Building evacuation, rules and reality

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The paper discusses some of the problems surrounding the simulation of the evacuation time in buildings. Building regulations offer little guidance to the designer in dealing with these problems, but good and safe solutions can easily be described qualitatively.

Key words: Evacuation, phased evacuation, tenability, waiting time

1 Introduction

The safe evacuation of the building occupants is the pre-eminent objective of fire safety measures required by building regulations. There is a substantial body of knowledge on the different stages of the evacuation process, on effective evacuation strategies, and on how the building design influences the possibilities of the occupants of a building to safely evacuate; see SFPE[4] for an overview of the state of the art. Applying that knowledge in the design of buildings has the potential to lead to optimised designs in terms of the level of safety, architectural freedom and costs. Traditional building rules targeting safe evacuation are however in most cases based on a much simplified model of the evacuation process, which does not allow the use of the currently available knowledge.

A general fire engineering design methodology does allow for any sound available knowledge to be introduced in the design. Whereas performance based building codes embrace the fire engineering methodology, the level of acceptance of such generalised methodologies, especially with authorities responsible for building permits, is still limited. Often, anything beyond the simplified approach is met with reluctance. This may be attributed on the one hand to the authorities being unfamiliar with the methodologies. It should however be recognized that the use of poorly validated methods and tools by engineers has done little to increase confidence. There are what could be called isolated successes where advanced calculation tools have gained a level of acceptance. Examples of these are the highly graphical computer models for calculating evacuation times based on following individual escape paths. The application of these tools is not without problems, especially where their results are to be coupled to the requirements of the building code.

This paper identifies and discusses a number of these issues, related to evacuation under fire conditions. The issues have come to attention in actual design processes occasionally but have, under the pressure of the "standard simplified approach" not been solved to any degree of satisfaction. Where the discussion involves building regulations, references are to the Dutch Building Decree and associated rules, see Bouwbesluit [1]. While many of the problems discussed will be present in other countries as well, the corresponding situation outside the Netherlands is beyond the scope of this paper.

2 Evacuation issues

2.1 ***Full or partial evacuation***

One of the essential concepts of fire safety in buildings is the rapid and adequate evacuation of all the occupants of the building in case of fire. Many of the fire safety measures introduced in the design and operation of the building are aimed at ensuring that the occupants can safely leave the building before they are overtaken by heat and toxic products, and before the building collapses.

The Dutch building regulations – as many other national building codes – assume that an unchecked fire will grow to involve the whole building, necessitating its complete evacuation. The fire department will normally be able to limit the extent of the fire to within one fire compartment; the probability of failure in this objective is however too high to count on successful repression and to let occupants of other fire compartments stay in the building.

Only in exceptional cases where it is sufficiently probable that the building can survive a fire, where fire compartmentation is rigorous, and where a full evacuation would take too much time, do some building codes accept a "defend in place" strategy. High rise buildings are an example where building codes (not the Dutch one!) allow to design according to this alternative strategy. Other examples are easily found where a full evacuation is unnecessary, such as large, spread-out building complexes with very limited connections between compartments. Actually, even medium rise apartment buildings are in practice almost never evacuated completely, since due to the high level of compartmentation a fire is easily contained to within one or two dwellings.

In cases such as described above a full evacuation can be shown to be unnecessary if not counterproductive: people may be put at risk when escorting them to safety through hazardous areas, where they would be better off staying in place while the fire is suppressed; the consequences of fire could easily grow much larger if the emergency teams have to spend part of their resources to rescue efforts instead of fighting the fire. In those cases it should be allowed to base the design, including the egress capacity, on the partial evacuation that is shown to be safe and practicable.

2.2 ***The application of advanced computer models***

The escape time tescape in a fire situation has three main components, according to Marchant [3]:

$t_{escape} = t_{perc} + t_{aware} + t_{travel}$

where t_{perc} is the time between ignition of the fire to perception of the emergency, t_{aware} the time between perception and awareness of the need to escape, end t_{travel} the travel time to a place of safety. Much of the knowledge and design tools that have been developed on evacuation over the last decades have focused on the mathematical modelling of the escape process, i.e. t_{travel}. This has lead to the emergence of more or less sophisticated software packages, that are increasingly being applied in building design. The computer models do allow better prediction of the travel time than the traditional simplified “hydraulic” approaches, but not of the other components of the evacuation time. More often than not, the other components are at least as large as the travel time, and vary substantially over the building.

The “advanced” programs also contain at best a crude model for the decision-making process of individual occupants. Getting reasonable travel times therefore requires significant input and “steering” by the operator of the computer program. The reverse side of this is a severe limitation of the predictive capability of the program. Two examples of the need for manipulating the simulations are given in the figures below.

