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EMERGENCY EVACUATION AND SAFETY IN COMPLEX ENVIRONMENTS

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Thinking is more interesting than knowing, but less interesting then looking
Johann Wolfang von Goethe (1749-1832)

Abstract

Effective egress system design and management are both fundamental in order to guarantee people's safety in case of compartment fires. In this thesis PASS (Preliminary Assessment of the egress System Safety), a method that allows a rapid screening of the egress system vulnerability, is proposed as a complementary tool to traditional safety assessment methods.

PASS is a set of simple analytical equations that allows assessing at different levels of analysis the egress system performance without simulating the evacuation process. Its equations incorporate factors for including in the analysis the main interrelationships between people-egress system-environment, and for linking the two main concepts of fire sciences: *ASET* and *RSET*. In PASS, *ASET* is estimated through the use of standard times, and simple tools were developed in order to allow their rapid calculation. The results obtained with these tools were compared with results from the computational fluid dynamics model FDS, and a good agreement was found for a set of reference scenarios.

Some factors adopted in PASS to consider people-egress system interrelationships were quantified through experiments carried out in the novel laboratory $\text{LabCUBE}_{\text{egress}}$. $\text{LabCUBE}_{\text{egress}}$ is a movable laboratory with a flexible configuration which can be customised to create several layouts and to reproduce different parts of an egress system. It was conceived and designed in order to quantify human behavioural factors. A set of experiments involving a wide cross-section of population were performed and the effects of exit signs on people's choice at a T-intersection were investigated. The results revealed that with a left exit sign only 70% of individuals choose the shown direction and this value drops to 60% for groups. These results were used to calibrate a PASS factor and were eventually integrated into the method.

Finally, PASS was applied to a case study. Its results were compared with two evacuation models (STEPS and FDS+Evac) and data collected from an announced evacuation drill. A good agreement between PASS analysis, experimental and numerical data was obtained for the scenario studied (a secondary school).

Thanks to the results achieved, PASS can be proposed as a simple and rapid standalone tool for the pre-design and management of the egress system safety. For extending the range of validity of PASS, in future works the method may be tested in different scenarios.

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In the mountains my mind could breathe and search for new ideas and inspiration. Thanks to the trusted belayers, besides friends, that shared with me those places and those times.

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Introduction

Nowadays growing attention is paid to people's evacuation in emergency. Fires, crowd gatherings, terrorist attacks are some examples of events which can generate hazards and threaten people's safety. In these cases, a measure that people can take for preserving their safety is evacuation, a process which requires people to move away from hazards and to reach a place where safety conditions are guaranteed (place of safety). This can be fulfilled by travelling a set of protected routes provided to connect any point within the area in which people are present with the place of safety. This set of routes is generally referred to as egress system.

Although evacuation may be required in different emergency scenarios, people's evacuation in fire is increasingly claiming the attention of both public opinion and researchers. Incidents such as the Gothenburg discotheque fire, where 63 teenagers perished during a party (Sweden, October 1998) (Cassuto and Tarnow, 2003); the Station Nightclub fire, where during a concert one hundred people died in a fire started by pyrotechnics that ignited polyurethane foam (Rhode Island, February 2003) (Grosshandler et al., 2005); or the recent Titisee-Neustadt fire, during which 14 people lost their lives (Germany, November 2012) (BCC, 2012), have enhanced the awareness of the importance of an egress system correctly designed and, most of all, managed. In fact, even the best designed safety solution does not ensure people's safety if an egress system, or a building, is poorly managed.

In the Gothenburg fire, for example, the fire started (probably by arson) in a corridor leading to the emergency exit staircase. The population inside the discotheque was three times than the designed population, and this caused people crowding at the main entrance door, which was partially obstructed by a table used to collect entrance tickets during the party. The Titisee-Neustadt fire was started by a gas leakage from a portable heater in a new building complying with regulations. In this case, an additional source of hazards was present inside the building, and generated a fire that claimed the lives of 14 people.

As emerges from these and many other fire incidents, people's evacuation has dual aspects, and both have to be addressed in order to guarantee the optimal performance of the egress system. The first is related to the correct design of an egress system. The second is the importance of its effective management. However, the latter is frequently overlooked and delegated to building managers, who have to guarantee people's safety during the lifetime of the building by using the available assessment tools.

Among the current tools available to design and assess the egress system safety, two main approaches can be used. Prescriptive codes are the simplest and more direct approach usable to tackle egress system safety issues. Despite their simple and rapid use, they do not allow the complete understanding of the evacuation process, do not explain the methodology to achieve safety, and are restrictive and inflexible when used for designing fire safety in no-standard buildings (heritage buildings or new complex architectures, for example).

These limitations are overcome by the performance-based approach that underlies the Fire Safety Engineering (ISO 13387-1, 1999). With this approach, the study of egress system performance is carried out in a flexible way and considering the characteristic of the egress system, the building occupants, the fire induced environment. In the performance approach the egress system safety is assessed by calculating the time necessary to achieve the untenable conditions inside a building ($ASET$) and the time that people take to reach a place of safety ($RSET$). An egress system is designed correctly if people can escape before they are threatened by the fire effects.

Fire Safety Engineering provides different methodologies for designing egress system safety, from hand-calculation tools to the most sophisticated fire and evacuation numerical models. However, these methodologies can be complex to understand, to use and, referring to the most sophisticated tools, they are time requiring. Therefore, although their flexibility and effectiveness, these tools can be difficult to apply when the context is dynamic, few input data are available, and assessment results have to be achieved rapidly (as for example during pre-design and management phases, or to support decision making in emergency). Different methodologies have then been introduced within the performance-based approach to fill this gap. Among these methodologies, no tools for assessing egress system safety through the vulnerability analysis approach have been proposed, despite this concept is also adopted in the Fire Safety Engineering (Barry, 2002).

The vulnerability of a system is related to its response capabilities against an impacting action. The degree of the system response depends on its strengths and weaknesses, and the identification of system critical points (weaknesses) allows evaluating its performance level for a given scenario. Hence, vulnerability analysis allows identifying the factors that improve (or reduce) the system response, and to determine the presence of critical points without simulating the evacuation process. Besides providing time savings, the identification of critical points in the egress system could be helpful in both the design and the management of the egress system safety. Indeed, once the critical points are identified, the egress system design and the correction measures can be rapidly defined.

According to this approach, in this thesis the method PASS (Preliminary Assessment of the egress System Safety) is proposed as a method complementary to evacuation models for handling egress system safety during both pre-design and management phases.

PASS approach to the egress system safety assessment is through checks. Checks are performed in order to evaluate the level of three performance indicators by using a set of simple tools (in the form of analytical equations). These tools can be used rapidly and allow identifying system weaknesses without simulating the evacuation. PASS intended use is for rapid analyses with few input data, as safety screenings during the pre-design phase or management of an egress system.

PASS evaluates the egress system vulnerability by comparing its actual performance with a standard performance required to guarantee people's safety. The egress system actual performance is assessed by including in the analysis factors that take into account the egress system geometrical features, the interactions between people and egress system, and the main aspects of human behaviour that affect the evacuation process. The use of factors (summarised in a tabular form) allows tailoring the tools to several scenarios. The standard performance is established by setting standard times which indirectly take into account the time for achieving untenable conditions in the different parts of the building.

PASS was initially developed and included in Gri.S.U. (Grimaz and Pini, 1999), a methodology for the assessment of fire risk and equivalent safety in no-conventional buildings (in particular heritage buildings) through the vulnerability analysis. In Tosolini (2008), PASS was extracted from its original context, partially calibrated and preliminary tested in a case study in order to explore its capabilities. The results showed that PASS allows obtaining rapidly results which are comparable with evacuation models and data collected during an evacuation drill. However, two issues that emerged from this preliminary application had to be addressed in order to present PASS as a stand-alone tool.

Firstly, in its first version (Grimaz and Pini, 1999), PASS adopted four fixed standard times to establish the required egress system performance level. Although these times were modified by considering the presence of hazardous contents, their values were not scenario dependent (in terms of the geometrical features of the egress system and characteristics of combustible materials).

Secondly, those factors related to the behavioural aspects were not entirely calibrated due to limitations of the current available tools in simulating some aspects of human behaviour, and to the lack of suitable experimental data.

In this work these two issues are addressed, and eventually PASS is proposed as a stand-alone tool for assessing with a multilevel analysis approach the egress system vulnerability.

Structure of the thesis

This thesis is organised in three main parts. In the first part the main concepts that underlie the egress system safety analysis are presented (Chapter 1). A global description of PASS along with its underlying principles is given in Chapter 2. These two chapters outline the basis of this thesis, which objectives and a general introduction on the methodologies used are presented in Chapter 3.

Part II is dedicated to the first objective. A methodology for estimating the standard times used in PASS in a scenario-dependent way and coherently with the approach of PASS analysis is developed. Chapter 4 presents a complete overview on the concept of *Available Safe Egress Time* (*ASET*), usable for defining a standard performance level for an egress system. The aspects outlined are then deepened in Chapter 5, where an analysis of the tenability criteria and input data for the *ASET* estimation is carried out. The results of this Chapter are the basis for developing two conceptual models used in order to estimate PASS standard times (Chapter 6). These two conceptual models are represented in engineering terms and their validity is analysed in Chapter 7. Eventually, the conceptual models are transformed into operative tools for estimating PASS standard times and compared with numerical results (Chapter 8).

In Part III a novel laboratory conceived during this research activity for studying human movement and behaviour in egress situations is presented. A background on the methodologies usable to study and collect data on human behaviour is given in Chapter 9. The characteristics of LabCUBE$_{egress}$, the laboratory conceived to collect data for calibrating PASS factors, are presented in Chapter 10. This Chapter presents also the results obtained from a set of experiments aimed at studying the effects of emergency signs on people's choice and at quantifying a PASS factor. Finally, PASS method is applied to a case study as a stand-alone tool for checking the egress system vulnerability, and the obtained results are compared with numerical and experimental data (Chapter 11).

The complete method is reported in Appendix.

I

Egress system performance assessment with PASS

1

The egress system performance

The increasing presence of highly populated buildings and the complexity of the layout that can be achieved in new constructions enhance the issue of people's safety in case of fire.

People's safety in a built environment is a challenge for the stakeholders involved in the design and management of the fire safety in new and heritage buildings, or in generic infrastructures aimed at accommodating people. When fires occur in confined spaces, especially when a high number of occupants are present, the complexity of the evacuation process emerges.

People's evacuation, in fact, depends on three main elements: the occupants, the built environment in which they move, and the fire. While escaping from a hazard, occupants influence each other and are influenced by both the built environment and fire hazards. Therefore, in addition to these main elements, numerous hidden factors influence the evacuation process, and these factors are related to the interrelationships between occupants, built environment and fire (Sime, 2001). Because of evacuation is determined by both main elements and interrelationships, it can be seen as a complex system, and can be studied with a holistic approach (Nilsson and Uhr, 2009).

This interpretation is fundamental in order to understand why design and assessment of people's evacuation is shifting from prescriptive codes to a performance-based approach, and eventually to put in context the work that is presented in this thesis.

Prescriptive codes are the traditional and more direct approach for handling the design and assessment of an egress system. They provide rigid rules, such as maximum length of travel paths, minimum door width, minimum number of emergency exits, which have to be observed in order to achieve fire safety goals.

Performance-based approach promoted by the Fire Safety Engineering (FSE) (ISO 13387-1, 1999), on the contrary, looks at the evacuation process with a holistic perspective and studies it as a complex system which is constituted by a set of interacting subsystems (initiation of fire, fire effluent movement, building structural response, detection-activation and suppression, people's evacuation). The analysis is focused on each subsystem and on their interactions.

Both prescriptive and performance-based approaches can be used for designing and managing fire safety, and provide different tools for its assessment. However, whichever tool is used and fire safety objective is fulfilled, all the analysis process can be summarised as an assessment of the occupant-built environment-fire system, and it aims at designing suitable safety solutions.

Therefore, a focus on what these approaches actually assess is needed, and for this aim the concept of complex system will be useful. This will also allow presenting PASS, a method proposed in this thesis as a novel approach for the egress system safety assessment (Chapter 2).

1.1 The concept of performance

Every approach and tool used for assessing the egress system safety aims at evaluating, directly or indirectly, its performance. Because of performance is the core of the assessment process, its meaning needs to be explored.

Several definitions of performance can be found. Oxford Dictionary (Oxf, 2011) defines performance as "how well or badly something works", and Merriam Webster Dictionary (Mer, 2008) as "the manner in which a mechanism carries out an action or pattern of behaviour". Although slightly different, both definitions refer to a system (something, a mechanism), to an action (to work, to carry out), and to how the system makes the action (well, badly, the manner). Therefore, performance is defined referring to a **system** which has one or more **tasks** to fulfil (the action). **Acceptance indicators** (well, badly) are used to measure how, or whether, each task is fulfilled.

Every system is designed to accomplish at least one task. Acceptance (or performance) indicators are defined by stakeholders who take part in the analysis process. The assessment process aims at quantifying, through these indicators, *how* a specific task is carried out.

Egress system, for example, is designed in order to allow people to *move away safely* from hazards to a place of safety. In this case, *move away* (or evacuate, escape) is the task, *safely* is how this task has to be fulfilled.

This interpretation of performance agrees with the definition adopted in different works in the fire safety field. In ISO 13943 (2008) the performance-based design is defined as "a design that is engineered *to achieve specified objectives and acceptance criteria*" and "acceptance criteria are criteria that form the basis for assessing the acceptability of the safety of a design of a built environment". Løvås (1995) defines the egress system performance as "how the egress system is *able to function, relative to its goal to safe evacuation*". Siddiqui and Gwynne (2012) define pedestrian performance as "whether agents perform the expected actions and take the expected amount of time to complete them". In this latter example, the objectives are the expected actions while the time taken to complete them is used as performance indicator.

For assessing how the system fulfils the required objectives, indicators have to be defined and qualitatively or quantitatively measured. Namely, a performance level and indicators for measuring it have to be established. An important goal is to define the key indicators that allow assessing correctly the system performance. Consider a system S, represented conceptually by a set of elements E which interact each other (Figure 1.1). More complex the system is, more elements E and interrelationships i are present.

