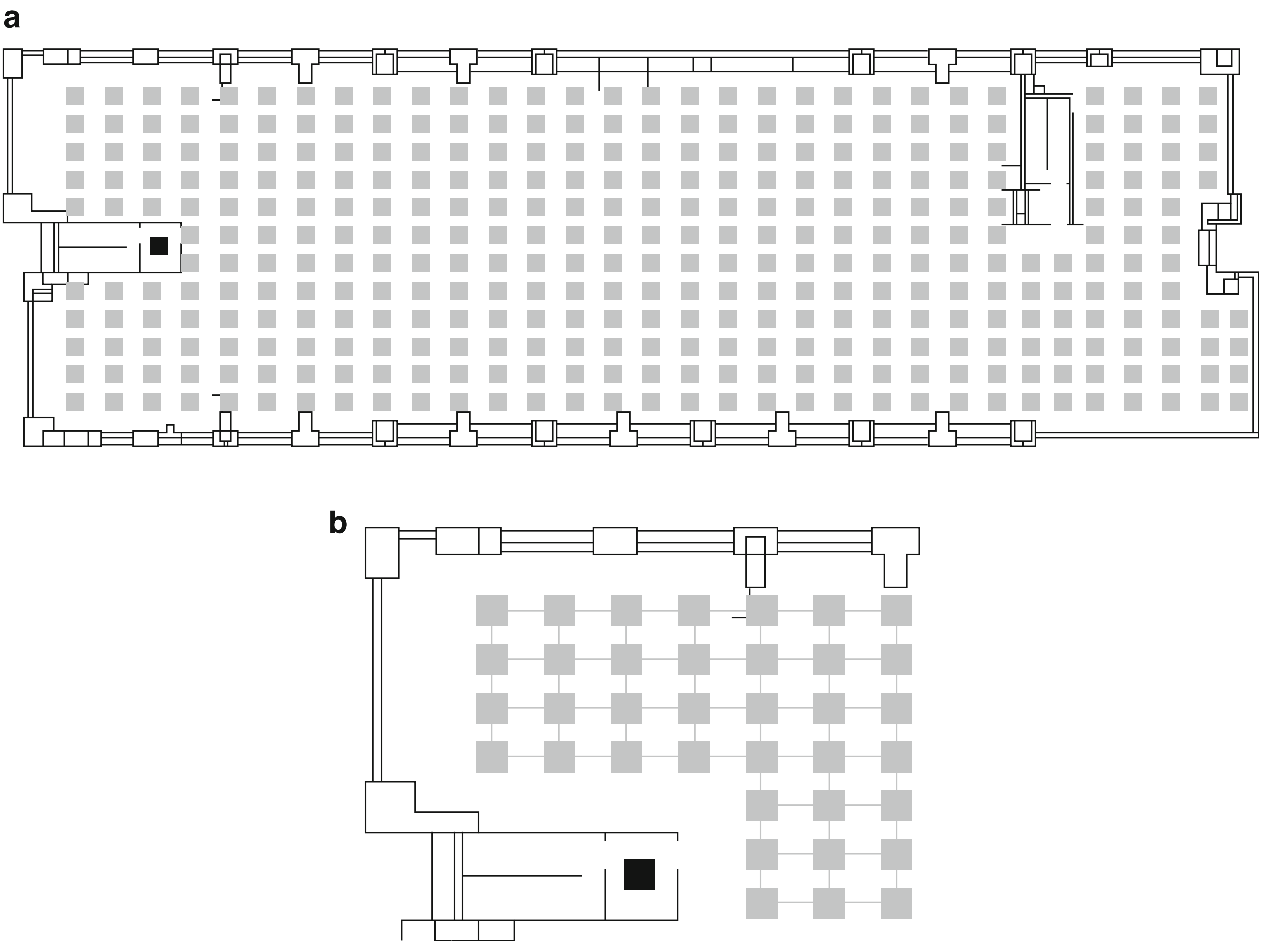


Fig. 60.11 (**a**) Fine nodal mesh; (**b**) horizontal and vertical connections between nodes

with compartments. In this floor plan, the physical structure adequately defines the separate spaces required. The main area of flexibility in the association of the design to a coarse network is the large hallway. Depending on the length of the hallway, the space might require multiple segmented areas rather than representing it as a single node.