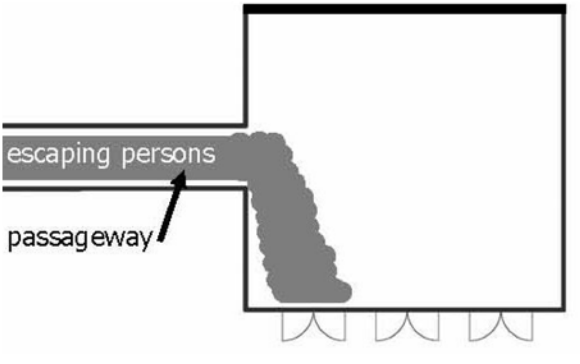

Figure 1. An example of the need for manipulation in advanced evacuation simulations. The distance map allocates all persons coming from the passageway on the left of the drawing to the first of three double exit doors. The other two doors are left unused. This had to be solved by arbitrarily allocating a third of the persons who were going through the passageway to each of the three exits.

These issues, as well as the fact that two major components of the escape time are not included in the computer simulations, could be dealt with in a crude fashion by introducing a safety factor on the RSET (the Required Safe Egress Time, i.e. the result of the calculation of evacuation time), before balancing it with ASET (Available Safe Egress Time). See Fahy [2] for a detailed discussion of the use of safety factors to compensate for uncertainty and bias in evacuation model results.

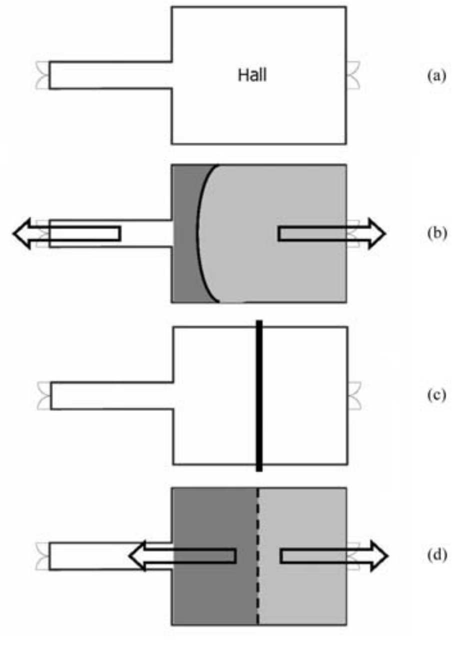

Figure 2. An example of the need for manipulation in advanced evacuation simulations. The figure shows artificial plan views An assembly hall with two exits, one at the end of a corridor (a)Each person is allocated to the exit closest to him on the basis of a calculated "distance map". In the example, virtually everybody in the hall is allocated to the exits on the right (b). By adding a "virtual wall" halfway in the drawing (c) an even distribution over both exits is obtained (d).

When evaluating the results of an advanced model, there is a tendency to compare the calculated evacuation time for a space or a building with the maximum time requirement set by the regulations. That maximum time requirement is in its origin directly associated with a simple hydraulic type travel time calculation. It should not come as a surprise that the more advanced model comes up with larger evacuation times, as it takes into account at least some of the complicating factors that the simple hydraulic calculation ignores completely.

The evacuation times calculated by the more advanced model being in general larger than the hydraulic results has proven to be a strong impediment to the application of the advanced model: Instead of profiting from the added effort in applying better knowledge, the user is penalised by being allowed less persons inside the building.

It could be argued that the more accurate prediction by the more advanced model requires a smaller safety factor on results than the hydraulic model.
In order to enable such a procedure in the Dutch regulatory context, it would be necessary to separate the implicit safety factors in the regulations from the requirements. In a simplified representation, the Dutch requirements come down to the following time requirements:

Table 1. Egress time requirements according to the Dutch regulations

Evacuation of :	**Maximum time**	
Room, smoke compartment[1]	1 minute	To be calculated taking into account the total available door width, assuming a flow capacity of 1.5 person per second per meter[2] of door width
Complete building	15 minutes	To be calculated taking into account the total available door, corridor and stair widths, assuming a flow capacity of 1.5 person per second per meter of door or corridor width, and 0.75 person per second per meter of stair width

The 1 minute requirement for a smoke compartment could be thought of as consisting of a time requirement of say, 3 minutes, combined with a safety factor of three to be applied to the actual evacuation time calculated with the simple rule as stated in table 1. A more advanced model that takes into account complicating factors such as the internal layout of the spaces and differences in mobility characteristics of the occupants could be rewarded with a reduction of the safety factor from, again say, 3.0 to 2.0[3]. In that case, an evacuation time of 1.5 minutes calculated by the advanced model would still be acceptable. In general, the better a model can be demonstrated to predict actual evacuation times, the smaller the safety factor that should be applied to its results.