The system S is a representation of the reality, a **conceptual model**. It is conceived

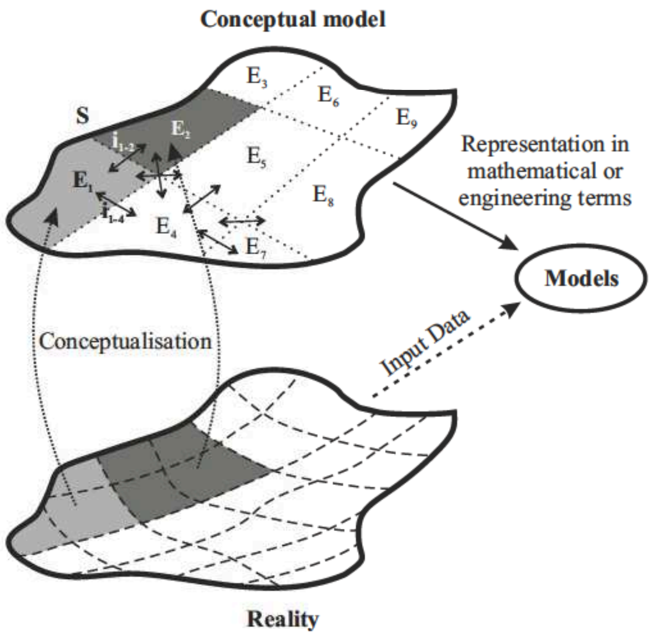


Figure 1.1. System S is a conceptual model of reality. It is composed of elements E and interrelationships i.

by the analyst or model developer, who extracts and focuses on certain parts (elements E) of reality and on their interrelationships i. The number of elements E extracted depends on the level of detail used to represent reality and on the analysis objectives (Nilsson and Uhr, 2009). Performance indicators are developed to measure how the system S fulfils its objectives. They can be defined for quantifying the level of performance of single elements, or that of elements and interrelationships. Referring again to the egress system example, prescriptive codes assess the egress system performance by checking the functionality of single elements. Performance-based approach aims at analysing the system elements E and interrelationships i.

The conceptualisation process is carried out also to develop analytical or numerical models. Models, also evacuation models, are a representation of the reality and rely on theoretical and numerical assumptions (Tavares, 2009b). Models reduce the complexity of the real problem to a dimension that can be managed, and are constituted by the main elements that govern a certain process and by the interrelationships among these elements. Elements and interrelationships are then represented in mathematical or engineering terms in order to allow the problem to be studied.

Objectives and performance indicators are used for assessing the performance level of a system. The analysis is carried out referring to the conceptual model and, in particular, is performed on a specific configuration of elements and interrelationships of the system. This configuration is a **scenario**. Since the system can have many, or infinite, configurations, usually the analysis is repeated for a set of conventional scenarios, which can include the most representative and the worst scenarios. Referring to the egress system, a scenario is constituted by a specific building-occupant-fire source configuration.

Mowrer (2003), for example, refers to a fire scenario as to a set of conditions that defines the development of a fire and spread of combustion products through a building. Therefore a fire scenario is constituted by a particular configuration of the elements of the system building plus combustible materials. Peacock et al. (2004) define the fire scenario as a "detailed description of the facility in which the fire occurs, the combustible products potentially involved in the fire, a specific fire incident, and the people occupying the facility". ISO 13943 (2008) as a "qualitative description of the course of a fire with respect to time, identifying key events that characterise the studied fire and differentiate it from other possible fires". Gwynne et al. (2012) define the occupant scenario as the set of key elements (in terms of geometrical, environmental, procedural and behavioural factors) of the occupants' response to the fire and the initial conditions that determine this response. In all this definitions, as it can be noticed, scenarios can be represented in terms of a specific configuration of elements and interrelationships of the system.

Given this, it seems reasonable to represent the performance assessment as an assessment of how a system, constituted by a set of interacting elements, works. The assessment is carried out once performance indicators (criteria) have been established, and for different scenarios. The level of detail achieved with the analysis depends on the number and characteristics of elements E and interrelationships i incorporated in the indicators adopted (Figure 1.2). Global, or macroscopic analysis, can be carried out by focusing on the main elements which affect system behaviour. As more specific elements and interrelationships are introduced, the analysis level is deepened and focuses on local characteristics of the system. While the analysis becomes more specific, also the data required for measuring the performance indicators and the time to dedicate to the analysis could increase. Therefore, a multilevel analysis approach can be achieved by adopting different indicators that allow analysing the system from a global to a local perspective, and each indicator can be quantified by using specific tools.

In pre-screening analysis, for example, usually general indicators are adopted. If the pre-screening analysis detects anomalous behaviours in the system, then the use of more specific performance indicators is needed. Consider, for example, the blood tests used for checking the global functionality of human body. They are usually used for checking at a global level whether an individual is healthy. They adopt general indicators (concentration of white blood cells, bilirubin, creatinine), and are performed quickly. If the indicators related to specific body functionalities (e.g. liver functions) lay beyond the range of normality, usually more specific tests are required. These tests adopt more specific indicators and allow a detailed screening of liver functionality, for example.

The main goal of the performance assessment is then to check whether the system acts as expected. The use of performance indicators allows monitoring the system behaviour with different levels of detail. If the system does not work correctly, namely the established levels for indicators are not reached, system **weaknesses** emerge. The analysis, therefore, identifies the presence of critical elements, interrelationships, or latent failures which affect system behaviour and hinder it from performing as designed. Hence, through the use of performance indicators, nature and severity of system weaknesses can

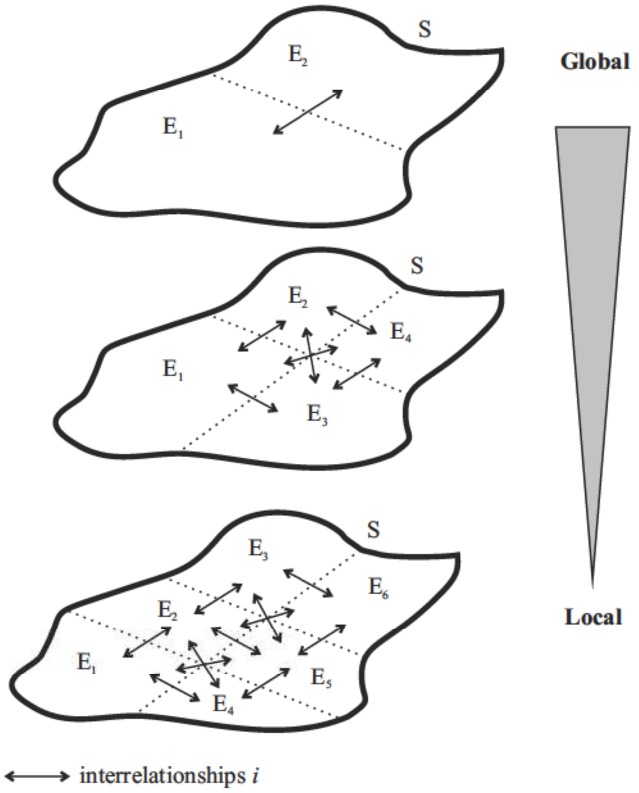


Figure 1.2. Multilevel analysis of system S. The number of elements E and interrelationships i considered by performance indicators increases from global to local analysis.

be identified. This allows designing tailored mitigation measures in order to restore the whole system functionality.

As anticipated through simple examples, the concepts introduced can be used to interpret the process of the egress system performance assessment.

1.2 The egress system performance assessment

If addressing the egress system safety assessment with a systemic approach, it is possible to put in context the tools currently used for evaluating the egress system performance.

The egress system can be seen as a complex system. Its main elements are the occupants, the built environment and a source of hazards (a fire). A comprehensive assessment of egress system safety has then to consider both elements and their interrelationships. As outlined before, an egress system can be currently designed and assessed with prescriptive codes or performance-based approach.

Prescriptive codes adopt as performance indicators the characteristics of single elements of the egress system (door number and width, stairs number, corridors length, presence of emergency signs, number of occupants) and establish threshold limits for each element. Although implicitly some kind of interactions between the elements are considered (for example the egress capacity for doors), no explicit reference to interrelationships is made. Furthermore, the assessment is carried out referring to conventional, or nominal, scenarios established by the regulator. This implies that prescriptive codes are inapplicable to complex or no-conventional scenarios, like heritage buildings or new architectures (Frantzich, 1998; Chu et al., 2007; Tavares, 2009a). However, prescriptive codes are easy and relatively fast to use.

On the other hand, the performance-based approach assesses both egress system elements and their interrelationships. It adopts time-based performance indicators such as the total evacuation time, or the flow time at specific points of the system. The threshold levels of performance indicators are not fixed, but scenario dependent. Performance-based approach allows calculating the time taken by occupants to be overcome by the effects of fire hazards ($ASET$, Available Safe Egress Time) along with the time taken by occupants to manage evacuation ($RSET$, Required Safe Egress Time), as reported in Figure 1.3. This is made considering the characteristics of occupants, building and fire dynamics. An egress system is considered to be safe if $RSET$ is less than $ASET$. When comparative assessment among different egress system configurations is carried out, the difference between $ASET$ and $RSET$ defines the margin of safety provided by each configuration (Babrauskas et al., 2010). Greater the margin of safety is, better the egress systems configuration performs.

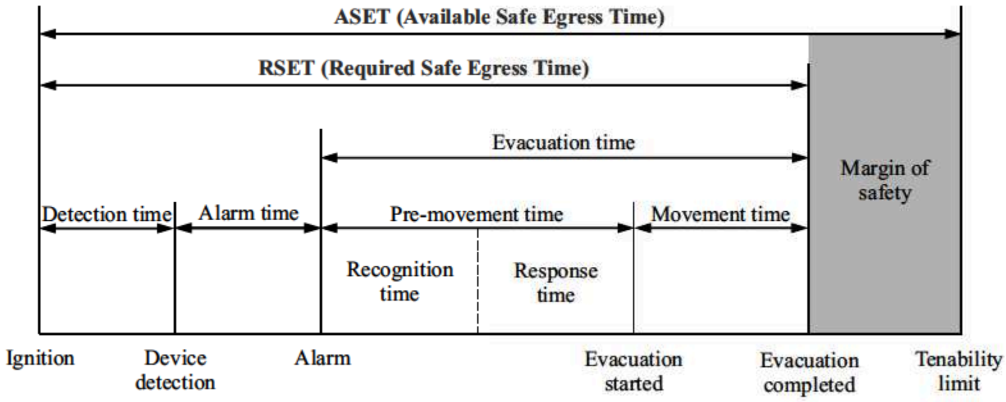


Figure 1.3. Evacuation timeline: Available Safe Egress Time ($ASET$) and Required Safe Egress Time ($RSET$). [Adapted from Proulx (2002).]

The design and assessment of the egress system safety with the performance-based approach is more complex than prescriptive codes, and requires numerical and temporal resources. However, this approach is flexible and suitable to study complex scenarios. Performance-based approach provides several tools to quantify the performance indicators, from the simpler hand-calculation tools (like empirical and analytical equations) to the more complex numerical models (evacuation models, two-zone fire models, Computational Fluid Dynamics models). Because of performance-based approach aims at studying the real system with a greater level of detail than prescriptive codes, it extracts from reality a higher number of elements and interrelationships. Therefore, the complexity of the models, the number of their input data and resources to manage them increases accordingly.

Each approach, prescriptive or performance-based, has pros and cons and the choice of one approach, or tool, depends on the aims of the analysis, on the availability of input data, and on the computational and temporal resources (Tavares, 2009a). For designing an egress system it is possible to use evacuation models. Currently more than 40 evacuation models which adopt different modelling approaches are available (Gwynne et al., 1999; Olenick and Carpenter, 2003; Castle, 2007; Zheng et al., 2009; Kuligowski et al., 2010). When using evacuation models input data are specified by the designer, who can also tailor the egress system design. Evacuation models, however, can be time consuming, especially when coupled with fire dynamics models or when several scenarios have to be considered. Hence, the use of fast tools for a pre-design analysis can be useful in identifying the critical scenarios to model, the weaknesses of the system, or to provide a validation check on computer simulations (Purser, 2010). Models can then be used in more finalised way, focusing the analysis on system weaknesses and critical scenarios, and design times can then be reduced.

However, once an egress system has been designed and built, it is fundamental to check whether the designed performance is maintained during its lifetime. Buildings and their contents, in fact, change. Temporary renovations can affect parts of the building, change its internal layout and introduce further sources of hazards.

The actual safety level could then be different from that of design, also referring to the worst case scenario considered during the design phase. In these cases, the egress system safety assessment has to be carried out again, in order to identify the presence of weaknesses and plan the intervention measures. But with different input data, less temporal resources and in a dynamic context. A fast screening, therefore, can be conducted in order to identify the critical elements that worsen the safety level and the suitable mitigation solutions. Once the safety performance level is restored, it can be assessed by using detailed analysis. Therefore, in order to manage correctly the egress system safety, simple and fast tools (like prescriptive codes), but effective and flexible (like performance-based approach) can be extremely useful.

Approaches and tools different from the traditional evacuation simulation models, but developed within the performance-based discipline, have been proposed to assess and study the egress system performance. Shen (2006) presented a method based on the network approach to identify the critical spaces in the egress system, and thus to simplify its performance evaluation. In order to save computational times and resources, Yuan et al. (2009) integrated a fine grid network for the occupants in a fire zone and a coarse grid network outside the fire zone in an integrated network approach for the simulation of occupant evacuation. Tavares and Galea (2009) combined the evacuation modelling with the operational research analysis in order to improve the enclosure design reducing the number of potential scenarios to model during the design process. Lin et al. (2008) proposed a model to optimise evacuation routes and schedule based on a time-varying dynamic network. Kraus et al. (2011) proposed a decision support system aimed at determining the ideal distribution of evacuees and the shorter evacuation path in large infrastructures using an optimisation algorithm, and considering evacuation path length, number of evacuees and safety devices. Capote et al. (2013) developed a real-time stochastic model integrated into a Decision Support System for managing in real-time the emergency evacuation in road tunnels. Chu et al. (2007) presented a probabilistic risk assessment method for evaluating risk for people in building fires that incorporates deterministic and stochastic characteristics of fire and evacuation process. Guanquan et al. (2012) presented a time-dependent approach for evaluating fire risk for occupants in buildings by including stochastic analysis, event tree analysis and coupling fire models and Monte Carlo method.