Fine Network Grid Figure 60.11a shows a meshed open floor plan for a fine network grid. In comparison to the coarse network, the fine network requires a larger number of small nodes to mesh the geometry. Also the fine network grid is performed at a different level of refinement with the mesh relating directly to occupiable space rather than compartments.

Instead of describing the passage of individuals between components, the nodes are describing the movement of evacuees at a much higher resolution. In Fig. 60.11b the initial steps in this process are shown where the nodes displayed are connected horizontally and vertically. Normally this process would continue to also include diagonal connections to provide the occupants with a greater degree of freedom in their movement.

Figure 60.12a shows the hotel floor plan partially meshed with a fine nodal grid. This is a time-consuming and error-prone procedure if performed manually, given the number of nodes that need to be produced and the precision with which they would need to be positioned. Normally this process would be automatic or semi-automatic, with the mesh being calculated and imposed by the model. Even so, the user would need to check and modify the mesh to determine whether the algorithm in question had represented the occupied space with sufficient accuracy. Figure 60.12b is color coded (shown in different shades of gray here) to show that the connectivity of the rooms should reflect the ability of the simulated occupants to move from space (or component) to space. In other words, the simulated occupant would not be able to pass through a physical barrier (e.g., a wall) that might be present in the actual structure.

Continuous Network Figure 60.13 shows the occupied space within the hotel structure as depicted by a continuous network. As previously described, a continuous network model represents the building floor plan as a continuous plane that simulates the occupants' movement on a coordinate-based system over all occupiable space. Instead of occupants occupying blocks of