2.3 ***Simultaneous or phased evacuation***

The standard concept of full evacuation is often accompanied by the notion that all occupants of the building start evacuating at exactly the same time. For the design of egress provisions, this has important consequences. This is due to the notion that any smoke compartment must be emptied within one minute (after alarm). Circulation spaces used by multiple smoke compartments as the primary area that exits lead to must then be sized to hold the occupants of all the associated smoke compartments who are allocated to that circulation space, before they continue their evacuation to a place of safety. In reality, there is a need for the fastest possible evacuation only in the smoke compartment where the fire originates, as smoke can fill the compartment in a very short time. The occupants of other smoke compartments are not subjected to a direct threat (fire, smoke, collapse) until much later, since the smoke

1 A fire compartment is subdivided in smoke compartments such that the maximum walking distance to the nearest exit is limited to (30..40 m, depending on occupancy). Smoke compartments are separated by smoke resisting structures.

2 In evacuation calculations within the scope of Dutch regulations, widths of doors, corridors, stairs are always actual or structural widths; as opposed to effective widths where a boundary layer is subtracted from the actual widths. In international literature flow capacities are mostly correlated with the effective width.

3 The safety factors in this section represent merely examples. Actual proposals should be founded on rigorous study

compartment boundaries constitutes a firm barrier against the entrance of smoke and heat. A situation can therefore be considered safe where the circulation space is sized to allow the smoke compartment of origin to empty into it within the first minute. The other smoke compartments have to wait until space becomes available as the circulation space empties into exits, stairs etc. Reasonable values of the delay of the alarm may be 1 – 2 minutes, and 2 – 5 minutes for the time after which the other compartments are empty.

The above issue is especially consequential for assembly buildings such as cinemas and theatres that can hold large numbers of people. If they are to be designed for simultaneous evacuation, the central lobbies need much more surface area than if they are designed for phased evacuation. Quite traditional designs cannot comply with the requirements if simultaneous evacuation is to be taken into account. A phased evacuation can safely take place in the cases mentioned since the compartments have a high level of fire separation from each other and from the escape routes, reducing hazards arising from delaying the evacuation.

It is clear that in practice there is a strong bias towards an earlier start of the evacuation in the compartment where a fire starts, as these occupants normally become aware of the need to evacuate before the occupants of other smoke compartments. The problems associated with a simultaneous evacuation will in practice only occur with a general alarm triggered by an automatic detection system.

An unanswered but highly interesting question is which forms of phased evacuation can safely be introduced in a design, and which conditions should be satisfied. Factors that should influence the decision to allow phased evacuation in the design are:

1. How probable it is that occupants of the other compartments can remain unaware of the evacuation of the compartment of origin; an evacuation alarm system should support the phasing by delaying the evacuation alarm in the compartments that “compete for circulation space” with the compartment of origin by an amount of, say, 1 or 2 minutes. Only adequate and audible spoken-word evacuation alarm systems can deliver this kind of support. The fire or an evacuation in progress in the compartment of origin should also not be visible from within adjacent compartments through transparent separating structures;
2. The openness of the compartment of origin; if a fire breaks out in a compartment where people are working in separate rooms with closed doors, it is unlikely that the occupants will start to evacuate at the same time as they will become aware of the fire at different times. An automatic fire alarm system can compensate for this. In an open-plan office, an automatic fire alarm is not needed to make all occupants aware of the emergency at about the same time.
3. The use of the building should favour phased evacuation. A continuous and intensive circulation between the compartments makes a successful phased evacuation less likely;

dwellings and other occupancies where people may be asleep or otherwise unable to respond quickly to an alarm condition should never be designed for simultaneous evacuation since it is highly unlikely that all occupants need the same evacuation space at exactly the same time.

Phased evacuation can take different forms. Examples are:

1. Phasing between compartments on the same storey, where a building has multiple smoke compartments on a storey. The main evacuation route from all smoke compartments passes through a common circulation zone where the escape staircases are located. A special form of this type is where the compartment of origin and the compartments directly adjacent to it are evacuated, while the rest is evacuated later;
2. Phasing between storeys. This is the simplest and least controversial form of phasing. The whole fire storey empties into the staircases before the non-fire storeys are alarmed. With fire resistant staircases and floors, both on the aspect of the threat to the non-fire compartments and of the risk of simultaneous evacuation taking place after all, this option scores high.

Dutch regulations allow phased evacuation as a basis for design in a general statement only; concrete requirements and “determination methods” are based on simultaneous evacuation. The above section provides arguments that may be used to defend a building permit request based on phased evacuation. An example of the effect of phased evacuation is shown in fig. 3 (page 244).

2.4 ***Waiting time***

A hot topic in evacuation time calculation is the question whether a design may be such that people are forced to wait, e.g. in front of an escape staircase, for a prolonged period of time before they can enter the staircase and continue their evacuation.

The official Dutch building regulations do not forbid such a situation to occur, as long as the occupants can leave the building within the required 15 minutes.