All these approaches intend to analyse the egress system safety in real-time or to reduce computational time and resources. However, another approach can be adopted, as proposed in this work.

As outlined before, the main objective of a safety assessment is the identification of egress system weaknesses. These can be identified also by checking the *health* of the system. If performance indicators are identified, then **checks** can be performed in order to evaluate if the indicators related to the examined system comply with established threshold levels. These levels express the performance required. By using suitable tools, checks can be performed easily and fast, since they do not necessarily rely on evacuation simulations. Checks, although simple, can be appropriate for both a macroscopic and local analysis of the egress system, depending on the characteristics of the performance indicators adopted, and can be a complementary approach to evacuation models.

PASS (Preliminary Assessment of egress System Safety) is a method presented in this thesis as a set of tools for checking the egress system vulnerability. Vulnerability analysis allows identifying the system weaknesses and, indirectly, to assess its performance. In the following section the vulnerability concept, and how it is related to the system performance, is illustrated. PASS tools, which allow evaluating key performance indicators and identifying egress system weaknesses in a simple, flexible and fast way, are introduced in Chapter 2 and reported in Appendix.

1.3 The egress system vulnerability

Vulnerability is a concept well established in the field of natural hazards and disasters management, although it has not been univocally defined. According to Hufschmidt (2011), vulnerability is defined, interpreted and applied in different ways, depending on the discipline (from social to environmental context) and more than 18 different definitions of vulnerability can be identified (Cutter, 1996; Weichselgartner, 2001). Because of an exact definition of vulnerability is not present, in this work that proposed by Fournier d'Albe (1979), and adopted by UNESCO, is used. Referring to earthquakes, Fournier d'Albe defines vulnerability as "a measure of the proportion of the value which may be expected to be lost as a result of a given earthquake". He also indicates that vulnerability "can be calculated in a deterministic manner for individual buildings and structures if their dynamic response to various ground motions is known".

This definition can be interpreted and translated to the fire safety field by adopting the scheme reported in Figure 1.4, where the framework of the process that leads to the generation of a damage starting from a source of hazards is sketched. Consider a system where both hazards source and targets are present. Hazards originate if the source is prone and then triggered to generate an adverse event. Hazards can than impact on targets, at which a value to preserve is assigned (health, capital value, integrity). The severity at which hazards impact on targets is related to the presence and characteristics of mitigation barriers. Depending on the characteristics of the system, hazards source and adverse event can generate inside (a building fire) or outside (an earthquake) the system.

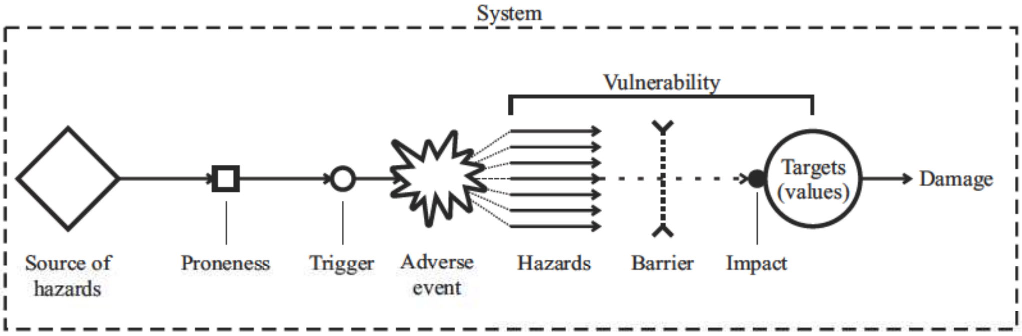


Figure 1.4. Generation of a damage from a source of hazards. [Adapted from Grimaz and Pini (1999).]

Consider, for example, the system composed of building, combustible contents and occupants. A fire (adverse event), can spread if combustible materials (hazards source) are in contact with air (proneness) and ignite (trigger). Smoke spreading (hazards) can be mitigated by the presence of heat and smoke evacuation systems, or fire doors (barriers). Alternatively, people (targets) can move away through the egress system from smoke before they are threatened (the impact is then avoided). It can be noticed that the part of the scheme that starts from the adverse event is a representation of the source-target concept proposed by Barry (2002) in the Handbook of Fire Protection Engineering.

The vulnerability definition proposed by Fournier d'Albe can be contextualised within this framework. He defines vulnerability starting from three concepts: a given earthquake, values, the expected proportion of loss. The first is the adverse event, the second are the targets and the third expresses the severity of hazards impact on target. Fournier d'Albe assumes that the adverse event is present, and no considerations on its probability of occurrence are made. He focuses the analysis on how the system responds to the hazards (ground motions) originated by the adverse event (earthquake) and referring to a value to be preserved. Vulnerability is then measured by the quality of the response capabilities of the system to hazards. The response capabilities aim at preserving the value of the targets, and depend on the intrinsic characteristics of the system, namely on its elements E and interrelationships i (see Section 1.1). Similar to performance, also vulnerability is measured referring to indicators. Vulnerability allows then analysing the coping capacity of the system and to identify its weaknesses. In fact, more weaknesses a system has, greater its vulnerability is. But, more weaknesses the system has, less its performance is. The performance of the system can then be assessed through vulnerability analysis. This interpretation agree with the definition of vulnerability proposed by Einarsson and Rausand for complex industrial systems, who define vulnerability as "the properties of an industrial system that may weaken its ability to survive and perform its mission in presence of threats" (Einarsson and Rausand, 1998).

Consider now people evacuation in case of a building fire. The system is constituted by the egress system, the occupants and the fire. All these elements are contained in the building. The given adverse event is the fire, the hazards are the fire hazards, and the targets are the occupants, which aim at preserving their integrity. Thanks to the presence of the egress system, occupants can move away from hazards and reduce their impact. Evacuation is then a possible response of the system and vulnerability, through indicators, is a measure of the quality of this response. As evacuation depends on the characteristics of the egress system, occupants, and fire, also the system response depends on these elements. The response of the system is worse if weaknesses are present (the system is more vulnerable). In other terms, its performance decreases.

The concepts introduced are used in Chapter 2 for describing PASS (Preliminary Assessment of egress System Safety), a method that allows a rapid analysis of the egress system vulnerability. PASS is proposed in this thesis as a tool usable for a screening of the egress system, for both design and management aims, and can be used complementary to evacuation simulation models. The method constitutes the framework of this research.

2
PASS

PASS (Preliminary Assessment of the egress System Safety) is a method that allows a rapid analysis of the egress system vulnerability. It comprises seven different tools that are used to check vulnerability at three different level of analysis. PASS adopts a check concept: it aims at identifying system weaknesses without resourcing to evacuation simulation, but checking three performance indicators for different standard scenarios. Its intended use is when rapid analyses with few input data are required, like safety screening during pre-designs or management of an egress system.

PASS was initially developed and included in Gri.S.U. (Grimaz and Pini, 1999), a methodology for the assessment of fire risk and equivalent safety in no-conventional buildings (in particular heritage buildings) through the vulnerability analysis. In Tosolini (2008) PASS was extracted from its original context, partially calibrated with an evacuation simulation model (STEPS, Mott MacDonald Simulation Group), and preliminary tested in a case study in order to explore its capabilities. A comparison between PASS analysis, numerical and experimental results was made. As results showed, although in a preliminary application, PASS allowed obtaining rapidly results comparable with evacuation models and data collected during an evacuation drill. The method was then proposed as a stand-alone tool in (Grimaz et al., 2010) and (Grimaz and Tosolini, 2011), where PASS was additionally compared with the evacuation simulation model Evac (Korhonen and Hostikka, 2010). The results, as it is shown in Chapter 11, confirmed the validity of method. However, during these studies two issues emerged, which constitute the objectives of this work.

Before presenting these objectives, a description of PASS is needed to put in context this work. The entire method is reported in Appendix[1].

2.1 The concepts

PASS (Preliminary Assessment of egress System Safety) is based on the *exodus-borders* conceptual model (Figure 2.1), conceived in order to represent the evacuation process with key elements that constitute the basis for PASS analysis. Table 2.1 reports the

[1] Appendix reports the method integrated with the results of this work. The original method can be found in Grimaz and Pini (1999) or Grimaz and Tosolini (2011).

elements adopted along with their definition. In the *exodus-borders* conceptual model the evacuation from a generic system (building, places of assembly, stadia) is conceived as the movement of people from a zone where hazards are generated, the hot zone, to a safe of place (safe or refuge zone). To reach a safe or refuge zone people have to escape from the hot zone, then may leave the system either by reaching directly a safe/refuge zone, or by passing firstly through warm and temporary-cold zones. These zones are characterised by different hazardous levels and separated by barriers with different protection ratings against hazards.

People pass to adjacent zones by using openings in the barriers (gaps). Each gap is connected by paths of travels (paths) that allow the movement within a zone and from gap to gap. For a safe evacuation, people have to leave each zone before they are threatened by untenable conditions (see Figure 1.3). This time is quantified in PASS by setting four standard times. Although these times are modified by coefficients that include the potential hazard levels in each zone, they are not scenario dependent (in terms of characteristics of combustible materials and geometrical characteristics of the zone). One objective of this work is to develop a methodology for a simple, flexible and scenario-dependent estimation of these standard times, as illustrated in Chapter 3.

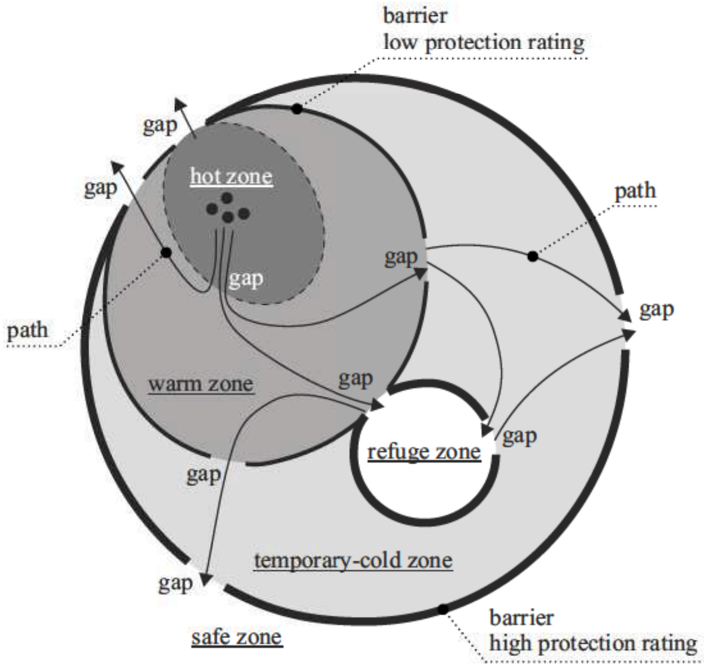


Figure 2.1. *Exodus-borders* conceptual model adopted in PASS. [Adapted from Grimaz and Pini (1999).]

Referring to the *exodus-borders* conceptual model, a safe evacuation is guaranteed if people can reach the gaps of each zone and pass through them within the standard times.

Table 2.1. Elements adopted in PASS in order to schematise the egress system.

Term	Definition	Example
Barrier	A physical element with different protection ratings against hazards (smoke, heat, etc.)	wall
Cell	A volume enclosed by barriers with at least one gap which people can pass through	room
Gap	An opening in the barriers that allows people to enter in or exit from a cell or zone	doorway
Path	Horizontal or vertical route that connects different gaps, cells or zones	corridor, stairway
Standard time	Maximum time available for people in order to leave a zone	
Hot zone	Area in a building where hazards are generated and that has to be evacuated rapidly	fire origin room
Warm zone	Area enclosed by protection barriers that contain the hot zone and where hazards can spread	fire compartment
Temporary-cold zone	Area adjacent the warm zone separated by protection barriers which guarantee a defined protection rating against hazards	area adjacent a fire compartment
Refuge zone	Area in the temporary-cold zone where tenability conditions are guaranteed and that can be safely leaved thanks to the intervention of rescue teams	area of refuge
Safe zone	Area where tenability conditions are guaranteed	area outside a building

These constitute the reference level for the three performance indicators used in PASS analysis:

1. possibility of reaching the gaps;
2. possibility of crossing the gaps;
3. presence of alternative gap/path.

PASS uses seven simple tools (in the form of analytical formulae) to check these performance indicators and identify egress system weaknesses. Weakness are present when the checks with PASS are not passed, namely when people cannot manage evacuation by reaching gaps, crossing gaps, and when cannot use alternative gaps or paths. In PASS, this emerges when the performance level of each indicator is below the required threshold level, established by the standard times.

Egress system analysis is carried out referring to its schematic form, developed according to the *exodus-borders* conceptual model, and to a set of given scenarios. Performance indicators are developed in order to analyse the egress system at three different levels of analysis, from global to local (Figure 2.2). Therefore, a multilevel approach analysis is adopted.