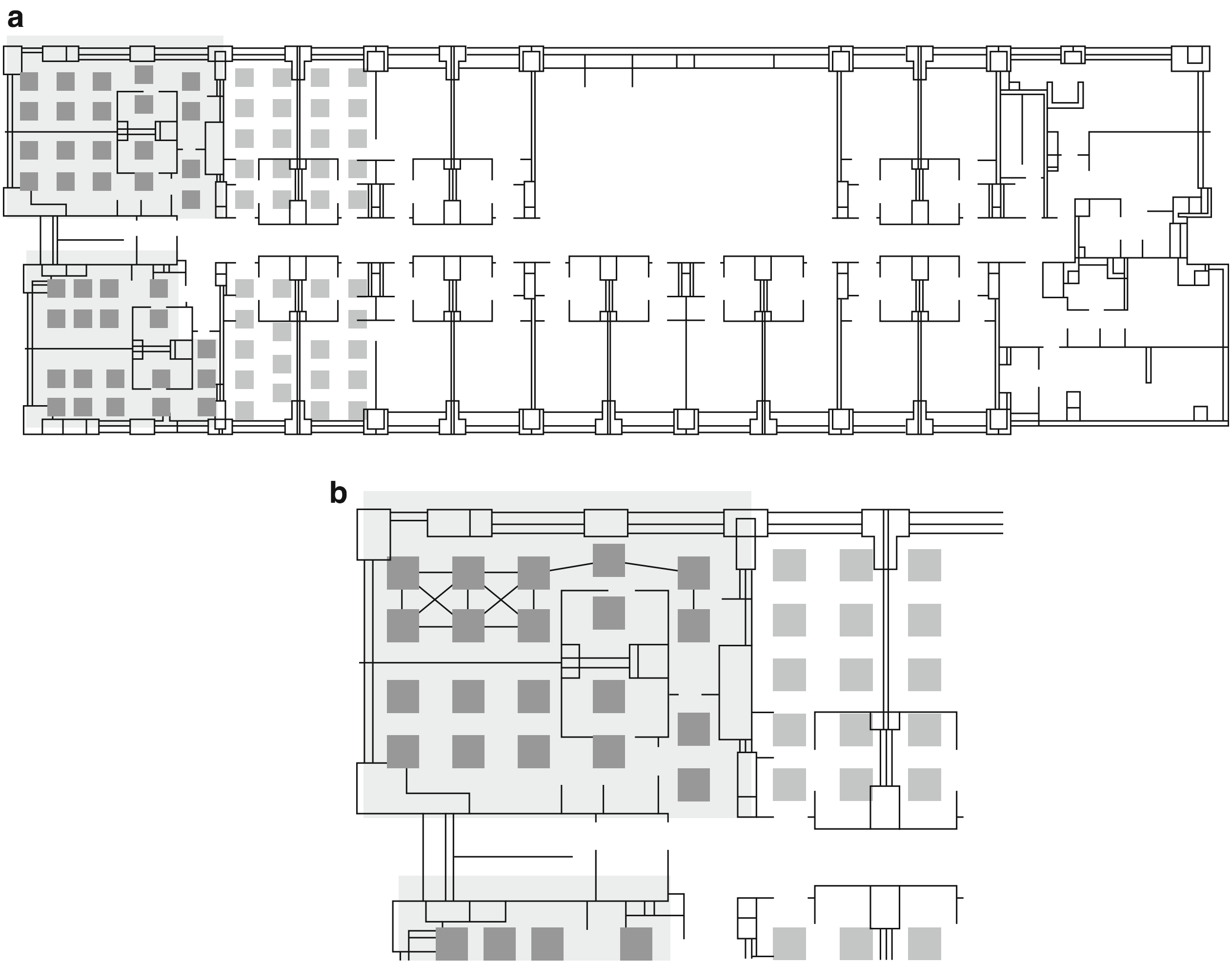


Fig. 60.12 (**a**) Example of fine mesh applied to hotel geometry; (**b**) connectivity of a section of this geometry

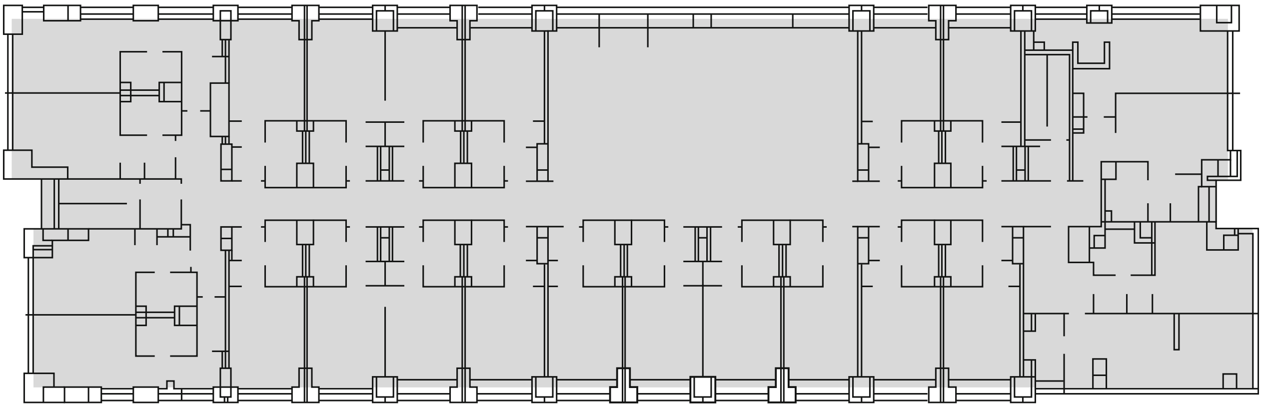
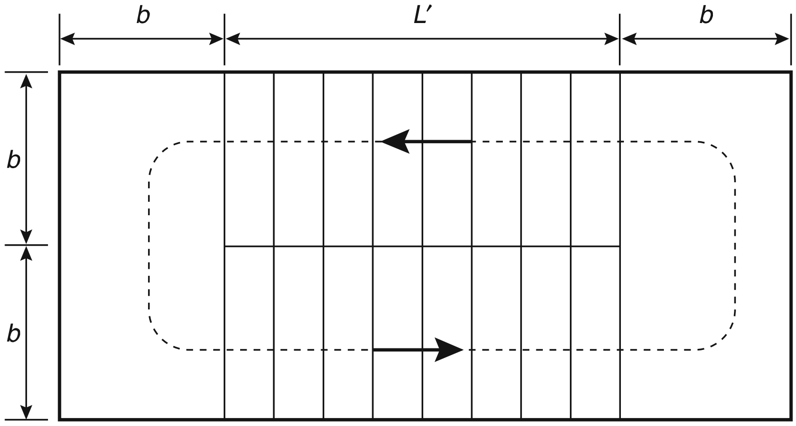