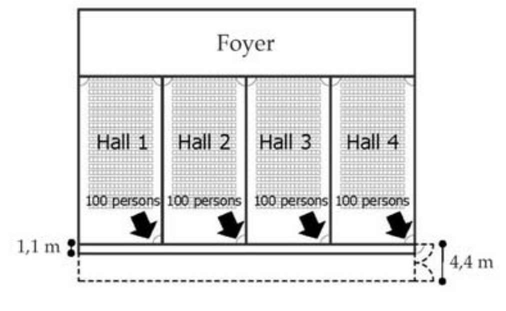

Figure 3. Example: a cinema with four halls of 10 x 20 m, 300 seats each, accessed through a central lobby. 100 persons in each hall allocated to an emergency exit giving access to a common passage with a single exit. A design was approved where the passage area and exit door width were sized for 100 persons (25 m2/1.1 m, phased evacuation). If simultaneous evacuation would have been obligatory, the passage would have to be sized for 400 persons (100 m²/4.4 m).

An informal design guide from the Dutch Ministry of the Interior states that "a group of people in motion shall not be slowed down extremely". This is mostly interpreted as saying that people should always feel that they are moving if they are to avoid panic reactions. In this view, forcing people to wait for more than half a minute before they can enter a staircase is not acceptable. The background of these concerns appears to be the incidents in mass gatherings where large numbers of people have been hurt or killed (Hillsborough football stadium, the yearly Hadj gatherings in Mecca). Obeying this rule leads to escape routes, including staircases, that have a more or less equal flow capacity over their total length. Whereas that may be in fact quite desirable from a safety point of view, it is at odds with many traditional designs for high occupancy buildings such as schools.

While the concerns raised must be considered real enough in the extreme occupancies mentioned as examples, they seem rather exaggerated in buildings with much smaller occupancy numbers. Factors that should be taken into account when deciding whether people can be forced to wait on their escape route are:

1. The number of people that need to make use of the route in question;
2. The level of threat that the waiting people perceive from the incident. If they see flames approaching, or if they are engulfed by hot smoke, or even if they have a hot smoke layer above them, they may feel directly threatened; clearly, a physical smoke-resistant or fire resistant barrier between the fire and the waiting area can be extremely effective in reducing the perceived level of threat. To what extent a heat and smoke venting system does a similar job when it maintains a smoke layer above the waiting area is doubtful. The height of the interface and the smoke temperature will certainly be of influence;

3. The waiting time; the acceptable waiting time depends on the level of threat. This could be expressed in terms of the dose of radiative or convective heat, or toxic gases, that may be accumulated;
4. The freedom they have or perceive in taking alternative routes; if people can move, and feel that they can possibly reach another route, even under the same level of threat they will be less given to panic than if they have no options other than wait in line;
5. Visual contact with the place of safety. If people know that the place of safety is close by, they may accept the direct threat more easily than if they have no idea how far beyond their view they have to move before they are out of reach of the threat.

2.5 ***Scenario-dependent or scenario-independent treatment***

The requirements in table 1 are – implicitly – scenario independent. This means that no assumption is made as to the location of a fire or as to its development in time. Since the requirements are in terms of the total free door width, it is assumed that all escape routes are available.

These assumptions are consistent with a scenario where the occupants of a smoke compartment of origin become aware of a fire sufficiently fast to allow them to leave the compartment before the path to the closest compartment exit becomes untenable.

In more detailed approaches, specific scenarios are analysed in which the fire is assumed to block escape routes, forcing occupants to choose a different route. By analysing all relevant positions and developments, it is possible to check the design for weaknesses causing excessive evacuation times.

It is important to note that when dealing with specific scenarios, the standard scenario-independent acceptance criteria (the 1/15 minutes, ref. to table 1) should not be applied. The scenario-independent evacuation time is the shortest possible one, all actual scenarios represent less optimistic situations. In a design where the scenario independent building evacuation time just remains below 15 minutes, it should be accepted that actual scenarios lead to evacuation times above 15 minutes.

A good design from the perspective of evacuation will not show excessive evacuation times for any realistic fire scenario. While the regulatory requirements allow quite bad designs in this respect, the designer should try to avoid these.

3 Recommendations

The present paper aims at promoting a more advanced, and less regulations-limited view of the evacuation process when designing buildings for safe egress. It identifies and discusses a number of factors which are in themselves well known, but which are virtually always ignored in building design in favour of the traditional model calculations dictated by the Dutch building regulations. Taking into account these factors enables much better designs, both from the point of view of safety and of economics. It also addresses main advantages and drawbacks of advanced models and implicitly provides areas for further discussion and research. Examples are the improvement of the predictive capabilities evacuation models by including psychological elements such as way finding, familiarity with the building and adaptive routing.

References

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