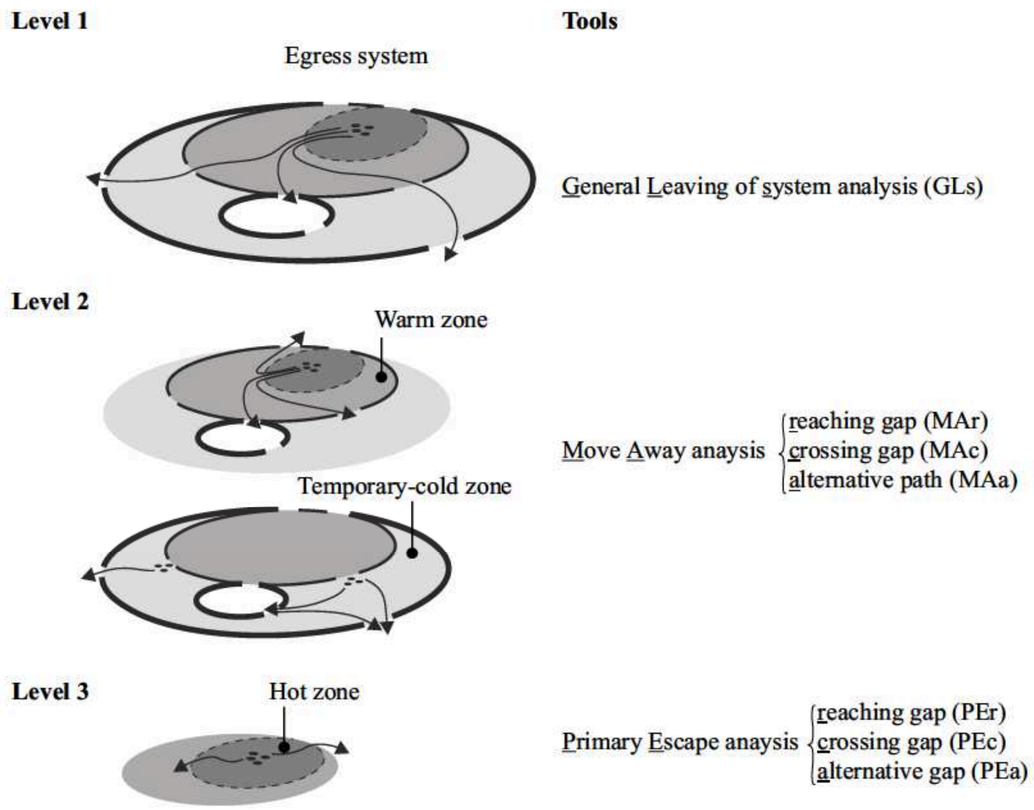


Figure 2.2. PASS is structured to achieve a multilevel analysis of egress system vulnerability. [Adapted from Grimaz and Tosolini (2011).]

At a global level (GLs, General Leaving of system) the global egress system is checked for assessing the possibility people have to reach safe or refuge zones. At this level, one tool (GLs) checks both the maximum egress route length and maximum flow achievable at gaps by considering the occupants number, spatial configuration of the egress system, occupant characteristics, and presence of emergency plans (see Appendix C). The reference level for performance indicators is established by a standard time for the global egress system, ET_{GL}.

At the second level, the analysis is enhanced by focusing on the warm and temporary-cold zones (MA, Move Away analysis). Three tools are introduced to check the possibility people have to reach the gaps (MAr, Move Away reaching gap), cross them (MAc, Move Away crossing gap), the presence of alternative paths (MAa, Move Away alternative path) and move away from warm and temporary-cold zone within the standard times.

The analysis is carried out by taking into account the geometrical characteristics of paths and gaps, presence of merging paths, presence of hazardous materials, number of occupants, people's egress capabilities (see Appendix D). The reference level for performance indicators is established by two standard times, $T_{TC-ZONE}$ (for the temporary-cold zone) and T_{w-zone} (for the warm zone).

The third level of analysis focuses on the hot zone, namely the zone where hazards are generated (PE, Primary Escape analysis). The maximum level of detail is achieved with three tools that check the possibility that people have to reach the gaps (PEr, Primary Escape reaching gap), cross them (PEc, Primary Escape crossing gap), and the presence of alternative gaps (PEa, Primary Escape alternative gap). The analysis considers the geometrical characteristics of paths and gaps, hazardous contents, number of people, people's egress capabilities (see Appendix E). Reference level for performance indicators is established through the standard time for the hot zone, T_{h-zone}.

The analysis is carried out through checks, and what changes between the three levels are the number of elements and interrelationships included in each tool. Performance analysis is fulfilled by including in the tools five different categories of factors (Figure 2.3):

- Interference factors. They take into account the presence of merging flows, egress system layout, high people density, which can interfere negatively with evacuation;
- Slowdown factors. They take into account the presence of obstacles, irregular or sloping paths, stairs, that can slowdown evacuation due to the intrinsic characteristics of the egress system;
- People's egress capabilities factors. They take into account the characteristics of people in terms of familiarity, mobility, and the presence of emergency signs;
- Hazard factors. They take into account the presence of hazardous materials and protection systems that can decrease or increase a given standard time;
- Safety factors. They take into account uncertainties in the analysis due to the variability of scenarios and human behaviour.

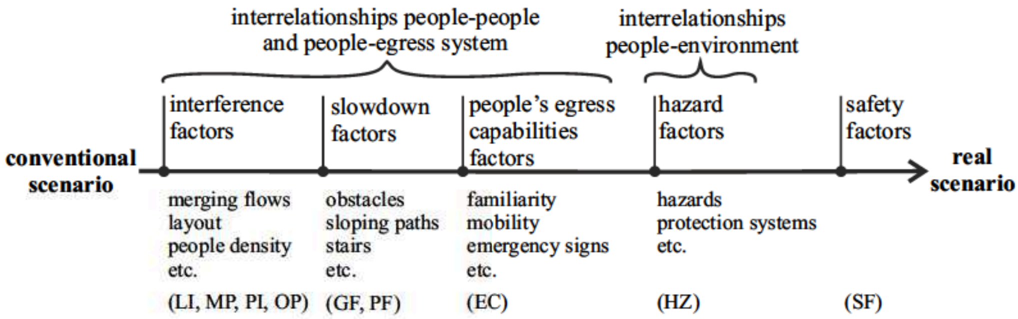


Figure 2.3. PASS tools adopt factors to include in the analysis people-built environment-fire interrelationships.

These factors are then adopted to include the effects of people-people, people-built environment and people-fire interrelationships in the analysis. They operate as penalty factors when the actual scenario has a configuration (in terms of geometrical layout, people's characteristics, hazardous contents) that can affect negatively evacuation. In other words, through the use of factors, PASS aims at achieving an assessment of the real scenario, although referred to standard scenarios developed with the *exodus-borders* conceptual model.

The factors are pre-codified and reported in a tabular form. Each scenario is characterised with a specific set of factor values. This allows tailoring the analysis to a wide set of scenarios, ensuring flexibility to the PASS tools.

The values assigned to each factor were partially calibrated in (Tosolini, 2008) by using an evacuation model. However, the difficulty with the calibration of those factors related to human behaviour, especially the people's egress capabilities factors, emerged. This was due to some limitations of the simulation model that, although sophisticated, did not allow simulating aspects of human behaviour. Although PASS demonstrated capabilities for analysing the egress system vulnerability, this remained an open issue, as some values of its factors were derived from expert judgements and did not rely on scientific basis. The development of an approach for quantifying in engineering terms such factors constitute the second objective of this research, as presented in Chapter 3.

2.2 Framework of PASS analysis

PASS analysis follows a specific process, as reported in Figure 2.4.

Firstly, the actual egress system is represented in a schematic form by adopting the *exodus-borders* conceptual model. In this way the main features of the egress system are identified. Given the schematic form, the scenarios to assess are then identified. This implies a zoning process of the schematic egress system, performed as follows:

- Identification of the hot zone by setting a fire in a cell containing combustible materials;
- Identification of the warm zone (area enclosed by fire barriers and including the hot zone);
- Identification of the temporary-cold zone (area outside the fire barriers);
- Identification of the safe and/or refuge zone (areas where tenability conditions are guaranteed).

Hot zone is defined only for cells that contain combustible materials, and temporary-cold zone is not present if fire barriers are not identified. The set of the standard scenarios for the analysis is established by repeating the zoning procedure for each cell of the schematic egress system. Differences among scenarios are then due to the different distribution of zones within the egress system. The multilevel analysis is applied to the set of scenarios identified, or alternatively to the worst scenario.

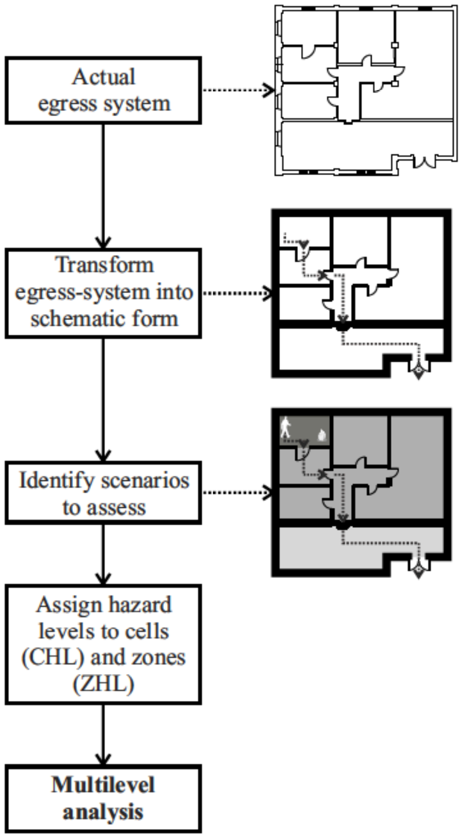


Figure 2.4. Framework of PASS analysis.

An important step for PASS analysis is the identification of potential hazard sources within each zone. When a fire spreads inside a building, people can be exposed to the threatening effects of the fire combustion products (smoke, toxic gases, and heat) generated by combustible materials (Bryan, 2002; Gann et al., 1994; Purser, 1996). The hazard levels that develop inside a building during the fire are strictly connected with the quantity and characteristics of the combustible contents present in the area involved by the fire, and with the combustion conditions (for example, the effects of a smouldering combustion are different than those of a fully developed fire) (Peacock et al., 2004; Neviaser and Gann, 2004; Babrauskas, 1992). As widely investigated, the presence of the fire hazards can reduce people's evacuation performance and eventually endanger the safety of the evacuees (Gann and Bryner, 2008; Proulx and Fahy, 2008; Purser, 2009; Wong and Lo, 2007; Kobes et al., 2009; Jin, 2002). Therefore, if combustible materials are present inside the building, or within the zones of the building that are required to be evacuated, the standard times ET_{GL}, $T_{TC-ZONE}$, T_{w-zone}, T_{h-zone} used in PASS to indirectly quantify the time available to people in order to escape can decrease.

In order to take into account the presence and characteristics of combustible contents and interior finishes inside the area required to be evacuated, and their potential impact on evacuees (people-fire interrelationships), Cell Hazard Levels (CHL) and Zone Hazard Levels (ZHL) are introduced in PASS tools (see Hazards Factor HZ, Figure 2.3). CHL and ZHL measure the potential level of fire hazards in cells and zones with respect to people's safety as a function of:

- characteristics of combustible contents;
- storage modalities of hazardous materials;
- presence and extent of interior finishes and bedding elements.

At each CHL and ZHL level is assigned a factor that reduces the PASS standard times. CHL levels range from 0 to IV and it is set for each cell identified in the schematic egress system. Starting from the CHL, five Zone Hazard Levels (ZHL) are then defined: L (low), O (ordinary), M (medium), H (high), and E (extreme). ZHL is a function of the hazard level of the cells within the analysed zone, and it is defined as a weighted average (in terms of cells floor area) between the different CHL of the zone. Details on the procedure for establishing CHL, ZHL and combustible materials considered are reported in Appendix B.

Once hazard levels are assigned at each zone of the schematic egress system and the conventional scenarios identified, PASS analysis is performed with the seven tools, according to the multilevel approach (see Chapter 11 for the application of PASS to a case study).

PASS is then a rapid method that does not rely on numerical simulation or integration. Instead, it uses seven tools to check rapidly the adopted performance indicators and identify system weaknesses. It allows determining the actual egress system performance in a flexible way and can be tailored to different scenarios. Once the system weaknesses are identified, suitable safety solutions or management strategies can be designed and checked to assess whether the egress system performance is restored to its required level.

Therefore, PASS can be applied when a rapid performance assessment and identification of safety solutions are required, for example during a preliminary design phase or for managing existing buildings involved in temporary renovations or changes. Due to the necessity to provide solution in dynamic scenarios, the use of sophisticated numerical tools in these contexts can be difficult. In fact, on one hand they are time requiring, on the other could require numerous input data.

Although these advantages, during the first application of PASS in Tosolini (2008) and Grimaz et al. (2010) two issues emerged. In particular, the need of a methodology compatible with PASS for a scenario-dependent estimation of the standard times and of a methodology to study, quantify in engineering terms, and calibrate people-people and people-egress system factors emerged. These are the two main objectives of this research, as presented in Chapter 3.

3

Research objectives

Chapter 1 showed that the egress system performance can be assessed also through its vulnerability analysis. Chapter 2 presented PASS, a method that comprises seven simple tools usable for checking with a multilevel analysis approach the egress system vulnerability and for identifying its weaknesses. In a first partial application, PASS demonstrated itself as a rapid, simple and reliable method, but two main issues emerged.

The first issue is related to the need to incorporate in PASS a methodology for estimating the standard times that the PASS tools adopt for establishing the performance reference levels.

The second issue is related to the need to calibrate the factors used in PASS for including human behaviour in the analysis. A methodology for quantifying in engineering terms these factors and integrating them in PASS has then to be developed. These issues constitute the two main research objectives of this thesis.

Objective 1

The first objective is to develop a rapid methodology that allows estimating the standard times ET_{GL}, $T_{TC-ZONE}$, T_{w-zone} and T_{h-zone} adopted in PASS tools. The required methodology should be flexible, in order to ensure its applicability to different scenarios, and compatible with PASS multilevel analysis approach. Namely, ET_{GL} has to be estimated relying on macro-characteristics of the egress system, while $T_{TC-ZONE}$, T_{w-zone} and T_{h-zone} from local characteristics, according to the level of analysis achievable with PASS tools. Because of PASS aims at checking rapidly the egress system performance, resource to numerical integration or simulation has to be limited, or avoided. This could constitute an issue, since the main equations developed in order to compute energy and mass balances in fire sciences usually can be solved with numerical computations.

This objective is addressed in Part II.

Objective 2

The second objective is to develop a methodology for studying human behaviour and movement in egress situations, and for collecting experimental data on the factors adopted in PASS to include human behaviour (people-people and people-egress system interrelationships) in the analysis. Data should allow calibrating these factors and integrating them in PASS.

This objective is addressed in Part III.

Methodology adopted

Besides the elements introduced in Chapter 1, each Part introduces the theory and tools necessary to handle the specific research objectives.

As regards Objective 1, conceptual models for describing fire dynamics in enclosures are developed referring to the current state of the art in the fire sciences. The conceptual models are represented in engineering terms and their validity checked with the use of Computational Fluid Dynamics tools. Conceptual models are not intended to substitute the actual tools available for studying the complexity of fire dynamics. Instead, according to PASS approach, they are intended as a complementary tool that simplifies the problem to a managerial dimension, as they introduce the main elements and interrelationships usable to describe in an effective way the physics of the problem.