Fig. 60.13 Occupiable space within the hotel structure, represented by a continuous plane

Fig. 60.14 Graphic drawn to explain the stair calculation (Predtechenskii and Milinskii [24], p. 28)



space (coarse network) or square nodes (fine grid), a continuous model simulates occupant movement on a flowing *x-y* (and *z* for multiple stories) coordinate system. In most instances, this provides a more accurate representation of the floor plan of a building.

Additional Building Information

In addition to the method with which sections of the building are represented and connected, the model also requires the user to identify information about the stairs and exits (location, width, etc.). In this example, there are two 1.1 m (3.6 ft) wide staircases, one at each end of every floor in the building. Depending on the model, the user may be required to provide the distance along the staircase between floors, either the diagonal distance or the horizontal distance. In both cases, the distance along the landings should be taken into account within the distance calculation. In addition, some models allow the user to incorporate certain distances that the simulated agents will remain away from the walls of the stairwell (e.g., to represent a handrail inside the staircase).

An example of a method used to calculate the diagonal distance along a two-flight staircase measuring 1.1 m (3.6 ft) in width, wall to wall, is provided here. For this example, a staircase flight is the portion of the stair that extends half the distance between floors (Fig. 60.14). Following the development of Predtechenskii and Milinskii [24], Equation 60.1 is used to calculate the diagonal distance of one of the stairs located in the hotel/office building.

$$L = \left[2L' / \cos(\theta)\right] + 4b \qquad (60.1)$$

where
L = the total diagonal distance of two flights
L' = the horizontal distance of one flight of steps
θ = the inclination of the stair at each flight
b = the width of the stair/landing

In the case of the example, b is equal to 1.1 m (3.6 ft), L' is equal to 2.0 m (6.56 ft), and the angle of the stairs is 37°, which corresponds to 3 m (10 ft) between floors with 8 steps at 19 cm by 25 cm (7.5 in. by 10 in.) riser and tread for each flight. With these values inserted into Equation 60.1, the diagonal distance of the stairs is calculated to be 9.5 m (31 ft).

Evacuation models also require the user to identify the location of the exits within the building. In this example, the exits are placed at the bottom of the staircase directly below floor 1. The occupants reach the exit once they have traveled down the final staircase and out of the 0.9 m (36 in.) door present.

Population Configuration

All evacuation models require the user to specify characteristics about the population in the building. These characteristics, depending on model sophistication, can include the number of people in the building, movement speeds/flows, pre-evacuation times, and specific behaviors. Macroscopic models, for example, require the user to provide only the number of occupants located in the building and/or in specific sections throughout the building and characteristics representative of the entire population instead of individuals. Therefore, the user need not identify specific information about the occupants other than the number and a representative speed and flow for the population. Identifying the number of occupants in the building, which is required by all models, will be described in the following paragraphs.