Real experiments are necessary to address Objective 2, due to the current limitations of evacuation models for simulating the aspects of human behaviour investigated in this work. Therefore, data are collected from several experiments and analysed with a statistical approach. Specifically, people-egress system interrelationships are studied at a macroscopic level and represented in engineering terms. Namely, the analysis of experiments is aimed at *reading* the actual scenarios with a cause-effect interpretation: given a critical element (cause), its effects on human movement and behaviour are investigated and quantified.

The results from Objective 1 and 2 are eventually integrated in PASS (described in Appendix) which is applied to a case study (Chapter 11).

II

Estimation of PASS standard times

4

Compartment fires and tenability conditions

In Chapter 2, where the main concepts that underlie PASS are summarised, emerges that PASS assesses the egress system performance by checking three performance indicators, and that the reference level for the performance assessment is expressed by the standard times ET_{GL} (for the global egress system), $T_{TC-ZONE}$ (for the temporary-cold zone), T_{w-zone} (for the warm zone), and T_{h-zone} (for the hot zone). The performance indicators are used to estimate the actual performance of the egress system, while the standard times indirectly indicate the minimum performance level that the egress system has to fulfil in order to guarantee people's safety.

Because of the egress system performance is strictly connected with the scenario assessed, the necessity of integrating PASS with a scenario dependent methodology for a rapid estimation of the standard times emerges. One objective of this thesis is to develop a simple methodology for a rapid estimation of ET_{GL}, $T_{TC-ZONE}$, T_{w-zone} and T_{h-zone} and to integrate it into PASS. This may replace the use of the established standard times that are currently adopted.

This Part covers this objective. Firstly, the concepts of the fire safety sciences that are necessary to define the problem are summarised. Then the conceptual models introduced for developing the framework of the methodology used for estimating the standard times are illustrated. The conceptual models are then represented in engineering terms. This allowed developing the rapid methodology for estimating ET_{GL}, $T_{TC-ZONE}$, T_{w-zone} and T_{h-zone}. Finally, a comparison between the developed methodology and traditional approaches (CFD simulations) is shown.

4.1 The concept of *Available Safe Egress Time*

People's safety in case of fires is guaranteed if occupants move away from a threatening zone before they are overcome by the fire hazards (smoke, toxic gases, heat). This concept was firstly translated in engineering terms by Cooper (1983), who proposed as criterion for a safe egress system design the following time-based relationship:

$$RSET < ASET \tag{4.1}$$

which is currently adopted in all the Fire Safety Engineering (FSE) standards (ISO 13387-1, 1999; ISO 16738, 2007). The left-hand term of Eq. (4.1) is the time required for people to reach a safe or refuge zone (Required Safe Egress Time, $RSET$), while the right-hand term is the time available to escape (Available Safe Egress Time, $ASET$).

According to Eq. (4.1), an egress system has to be designed in order to allow evacuees to reach a safe area within the $ASET$. $RSET$ is estimated by calculating the time people take to escape and it is dependent on occupant characteristics, egress system layout, fire-induced conditions (see Chapter 9) and usually is calculated with simulation evacuation models. With $RSET$ calculation, the actual egress system performance is estimated: lower the $RSET$ is, better the egress system performance is. However, in order to assess the goodness of this performance, a basis for the judgement has to be established. Without such a basis, it is not possible to conclude whether a low $RSET$ is actually good. $ASET$ provides this basis for the judgement, namely a minimum performance level that is fundamental to guarantee in order to fulfil people's safety. Once $ASET$ is estimated, the safety margin $ASET - RSET$ guaranteed by the egress system is directly calculated, and the performance level assessed: greater the margin of safety is, better the egress system performs. The required performance level is usually established by stakeholders.

$ASET$ depends on factors associated with the development of fire hazards inside the area required to be evacuated, such as geometrical configuration of a building, characteristics of combustible contents, fire protection features (Guanquan et al., 2012; ISO 13387-1, 1999; ISO 16738, 2007). It is estimated by adopting tenability criteria (namely performance indicators), setting their threshold limits, and calculating the time when these threshold limits are reached. This time corresponds to that time occupants will receive an incapacitating exposure to fire hazards.

Fire hazards distribute within a building following the fire-driven fluid flow, which mostly depends on the characteristics of the building (number, geometric characteristics and material properties of enclosures, presence of openings), characteristics of the combustible materials, combustion conditions, quantity of energy released by the fire in the environment. Albeit fire dynamics are a complex chemical-physical process, for most engineering estimations it can be easily described in qualitative terms.

4.1.1 Qualitative description of fire dynamics in enclosures

The development of a fire in an enclosure and its flow through openings can be described qualitatively with a set of different stages (Figure 4.1).

The origin of a fire is the ignition of the combustible material (fuel) that is present in the enclosure. After ignition, the fire grows producing energy and fire combustion products (smoke, toxic gases) which are released into the environment. At this stage the combustion is fuel-controlled, since the oxygen concentration is sufficient to sustain it.

During the combustion a buoyant hot gas stream (fire plume) rises above the burning fuel and entrains cold air into the hot plume. This mixture of fresh air and fire combustion products eventually impinges the ceiling of the enclosure and causes a layer of hot gases to be formed. Because fresh air is entrained into the plume, the total mass of the plume increases with the height while, due to dilution, its temperature and concentration of combustion products decrease.

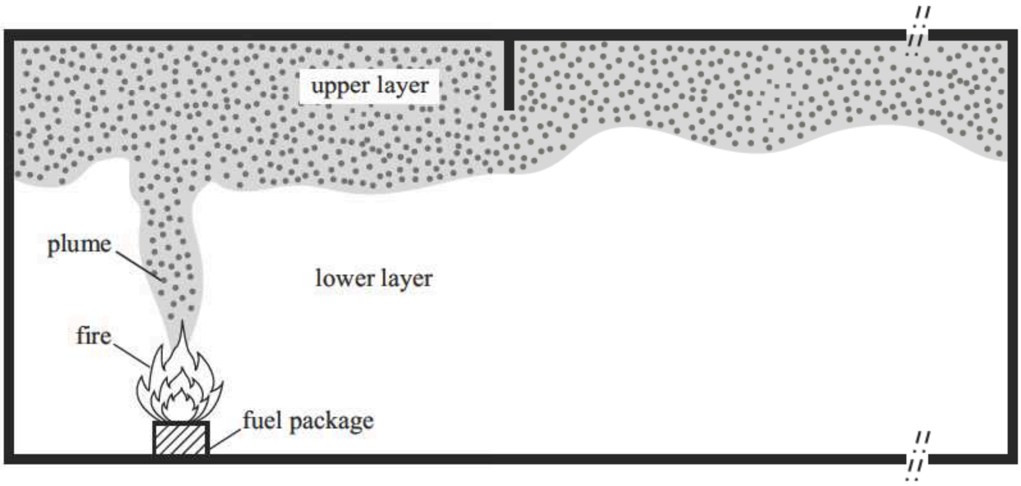


Figure 4.1. Qualitative description of enclosure fire dynamics (left) and smoke spreading to adjacent enclosures (right).

A layer of hot gas gradually develops under the ceiling and, as fuel combustion proceeds, two distinct layers form. Several experiments (see for example Zhang et al. (2012) or Yang et al. (2010)) show that the enclosure is divided into a hot upper layer composed of combustion products and entrained air, and in a cold lower layer composed of fresh air. The plume continues transferring energy and combustion products from the fuel to the hot layer as the fuel burns. The hot upper layer grows in volume and the layer interface descends towards the floor with a rate that depends on the velocity of the fire growth which, in turn, depends on the fuel characteristics and oxygen availability.

As combustion continues, the temperature of the upper layer increases and heat is transferred by radiation, conduction and convection to the enclosure bounding surfaces and to other fuel packages in the enclosure. Enclosure temperature grows rapidly enhancing the combustion velocity and the fuel packages ignite when reach their autoignition temperature. Additional energy is then released into the enclosure, and a sudden transition from a growing fire to a fully development fire can occur. At this stage the total surface of the fuel packages within the enclosure is involved by the fire. The transition point from a growing fire stage to a fully developed fire stage is called flashover. A quantitative criterion for flashover commonly used is the time at which the radiant heat flux to the centre of the floor reaches 20 kW m^{-2}(corresponding to an air temperature of about 500-600°C) (Peacock et al., 1999; Krasny et al., 2001; Quintiere, 2006).

The fully developed fire stage is ventilation-controlled since the oxygen needed for the combustion is not entirely provided. It can last for a number of hours, until fuel and oxygen are available for combustion. During this stage the temperature in the enclosure reaches its maximum values (up to 1200°C), the fuel is consumed and, eventually, the energy release rate decreases. The decay or cooling stage is assumed to begin when the average temperature falls to 80% if its peak value (Drysdale, 1999).

While the structure integrity is threatened during the fully developed stage, it is during the growing stage (or pre-flashover stage) that the survivability conditions in the fire origin enclosure are jeopardized, and occupants within the building begin to be threatened (Drysdale, 1999; Krasny et al., 2001; Mowrer, 1999). In fact, if openings are present in the fire origin enclosure, mass and energy can spread to the adjacent enclosures (rooms, corridors, shafts) and affect the survivability conditions also in the other parts of a building.

According to Karlsson and Quintiere (Karlsson and Quintiere, 2000), three main stages govern the mass and energy flow across an opening (Figure 4.2). In the first stage (Figure 4.2(a)) the pressure inside the enclosure is higher than the pressure outside, due to the expansion of hot gases produced by the fire. If an opening is present (like a door) outflow of cold gases begins. In the second stage (Figure 4.2(b)) the upper layer has reached the top of the opening and hot gases flow out. Since the mass balance through the opening has to be respected, a mass inflow of cold air through the lower part of the opening starts. This stage lasts until the room is completely filled with smoke. The third stage (Figure 4.2(c)) is the *well-mixed* or *one-zone* stage, where the fire origin enclosure is filled with a uniform layer of smoke which is assumed to have a single average temperature and composition. This can happen during post-flashover stages or when the fire is weak in relation to the room volume and the smoke spreads in the room.

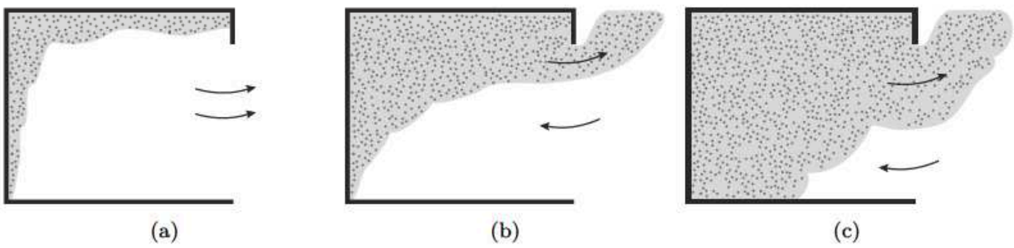


Figure 4.2. Vent smoke flow. [Adapted from Karlsson and Quintiere (2000).]

The generation of heat and combustion products and their flow through an enclosure is then a complex process. Geometrical characteristics of fuel and enclosure play an important role in fire dynamics, and many chemical and physical processes are involved. In order to study fire dynamics, different approaches and methods can be used (Olenick and Carpenter, 2003; Walton, 2002; Cox and Kumar, 2002).

Computational Fluid Dynamics (CFD) models are the more sophisticated tools that can be used to simulate fire dynamics. The considered volume is divided in three-dimensional sub-volumes and the equations of mass, momentum, energy conservation are solved in each sub-volume. Depending on the model adopted, it is possible to include the pyrolysis, flame spread, combustion reactions. The capabilities of CFD simulations are considerable and complex scenarios can be investigated. However, they need expertise, a lot of input data and computational resources.

With respect to CFD models, two-zone models are simpler to use, require less input data and computational resources, but provide lesser outputs. Two-zone models approximate the fire dynamics dividing the considered volume in two main volumes (upper layer and lower layer). A fire plume is modelled in order to include mass and energy transfer from the lower to the upper layer. Conservation of energy and mass equations are solved numerically for each volume and flow through openings can be modelled with analytically derived expressions.

Finally, hand-calculation methods describe analytically the fire dynamics by adopting a set of experimental and analytical equations to estimate flame heights, mass flow rates, layer interface descendent rate, temperatures, and other variables. Their use is simple and quite rapid, albeit the results obtained are approximate. However, they are suitable for preliminary engineering estimations (Mowrer, 1999). In facts, for engineering purposes complex combustion reaction mechanisms or flame spread are not predicted with accuracy adopting grid sized typical of fire modelling applications (Jahn et al., 2011). Rather, the estimation of the energy release rates and yields of combustion products can be considered at all by using approximate methods and experimental measurements (Beyler and Hirschler, 2002).

As emerges from the qualitative description of the fire dynamics, enclosure fires can be easily described in terms of the energy released during the fire (Heat Release Rate, HRR) or temperature rise in the enclosure. Figure 4.3 shows an example of this approach, where a conventional curve of the energy released by a fire is reported. According to Walton and Thomas (2002) different fire stages that characterise an enclosure fire can be identified, and refer to the previous qualitative description:

1. Initiation stage: the fire begins when the combustible materials (fuel) are ignited;
2. Growth stage: in this phase the fire grows (with slow or fast rate) in size from a small incipient fire up to flashover (pre-flashover stage). The fire can be described in terms of the heat and combustion products yields released;
3. Flashover: is the point at which the transition to a fully development state occurs and all the fuel packages in the enclosure are involved in the fire. It is the demarcation point between the pre-flashover (initiation and growth) and post-flashover (fully developed fire) stages;
4. Fully developed fire: this ventilation controlled stage is characterised by a steady state burning rate during which all the combustible items are involved by the fire (post-flashover stage)
5. Decay/Cooling stage: it occurs when the fuel is consumed and the energy release declines.

In the fire stages, a critical point during the fire development is the flashover. In fact, once fires had proceeded beyond flashover, lethal environments outside the fire origin room are produced and occupants can be threatened directly (Gann et al., 1994; Drysdale, 1999; Peacock et al., 2004). Considering people's safety issues, the egress system should ensure that occupants escape from a fire compartment [1] during the pre-flashover stage

[1] Here a fire compartment is defined according to (ISO 13943, 2008): enclosed space, which may be subdivided, separated from adjoining spaces by separating elements that exhibit fire integrity or fire stability or thermal insulation for a period of time under specified conditions.

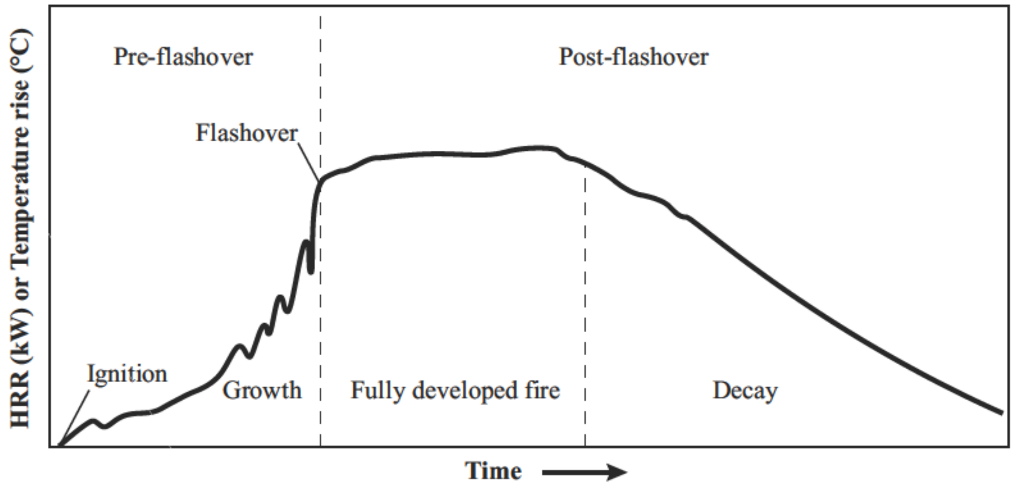


Figure 4.3. Qualitative description in terms of *HRR* (kW) or temperature rise (°C) of an enclosure fire. [Adapted from Walton and Thomas (2002).]

and before flashover is reached. Therefore, when evaluating people's safety in case of fire, particular attention is paid to the pre-flashover stage of the fire.

For design and modelling purposes, usually the pre-flashover phase is approximated by adopting a parabolic growth rate (Figure 4.4) and can be described by *t-squared* fires (as defined in Drysdale (1999) and ISO 13387-2 (1999)):

$$HRR(t) = \alpha_{HRR}\, t^2 \tag{4.2}$$

where *HRR* is the heat (kW) released at the time t (s) after ignition has been well established, and α_{HRR} is a fire-growth coefficient (kW s^{-2}) that ranges from 0.003 kW s^{-2} for slow fire growth to 0.192 kW s^{-2} for very fast fire growth (Drysdale, 1999). The area that underlies the parabolic curve described by Eq. (4.2) is the total energy released during the pre-flashover stage of the fire.

The minimum *HRR* (kW) that causes the enclosure flashover can be determined by using Thomas' flashover correlation (Thomas, 1981):

$$HRR_{flashover} = 7.8\, A_{room} + 378\, A_{vent}\sqrt{h_{vent}} \tag{4.3}$$

A_{room} is the total internal area of the room (m^2), A_{vent} is the area of the opening (m^2), and h_{vent} is the height of the opening (m). This correlation is the result of a simplification of an energy balance of an enclosure fire and the constants represent values correlated to experimental data.

By adopting *t-squared* fires therefore the description of the pre-flashover stage of an enclosure fire is possible and with Eq. (4.3) the time to flashover is easily calculated. Since it is during this stage that in most cases evacuation has to be performed, *t-squared* fires allow also estimating *ASET*.

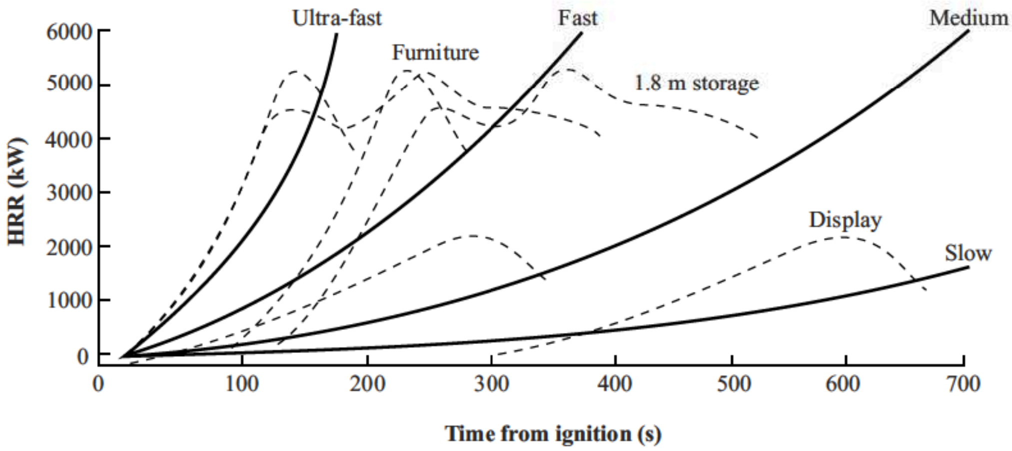


Figure 4.4. *HRR* in *t-squared* fires. [Adapted from NFPA 92B (2009).]

4.2 Estimation of *ASET*

ASET estimation is possible once one or more tenability criteria are adopted, their threshold limits are established and the time to reach these limits is calculated. Tenability criteria are used to quantify the time it takes to reach untenable conditions, and hence the time it takes to incapacitate building occupants[2]. According to Coté (2000), ISO 13571 (2007) or ISO 16738 (2007) several tenability criteria can be adopted, as shown in Table 4.1.

As it can be seen, tenability criteria can be classified in two groups. Group A criteria are macroscopic criteria and they adopt the two-zone characterisation of the fire induced environment in an enclosure (Figure 4.1). In the upper layer heat and fire combustion products are present. In the lower layer fresh air is present and tenability conditions are guaranteed. The two layers are supposed to be uniform in terms of temperature and composition and hence the smoke composition and temperature distributions are averaged within these layers. It is assumed that, when the Lower Layer Height (LLH) drops to some established level or the Upper Layer Temperature (ULT) grows to some specified value, the enclosure is supposed to be untenable (Cooper, 1983; Coté, 2000; ISO 16738, 2007). These criteria are used by adopting the so-called *zero exposure* criteria (ISO 16738, 2007): LLH and ULT threshold limits are established to guarantee that people are not threatened by fire hazards. Therefore, with the *zero exposure* criteria people-fire interrelationships are considered at all, by preventing that people are exposed to the fire adverse effects. Although this is an oversimplification of the evacuation analysis, it is on the safe side (conservative approach).

Group B criteria are punctual criteria and are used when it is possible to characterize in detail the combustible characteristics, the combustion conditions, the combustion products and their distribution inside the enclosure. The use of these criteria needs

[2]Incapacitation can be measured as an inability to move or react (Gann, 2004).

Table 4.1. Tenability criteria for assessing the *ASET*.

Group	Tenability criterion	Symbol	Significance
A	Lower Layer Height	LLH	Minimum smoke-free layer above the floor
A	Upper Layer Temperature	ULT	Maximum tenability temperature of the upper layer of smoke
B	smoke Optical Density	OD	Visibility in a smoke-filled environment
B	maximum Fractional Effective Concentration of irritant gases	$FEC_{irritant}$	Ratio of the concentration of an irritant gas to that expected to produce a given effect on an exposed subject
B	maximum Fractional Effective Dose of toxic gases	FED_{toxic}	Ratio of the dose of an asphyxiant gas to that expected to produce a given effect on an exposed subject
B	maximum Fractional Effective Dose of heat	FED_{heat}	Ratio of the dose of convective and radiant heat to that expected to produce a given effect on an exposed subject

the evaluation of the smoke concentration OD (an indirect measure of visibility), toxic gases concentration and heat in every point of an enclosure. The smoke concentration is estimated through the optical density OD (m^{-1}):

$$\mathrm{OD} = \frac{1}{L} \log \frac{I_0}{I} \tag{4.4}$$

where L is the light path length (m), I_0 is the intensity of the incident light and I is the intensity of the light through the smoky light path L (Mulholland, 2002).

In order to define $FEC_{irritant}$, FED_{toxic} and FED_{heat}, concentration and doses for toxic gases and heat have to be calculated (see details in Purser (2002)):

$$\mathrm{FEC_{irritant}} = \sum \frac{[irritant_i]}{F_{Ci}} \tag{4.5}$$

where $[irritant]$ is the concentration in ppm of the irritant gas i and F_{Ci} is the irritant gas concentrations in ppm that are expected to compromise occupants capability to escape.

$$\mathrm{FED_{toxic}} = [\mathrm{FED_{CO}} + \mathrm{FED_{HCN}}]\ \mathrm{HV_{CO_2}} + \mathrm{FED_{O_2}} \tag{4.6}$$

where FED_{CO} is the fraction of incapacitating dose of CO, FED_{HCN} that of HCN, FED_{O_2} the fraction of an incapacitating dose of low O_2 hypoxia, and HV_{CO_2} the hyperventilation factor induced by CO_2.

$$\mathrm{FED}_{\mathrm{heat}} = \sum_{t_1}^{t_2} \left(\frac{q^{1.33}}{1.33} + \frac{T^{3.4}}{5 \cdot 10^7} \right) \Delta t \tag{4.7}$$

where $\Delta t = t_2 - t_1$ is the period of time during exposure, q is the radiant flux (kW m^{-2}) and T is the air temperature (°C).

Each Group A and Group B criteria aims at quantifying the impact on people of smoke, toxic gases (LLH, OD, $\mathrm{FEC}_{\mathrm{irritant}}$, $\mathrm{FED}_{\mathrm{toxic}}$) and heat (ULT, $\mathrm{FED}_{\mathrm{heat}}$). According to the *limiting hazard* concept (Gann et al., 1994), untenable conditions are reached when one of these tenability criteria reaches its threshold limit first.

The choice of the tenability criteria to adopt depends on the aims of the analysis carried out (detailed analysis or rapid assessment), the available input data (detailed characterisation of combustible materials or not), the tools used (hand-calculation methods, two-zone models or CFD models), regulation adopted.

Group A criteria can be easily estimated also with hand-calculation methodologies or simple computational tools (two-zone models), while Group B criteria are estimated by adopting CFD models with which it is possible to achieve a high precision in the analysis.

The $ASET$ estimation is then a process that involves different aspects:

- Definition of the physical domain (for example characteristics of the fire origin room and adjacent spaces);
- Characterisation of the fire source (in terms of heat, yields of toxic gases and soot particulate released during the fire);
- Adoption of one or more tenability criteria with their corresponding threshold limits (LLH, ULT, OD, FEC, FEDs);
- Study of the fire dynamics and distribution of fire combustion products within the physical domain;
- Estimation of the time taken to reach the tenability criteria threshold limits ($ASET$).

Because of $ASET$ indirectly expresses the basis for assessing the performance level of the egress system, it can be used to define the standard times adopted in PASS.

The direct use in PASS of traditional tools for $ASET$ calculation (hand-calculation or simulation models) is not possible because they are time requiring (also with hand-calculation tools it is necessary to resource to numerical integration). In fact, PASS is a tool which aims at achieving a rapid assessment of egress system vulnerability without resourcing to numerical computations (see Chapter 2). Therefore, the development of a methodology usable for a rapid estimation of standard times that can be integrated in PASS is necessary. In this Part it is described how a methodology that fulfils PASS needs was developed, tested and integrated.

4.3 Definition of objectives

In order to develop a methodology usable for a rapid estimation of the standard times adopted in PASS, a set of objectives have to be defined. In fact, firstly the key parameters for describing the smoke filling process and for estimating the *ASET* have to be identified. Once these parameters are identified, a conceptual model usable for developing the methodology can be introduced and, eventually, the factors included in the conceptual model have to be represented in engineering terms. This will allow using the methodology for engineering assessments.

Given this, the research objectives can be summarised as follows:

1. Analysis of the tenability criteria variation as a function of the variation of the input data currently available to estimate the *ASET* (Chapter 5). This will allow identifying, on the one hand, the suitable tenability criteria to estimate rapidly *ASET* and its safety margin with respect to the other tenability criteria, and on the other the most important data needed for its estimation;

2. Development of conceptual models for estimating the standard times (Chapter 6). This will allow developing a framework for a methodology for a rapid *ASET* estimation;

3. Representation of the conceptual models in engineering terms (Chapter 7). This will allow to quantify in engineering terms the key factors adopted in the conceptual models, and eventually to calculate the standard times;

4. Development of the operative tools for a rapid estimation of the standard times and comparison with traditional approaches (Chapter 8). This will allow to develop simple, rapid and reliable tools for estimating the standard times and to integrate them in PASS.

5

Analysis of tenability criteria and input data for ASET estimation

As outlined in Section 4.2, *ASET* is estimated with different tenability criteria. Lower Layer Height (LLH) and the Upper Layer Temperature (ULT) are criteria adopted with simple computational tools (two-zone models or hand-calculation methodologies). In addition to these criteria, visibility (through the optical density), toxic gases and heat doses can be calculated when more sophisticated tools are used (CFD codes).

At least two issues arise when adopting one or more tenability criterion. The first issue concerns the differences in the *ASET* estimation that can emerge using two or more tenability criteria at the same time. For example, some tenability criteria may allow obtaining estimations with a greater margin of safety than others. The second issue concerns the type of input data which have to be necessarily considered in order to calculate *ASET*, given one or more tenability criterion. In fact, some input data required by the adopted methodology, whichever it is, may be fundamental in order to calculate the *ASET*, while others can only have a little effect on the *ASET* estimation. It is worthwhile highlighting that the input data required for *ASET* calculation are strictly connected with the tool adopted (in general, more sophisticated the tool is, more input data are required). Exploring these two issues allows identifying both the tenability criteria and their most important input data usable for a rapid *ASET* estimation.

Given these results, key elements for developing conceptual models for estimating PASS standard times can be identified.