Number of People Most building evacuation computer models require the user to specify the number of people in the simulated building evacuation. If the project does not specify the number of people, the user can use information on the building type and available floor space to calculate the number of people using occupant load factors [30]. The occupant load factors provided by NFPA *101*®, *Life Safety Code*®, are estimations of the maximum probable number of occupants present in the building type at any time. (Studies have been done [31] showing that the design loads in NFPA *101* may grossly overestimate the number of people expected to be in particular types of buildings.) For a day-time scenario, the NFPA occupant load factors would be used to estimate a conservative number of occupants on each floor of the office space. The maximum occupancy of the hotel rooms will be used as an example to estimate the occupancy of the hotel floor plans.

For a fire initiating at 2 a.m. on the fifth floor of the office/hotel building, it is expected that there will be more people located in the hotel portion of the building compared with the office floors. Using the maximum occupancy figures for each hotel room, 100 occupants per floor are estimated for the hotel room floors. However, due to the time of the scenario (2 a.m.), only 10 people per floor are assumed for the office floors. These people are included to simulate cleaning staff and the possibility of overnight workers.

Overall, the population of the building is estimated to be 1100 people in the entire 20-story building. This number includes 100 people per floor on the hotel floors and 10 people per floor on the office floors.

Movement Another occupant characteristic provided by the user is unimpeded movement speeds of the population and/or individual occupants in the simulated building. For macroscopic models, the user is required to provide an average or overall speed (unimpeded) for the entire population. On the other hand, microscopic models require the user to provide specific information on characteristics of groups within the simulation in addition to the number of occupants in the building. These can include individual speeds (unimpeded), body sizes, and disabilities.

For the hotel/office building example, there are certain factors that can affect the movement speed of individuals in a building. The following list includes factors to consider when choosing unimpeded movement speeds for members of the population:

- The distribution of men/women within the structure
- The age of the occupants simulated
- The body size of the occupants simulated
- The presence of occupants with disabilities

In the case of the 2 a.m. fire scenario, it is of particular interest that the user understands the characteristics of the hotel population expected in the building at the time of the fire. As discussed earlier, some evacuation models require the user to supply only movement speeds for the entire population. For this type of information, please see Chap. 64. However, there are evacuation models that require the user to specify information about the individuals in the simulated building. Since the majority of the people in the building at the time of the fire will be located in the hotel floors, the majority of the research on individual characteristics for this scenario will be made on the hotel population.

Occupant Characteristics Although difficult, the user can obtain information about the gender and the age of the occupants expected to be in the hotel portion of the building at the time of the fire. The scenario information provided in this example specifies that the hotel is expected to house individuals on both leisure and business travel at any time throughout the year. References such as D.K. Shifflet's DIRECTIONS Travel Information System [32] and the American Hotel and Lodging Association [33] contain a wide variety of information from U.S. hotels such as the percentages of male and female guests, a distribution of the ages staying at hotels for all types of stays (e.g., business or leisure stay), and the additional percentage of children present during leisure trips.

With this type of information, the user can identify the type of occupants in the building, according to the requirement of the evacuation model used. Once an occupant population is determined, information on movement speeds of individuals or groups of individuals based on occupant characteristics can be found in Chap. 64. An example of how hotel distribution information has been used to identify the probability of certain occupant sets has been completed by Stiefel et al. [34].

In addition, if the user and/or the project require the simulation of occupants with disabilities, it is important to understand the number of occupants with disabilities expected to frequent this hotel or, in general, hotels within the United States. With that number in mind, there are sources that provide information on unimpeded speeds of occupants with disabilities [35–37].

Pre-evacuation Time Depending on the model, the user may have the opportunity to provide information on pre-evacuation time for the overall population or individual/groups within the building. In the case of the hotel/office building, the literature provides some guidance on data that could be used to represent the pre-evacuation times for an office building and for a hotel building, depending on the factors just mentioned (see Chap. 64).