In this Chapter these issues are addressed by using *Fire Dynamics Simulator* (FDS) numerical model, currently one of the most suitable Computational Fluid Dynamics (CFD) models for studying the fire dynamics in enclosures (buildings, tunnels). FDS allows calculating the main tenability criteria with a high degree of precision (all the tenability criteria reported in Table 4.1 but $\mathrm{FEC_{irritant}}$) once fire source and enclosure geometrical configuration are defined.

In order to carry out the analyses a geometrical scenario was established. Then, a study on mesh refinement and boundary conditions was made with FDS (Version 5.5.3) in order to set the main geometrical parameters in the model. Finally, the analysis of the tenability criteria variation as a function of the variation of input data was conducted.

5.1 Fire Dynamics Simulator model

Fire Dynamics Simulator (FDS) is a Computational Fluid Dynamics (CFD) model developed by the National Institute of Standard and Technology (NIST) for studying fire-driven fluid flow (McGrattan et al., 2010a,b). The model solves Navier-Stokes equations for low-speed, thermally-driven flow of smoke and heat from fires. It is suitable for studying low-speed flows (Mach numbers less than 0.3) and hence can be applied to the analysis of building fires. It adopts a rectilinear numerical grid and all the geometry has to be described by adopting a rectangular mesh. FDS can be used reliably when the heat released by the fire is specified (hence when using prescribed HRR, such as *t-squared* fires) and the transport of heat and fire combustion products is the principal aim of the simulations. The spatial derivatives are solved as second-order central finite differences and the flow variables by using an explicit second-order Runge-Kutta scheme updated with time on each rectilinear grid cell. Turbulence is treated with either Direct Numerical Simulation (DNS) or Large Eddy Simulation (LSD). LES is the default mode of operation.

To model combustion FDS uses a mixture fraction model, a conserved scalar quantity that is the fraction of gas at a given point in the flow field. It assumes that combustion is mixing-controlled and that the reaction of fuel and oxygen is infinitely fast (this assumption is good for large-scale, well-ventilated fires). If the fire is in an under-ventilated environment, the fuel and oxygen are allowed to mix but not to burn. Radiative heat transfer is included in FDS via the solution of radiation transport equation for a grey gas. Thermal radiation is solved using finite volume methods for fluid driven flow. All solid surfaces are assigned thermal boundary conditions and heat and mass transfer from solid surfaces is handled with empirical correlations. Furthermore, the model allows modelling sprinkler, heat and smoke detectors. Sprinkler sprays are modelled by Lagrangian particles to represent the water droplets ejected from the sprinkler.

The input parameters are the geometrical characteristics of the scenario modelled via the rectangular mesh. Materials are defined by their thermal conductivity, specific heat, density, thickness and burning behaviour. The fire products can be calculated once the fuel composition, soot and CO yields, fraction of the atoms in the soot that are hydrogen and the fraction of fuel mass converted into hydrogen are specified.

FDS allows computing the gas temperature, gas velocity, gas species concentrations, smoke concentration and visibility estimates, gas density, radiative and convective heat fluxes, total Heat Release Rate (HRR), mass and energy fluxes through openings. Lower Layer Height (LLH) and Upper Layer Temperature (ULT) can be calculated at each x, y point while Optical Density (OD) and Fractional Effective Dose of toxic gases (FED_{toxic}) at each x, y, z point within the numerical grid.

FDS is verified and validated with laboratory and large-scale experiments (see for example Matheislová et al. (2010) for a comparison between FDS simulations and large-scale experiments). Recently, FDS has been integrated with an evacuation module for coupling fire and evacuation simulations (Korhonen and Hostikka, 2010).

5.2 Scenario adopted for the analysis and definition of threshold limits for tenability criteria

The scenario for the analyses of mesh refinement, bounding surface characteristics, input data for the fire source characterisation and tenability criteria variation consists in a 4.0 m × 4.0 m × 2.4 m room with a 0.8 m × 2.0 m opening located in the middle of a side (Figure 5.1). The design HRR adopted in order to model the energy released by the fire has a linear growth rate of 10 kWs^{-1} up to the HRR of flashover. The HRR of flashover was estimated with the Thomas' flashover correlation (Eq. (4.3)) and, for the enclosure of Figure 5.1, it is of about 1400 kW. With a linear growth rate of 10 kWs^{-1} flashover is achieved in 140 s (this condition is valid for a fuel-controlled fire).

A soot yield y_{soot} equal to 0.30, a CO yield y_{CO} equal to 0.45, and a heat of combustion $\Delta H_c = 50600$ kJ kg^{-1} are used for the combustion reaction, as required by FDS. In order to operate conservatively (on the safe side) the soot yield (y_{soot}) and CO yield (y_{CO}) are the higher values found in the literature (Tewarson, 2002). The bounding surfaces of the domain (walls) are supposed to be a non-reacting solid whose temperature is fixed at 20°C (inert surface).

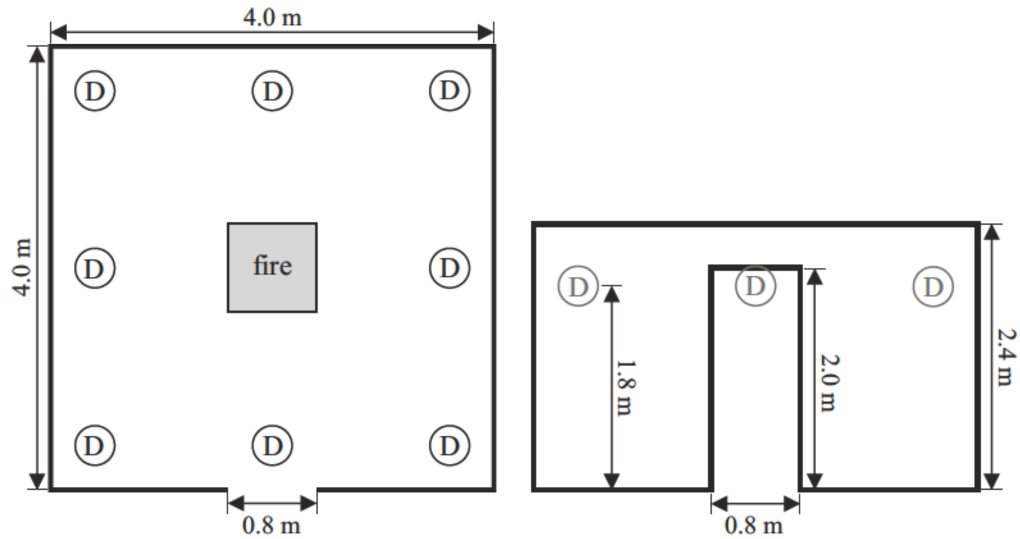


Figure 5.1. Geometric characteristics of the scenario adopted in the analysis (D: devices).

Because FDS outputs can be collected only at defined points, eight devices are adopted and distributed across the room (see D points in Figure 5.1). The collected output quantities (average between eight devices) are LLH, ULT, OD, $\mathrm{FED_{toxic}}$. In FDS, $\mathrm{FED_{heat}}$ is not be measured directly but can be estimated with Eq. (4.7). Devices to monitor the local temperature and the radiant heat flux are then included in the model.

OD, $\mathrm{FED_{toxic}}$ and $\mathrm{FED_{heat}}$ are measured at an height of 1.8 m, while LLH and ULT across the height z of the room. $\mathrm{FEC_{irritant}}$ is neglected due to limitations of FDS and lack of data for its calculation (since $FEC_{irritant}$ refers to irritant gases contained in the smoke that can slow down evacuation, its evaluation can be included in OD).

Threshold limits for each tenability criterion are established in order to study the variation of outputs as a function of mesh size, characteristics of the bounding surfaces and variation of the input data used to model the combustion reaction in FDS (HRR, y_{soot}, y_{CO}, ΔH_c). The values, set according to FSE standards and values proposed in the literature, are reported in Table 5.1. The ULT tenability limit (200 °C) corresponds at radiant flux of approximately 2.5 kW m^{-2} (which is the tenability limit for exposure of skin to radiant heat). The value adopted for OD corresponds to a visibility distance in a smoke-filled environment of about 3 m (for a mix of irritant and non-irritant smoke): with this visibility distance the 30% of people usually turn back when negotiating a smoke filled escape route (Purser, 1996; SFPE, 2003). The values of FED_{toxic} and FED_{heat} are set considering the presence of susceptible population (children, elderly) among the occupants (ISO 13571, 2007; Gann et al., 2001).

Table 5.1. Threshold limit for each tenability criterion adopted in order to estimate the *ASET*.

Group	Tenability criterion	Threshold limit	Height of measure (m)	Source
A	LLH (m)	2.0	$0.0 < z < 2.4$	Coté (2000)
A	ULT (°C)	200	$0.0 < z < 2.4$	ISO 16738 (2007)
B	OD (m^{-1})	0.33	$z = 1.8$	Purser (2002)
B	FED_{toxic}	0.3	$z = 1.8$	ISO 13571 (2007)
B	FED_{heat}	0.3	$z = 1.8$	ISO 13571 (2007)

5.3 Analysis of mesh refinement and boundary conditions

The characteristics of geometrical features used in CFD models can affect the results obtained from simulations (Lin et al., 2009; Hadjisophocleous and McCartney, 2005; Bounagui et al., 2003). Therefore, before studying the differences in *ASET* estimations among the tenability criteria and the effects of input data variation on the *ASET*, it is necessary to set the characteristics of the geometry modelled in FDS. An analysis of mesh refinement and characteristics of boundary conditions for the geometrical scenario reported in Figure 5.1 was then carried out. The outputs used to check the results of mesh refinement and surface characteristics are the tenability criteria reported in Table 5.1.

Initially, a mesh refinement (or mesh sensitivity) study was conducted. Grid size was refined starting from a size of 0.40 m and gradually refining the mesh until no appreciable differences in the results were noticed. The grid sizes checked were 0.40 m, 0.20 m, 0.10 m. In Figure 5.2 the trends of each tenability criterion as a function of the three grid sizes are shown. Because *ASET* is reached for all the tenability criteria within the first

120 s (before flashover, which is estimated to occur at 140 s), trends of criteria for each grid size are plotted up to 120 s. In Table 5.3 the *ASET* for each case is summarised. Figure 5.2 does not show a variation of tenability criteria trends as a function of grid size, except in Figure 5.2(a), where, for a grid size of 0.10 cm, LLH decreases slowly compared with the grid sizes of 0.20 m or 0.40 m. In this case the adoption of a coarse mesh size may allow obtaining a conservative (on the safe side) *ASET* estimation. However, as Table 5.3 shows, there are no significant differences in the *ASET* estimations between the three mesh sizes checked. Given these results, in order to reach a compromise between precision achievable when modelling the geometry and computational times, a grid size of 0.20 m is adopted.

Following the mesh refinement study, an analysis on the characteristics of bounding surfaces was made. FDS allows defining the material characteristics of the solids present in the domain and the walls properties as well. In order to identify the characteristics of the walls of the domain (bounding surfaces), three different conditions were checked, as summarised in Table 5.2.

Figure 5.3 shows the trend of each tenability criterion as a function of the bounding surface material. Table 5.4 summarises *ASET* values obtained for each case studied. Referring to Figure 5.3, no differences between the three bounding surfaces can be seen. Only in Figure 5.3(b), which refers to ULT trend, a slight difference between inert material and brick or concrete emerges. This difference is confirmed by the results of *ASET* estimation reported in Table 5.4. However, this difference is about 5% and reasonably can be concluded that the characteristics of the bounding surfaces do not influence the *ASET* estimation, at least for the pre-flashover stage of a fire. Therefore, an inert surface is adopted.

Table 5.2. Characteristics of the three bounding surfaces tested to establish the wall characteristics.

Material	Density ρ kg m^{-3}	Thermal conductivity k W m^{-1}K^{-1}	Specific heat c_p kJ kg^{-1}K^{-1}
Concrete	2200	1.20	0.88
Brick	1600	0.69	0.84
Inert	non-reacting solid boundary whose temperature is fixed at 20°C.		

It is important to point out that these conclusions are acceptable if the analysis is focused on the growth phase of a fire (pre-flashover stage), namely when the energy released by the fire is low and the time of analysis is short (of the order of minutes). If the analysis is extended to the fully development phase of the fire (that could last up to an hour or more), the characteristics of the bounding surfaces can affect the temperatures achieved within the enclosure and hence the structure integrity (the temperature will be higher because the heat transfer to the solid surface is lower compared with an inert surface). It is worthwhile noticing that at this stage there is no chance for people to survive. This topic is not addressed in this work, since here the focus is on people's evacuation from enclosures which, as discussed previously, in most cases has to be concluded within the pre-flashover stage of a fire.

Table 5.3. *ASET* (s) for each tenability criterion as a function of the grid size.

Tenability criterion	*ASET*(s) 0.40 cm	0.20 cm	0.10 cm
LLH	13	13	13
ULT	67	69	70
OD	11	10	10
FED_{toxic}	67	67	64
FED_{heat}	60	61	61

Table 5.4. *ASET* (s) for each tenability criterion as a function of bounding surface characteristics.