If the model allows for the assignment of pre-evacuation times to individuals, the office occupants should be assigned a separate distribution from the hotel guests, thereby implicitly simulating the different responses that may be expected given the role and activity of those involved. However, if the model views the population from a macro level, as with the movement data, an average can be assigned to the entire population, being less sensitive to the differences within the populations in question.

When simulating pre-evacuation times, the hotel population should be assigned a pre-evacuation time that takes into account the time of day that the fire will occur. Since the fire in this example occurs at 2 a.m., it is very likely that the hotel population will be sleeping. Before evacuating their room, the occupants will likely need time to wake up to the sound of the alarm, dress, retrieve needed items (i.e., glasses, wallet, purse, etc.), and wake any other occupants sleeping in their room or in other rooms nearby. When assigning pre-evacuation times to hotel buildings, because there isn't a large amount of recent information [35], it might be more useful to research pre-evacuation times for apartment buildings as well [38].

Behavior/Actions Finally, the user may wish to assign behavior itineraries or actions to certain individuals during the simulated fire evacuation. Many of the evacuation models available do not provide this option to the user; however, for those models that do, the user should be aware of the lack of data in this area. There have been studies done on behaviors performed by occupants in certain building fire evacuations (e.g., see Chap. 58), which can be used to simulate specific behaviors during an evacuation.

For the example with the hotel/office building evacuation, the user can specify that certain hotel occupants, before evacuating, "visit" other hotel rooms to awaken occupants for evacuation. Or, if there are sufficient data available on turn-back behavior in smoke, the user can simulate that certain occupants turn back when/if the smoke becomes too hazardous to travel through. These are only examples of behaviors that can be simulated. Any behaviors that users do simulate, however, should be accompanied by the appropriate data to support such simulations.

Procedural Configuration

Route Choice In the case of the hotel/office building, even though the choice of exits might appear obvious, it would be beneficial to run several different scenarios where the routes adopted by the occupants differ to determine the sensitivity of the results to the choice of route and the robustness of the structural and procedural design. If alternative scenarios are run such as simulating a predefined route as well as a shortest-route option, the user can compare the results and then make suggestions for improvement. If the user is interested in simulating occupants traveling first to a daycare center or other points located in the building and then evacuating, the user would have to make sure that the model had the capability of a predefined route choice.

Representation of Emergency Responders Another procedural choice of the user is to decide whether it is necessary to include the simulation of emergency responders during the evacuation. In the case of the hotel/office building example, the local fire station is located directly across the street from the simulated building. Since the response time of the fire department is expected to be less than 2 min, it is important to consider the simulation of counterflow of the fire department in the stairs, as long as the evacuation model is capable of simulating such activity. Because the response time of the fire department is expected to be short and the response time of the occupants to evacuate is expected to be higher (greater than 10 min), the simulation of the interaction of fire fighters and occupants in the stairways should be considered.

Representation of Technological and Human Resources Last, although many evacuation models do not have the capability of simulating the presence of staff or alarms, the user should consider whether this is an important part of the evacuation to simulate. With the hotel/office building example, staff is available 24 h per day; however, the nighttime staff is limited. Similarly, the same hotel may have a voice alarm system that is present in each of the guest rooms. The user might consider whether these factors will have an effect on the pre-evacuation time of the occupants if they are active during the incident. There are limited data on this feature of an evacuation scenario, but they should be kept in mind when running scenarios of a fire evacuation and should certainly be discussed when presenting the assumptions on which the simulated scenarios are based.

Incident information

When performing a life safety analysis of a building, the user should simulate a number of different scenarios. In each fire scenario, the user has to decide the location of the fire source. In the hotel/office building example, there are many different locations where a fire could be assumed to begin. Statistics on fires in offices and/or hotels can be consulted to obtain probable places of origin [39]. These statistics depend on the type of building, the time of day, the type of facilities in the building (e.g., hotel kitchen, laundry area, office space, main lobby, etc.), and the possible activities of the occupants (e.g., can occupants smoke in their hotel rooms?). Information can be obtained from NFPA statistics, including the top causes of civilian deaths, causes of injuries, causes of property damage, and frequent areas of origin. The guest room was chosen as the area of origin for this example because even though only 12 % of hotel and motel fires began in bedrooms, these fires caused a majority of the deaths and injuries [39]. Potential causes of this scenario's fire, based on NFPA data, could be intentional, cooking equipment (in the room), and even heating equipment [39]. Scenarios should be run with guestroom doors held open and closed along with fires beginning in other areas/rooms throughout the building.

User Checklist

The discussion in the previous section outlines the types of factors that need to be examined when configuring and applying computational tools. In many cases, it may not be possible to represent all of the factors in the detail desired. This might be due to issues of time, cost, data available and/or modeling limitations. However, irrespective of whether these factors are addressed, the engineer should be mindful of them when configuring the tool, describing what is (and what is not) addressed in the scenarios examined, and in presenting the results.

Figure 60.15 provides a brief checklist of the types of factors and issues that the user should address when selecting and configuring an evacuation model ready for application within a project specification. This list is by no means exhaustive but should at least prompt the user to address the issues that have been discussed in this chapter. Reference should also be made to Chap. 57, where matters of scenario design are discussed in more detail.

Summary

This chapter has provided an overview of 26 current egress models and developed a checklist to be applied when using a new model. Guidance for applying many of the features found in these egress models has been provided. It is not suggested that the guidance provided in this chapter is sufficient for the user to perform the analysis required. However, it is contended that for many, especially those who are relatively inexperienced in egress modeling techniques, the guidance provided is necessary. This chapter could then act as a companion chapter to those provided within this volume to outline the process of egress analysis from the initial identification to the delivery of the end product.

All modeling is a result of compromise and represents a simplification. The guidance provided in this chapter should highlight the decisions that need to be made, the information that is required to make these decisions, and the tools needed to complete the simulation and analytical process. In effect, it acknowledges that compromises have to made, but such compromises must be informed so that they can be defended.

- ❑ Project specifications
  - ❑ What is the nature and scope of the project?
  - ❑ What are the deliverables of the project?
  - ❑ What information is available within the project to frame the egress analysis?
  - ❑ How much time and funding are available to complete the project?
- ❑ Model selection
  - ❑ Background of the model
    - ❑ Who is the model developer or developing institution?
    - ❑ Is the model validated for this type of application? How?
  - ❑ Model characteristics
    - ❑ What is the modeling method inherent in the model?
    - ❑ What is the scope of the model regarding the building, individuals, and the scenarios?
    - ❑ What kind of output does the model produce?
    - ❑ How is the model available for use?
    - ❑ How old is the model and what advancements has it made since its release? Is the model still supported?
    - ❑ What refinement is used in the model for the building and individuals?
- ❑ Model scenarios
  - ❑ What is involved in building configuration?
    - ❑ How does the model allow for structure generation?
    - ❑ How does the model allow for structure representation?
    - ❑ What other kinds of information are needed to supplement the building grid?
  - ❑ What is involved in occupant configuration?
    - ❑ How many occupants are in the building?
    - ❑ What movement data are required by the model?
    - ❑ What occupant characteristics are required by the model?
    - ❑ What pre-evacuation data are required by the model?
    - ❑ What kinds of behavioral inputs are of interest for the population and is there information available to provide as input?
  - ❑ What is involved in scenario configuration?
    - ❑ What fire information, if any, can be provided to the model?
    - ❑ What options for exit route choice are available in the model?
    - ❑ Can the model simulate the influence of counterflow?
    - ❑ Can the model simulate the influence of building staff?
- ❑ What are the computer requirements to run the model?
- ❑ What is the format of the output?
- ❑ How can the output be organized in a manner required by the client?

Fig. 60.15 Factors and issues in selecting and configuring an evacuation model

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