Tenability criterion	*ASET*(s) Inert	Brick	Concrete
LLH	13	13	13
ULT	69	66	66
OD	10	10	10
FED_{toxic}	67	67	67
FED_{heat}	61	61	61

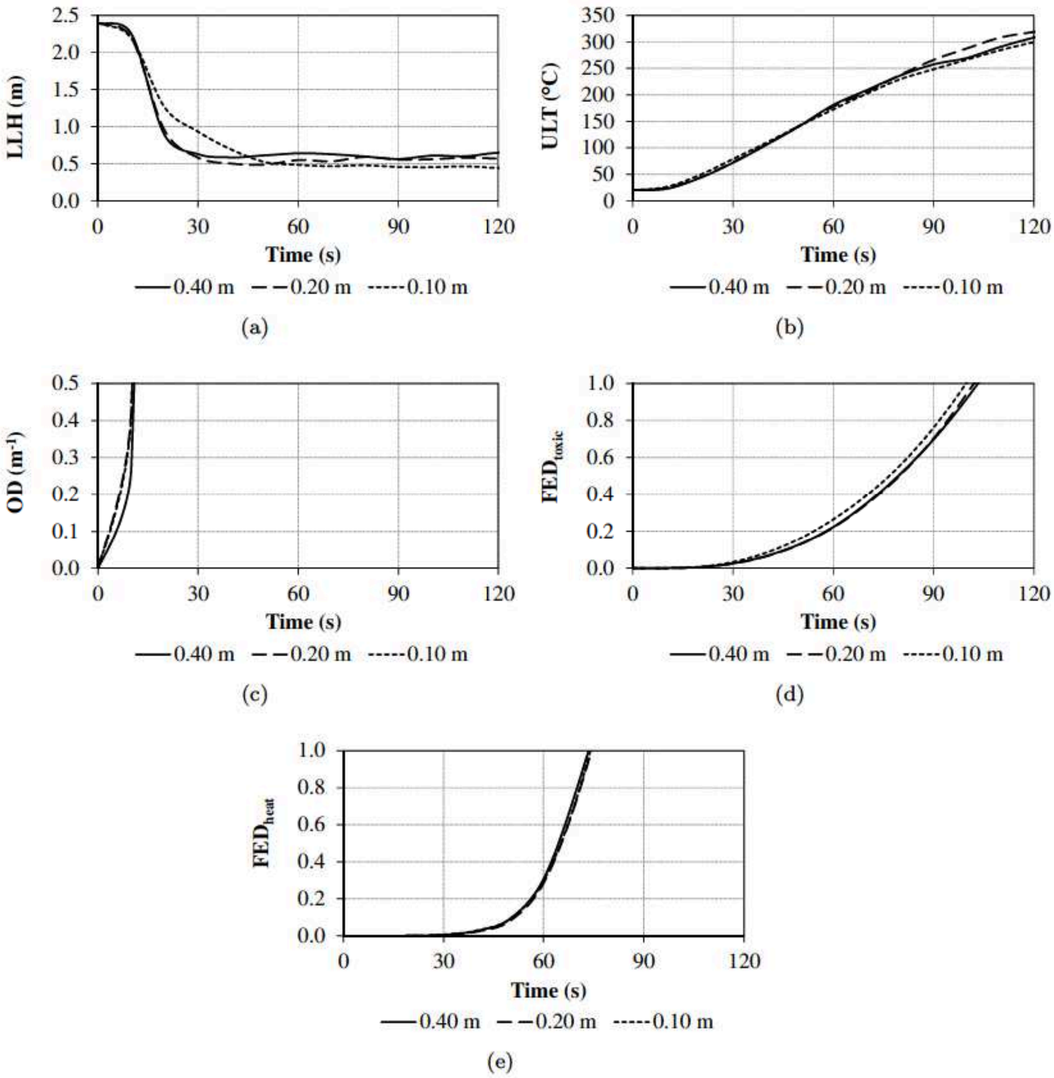


Figure 5.2. Trend of: (a) LLH, (b) ULT, (c) OD, (d) FED_{toxic}, (e) FED_{heat} as a function of grid size.

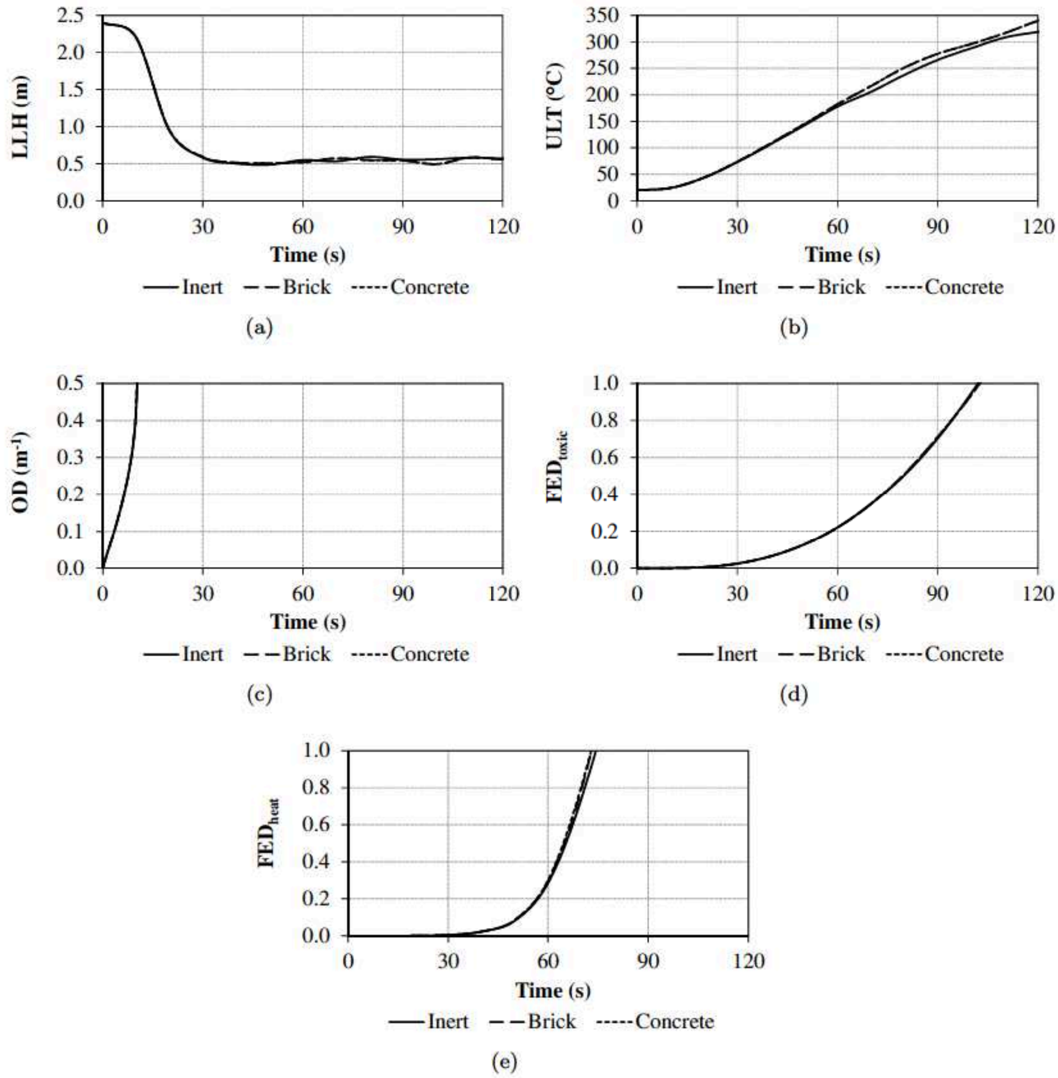


Figure 5.3. Trend of: (a) LLH, (b) ULT, (c) OD, (d) FED_{toxic}, (e) FED_{heat} as a function of bounding surface (walls) characteristics.

5.4 Analysis of tenability criteria variation

The study on mesh refinement and bounding surface characteristics of the geometrical scenario reported in Figure 5.1 allowed defining the setting of FDS model in terms of grid size and bounding surface for the analysis of the tenability criteria variation.

Variation of $ASET$ calculated for each tenability criterion (Table 5.1) as a function of the variation of input data used in FDS to characterise the fire, and specifically the gas phase combustion reaction, was analysed. Because the adopted grid size (0.20 m) does not allow predicting with accuracy pyrolysis reactions, here the pyrolysis model embedded in FDS was not studied. Combustion reaction was therefore prescribed in FDS by specifying a design *t-squared HRR* (described with a maximum HRR_{peak} and the fire-growth coefficient α_{HRR}), the heat of combustion ΔH_c, the fraction of mass fuel converted into carbon monoxide y_{CO} and that into smoke particulate y_{soot}. In FDS all these input data have to be specified by the user and concern the characteristics of the materials involved in the combustion.

The study of the effects that the variation of FDS input data has on the $ASET$, allows identifying the differences between the $ASET$ estimated with the five tenability criteria, and the most important input data required for their calculation. Namely, those fire input data that the user has to collect with accuracy in order to obtain reliable outputs can be identified. This could be helpful, for example, when there are numerous and different combustible materials that can be contained in an enclosure and their characteristics can be difficult to collect. In this case the combustible material can be described in terms of some key input data.

Range of input data variation explored was developed by adopting the scale:

$$input\_data_{max},\ 0.50 \cdot input\_data_{max},\ 0.25 \cdot input\_data_{max},\ 0.125 \cdot input\_data_{max}$$

for all the input data except α_{HRR}, which was varied between an ultrafast to a slow fire growth.

The maximum values $input\_data_{max}$ were identified among the maximum values reported in the available literature, as summarised in Table 5.5. $HRR_{peak_{max}}$ was calculated with Eq. (4.3). Ultrafast, fast, medium and slow *t-squared* fires were adopted in order to model the fire growth stage. The fire-growth coefficient α_{HRR} is then equal to 0.192 kW s^{-2} for ultrafast fires, 0.047 kW s^{-2} for fast fires, 0.012 kW s^{-2} for medium fires and 0.003 kW s^{-2} for slow fires.

Input data were changed individually. Because at the maximum values of the input data correspond the worse conditions in terms of people's safety (here the analysis is focused on this aspect), in order to operate conservatively the input data that were not changed were set fixed at their maximum values. The worst case scenario (all the values of the input data are set to their maximum) is the benchmark scenario (bold values in Table 5.5).

Figures 5.4, 5.5, 5.6, 5.7 and 5.8 show the results obtained by changing the values of HRR_{peak}, α_{HRR}, ΔH_c, y_{CO} and y_{soot}.

In Figure 5.4 it can be seen that HRR_{peak} variation affects ULT, FED_{toxic} and FED_{heat}. If HRR_{peak} is less than $0.25 \cdot HRR_{peak_{max}}$ the energy released in the enclosure

Table 5.5. Set of input data explored in the analysis of tenability criteria variation.

Input data	% of input_data$_{max}$				Source
	100%	50%	25%	12.5%	
HRR_{peak} (kW)	**1400**	700	350	175	Eq. (4.3)
α_{HRR} (kW s^{-2})	**0.192**	0.047	0.012	0.003	(Drysdale, 1999)
ΔH_c (kJ kg^{-1})	**50600**	25300	12650	6325	(Tewarson, 2002)
y_{CO}	**0.450**	0.225	0.112	0.056	(Tewarson, 2002)
y_{soot}	**0.300**	0.150	0.075	0.038	(Tewarson, 2002; Gann et al., 2001)

is not sufficient to achieve the threshold limit for ULT (Figure 5.4(b)). However, the dose of heat absorbed by people increases with time (the exposure is continuous). This causes threshold limit for FED_{heat} to be reached in all cases (see Figure 5.4(e)). Figure 5.4(d) shows that the time taken to reach the threshold limit for FED_{toxic} increases as HRR_{peak} decreases.

As illustrated in Figure 5.5, the variation of α_{HRR} (and hence of *HRR*) influences all the tenability criteria: as the fire-growth coefficient (namely the velocity at which the energy is released by the fire) increases, the time taken to reach the threshold limit decreases.

Figure 5.6 shows the variation of tenability criteria as a function of the variation of the heat of combustion ΔH_c. This input data affects slightly OD and significantly FED_{toxic}: for these two tenability criteria the time to reach the threshold limit decreases as ΔH_c decreases. OD and FED_{toxic} take into account the production of soot and CO, estimated through y_{soot} and y_{CO}. In FDS the burning rate (rate that influence the production of soot and CO) is inversely proportional to ΔH_c (McGrattan et al., 2010a). Hence, the lower ΔH_c is, the higher the burning rate and hence soot and CO production are. A low ΔH_c implied also a low maximum temperature of the upper layer (ULT, Figure 5.6(b)).

The effects of y_{CO} variation on tenability criteria are shown in Figure 5.7. CO yield affects only FED_{toxic}. This tenability criteria, in facts, is computed referring to y_{CO}.

Variation of soot yield y_{soot} (Figure 5.8) affects significantly OD (because the optical density is dependent on the smoke concentration) and FED_{heat} for values above the threshold limit (set equal to 0.3). A high concentration of smoke particulate, in fact, contribute to increase the radiated heat and hence to increase FED_{heat}.

Table 5.6 reports the *ASET* for each case studied. Table 5.7 summarises the findings of the analysis of the *ASET* variation as a function of input data variation. For each tenability criterion whether an input data influence *ASET* estimation is reported.

LLH and ULT are those tenability criteria that depend on less input data (Table 5.7). In fact, only the the fire-growth coefficient α_{HRR} has to be specified in order to calculate *ASET* when using LLH and/or ULT (hence group A criteria, see Table 4.1). On the contrary, if a detailed analysis of *ASET* with OD, FED_{toxic} and/or FED_{heat} (Group B criteria) is carried out, the fire source has to be characterised with more input data.

Moreover, α_{HRR} is the only input data that has a strong effect on all five tenability

Table 5.6. $ASET$(s) obtained from the variation of each input data.

Input data		LLH	ULT	OD	FED_{toxic}	FED_{heat}
HRR_{peak}	$1.000 \cdot HRR_{peak}$	17	68	22	104	67
	$0.500 \cdot HRR_{peak}$	17	68	22	120	67
	$0.250 \cdot HRR_{peak}$	17	–	22	161	86
	$0.125 \cdot HRR_{peak}$	17	–	22	237	160
α_{HRR}	$1.000 \cdot \alpha_{HRR}$	17	68	22	104	67
	$0.500 \cdot \alpha_{HRR}$	26	117	31	154	110
	$0.250 \cdot \alpha_{HRR}$	44	221	46	230	181
	$0.125 \cdot \alpha_{HRR}$	67	416	71	343	298
ΔH_c	$1.000 \cdot \Delta H_c$	17	68	22	104	67
	$0.500 \cdot \Delta H_c$	17	68	20	94	66
	$0.250 \cdot \Delta H_c$	17	68	17	77	66
	$0.125 \cdot \Delta H_c$	17	68	15	64	65
y_{CO}	$1.000 \cdot y_{CO}$	17	68	22	104	67
	$0.500 \cdot y_{CO}$	17	68	22	130	67
	$0.250 \cdot y_{CO}$	17	68	22	181	67
	$0.125 \cdot y_{CO}$	17	68	22	277	67
y_{soot}	$1.000 \cdot y_{soot}$	17	68	22	104	67
	$0.500 \cdot y_{soot}$	17	68	27	104	68
	$0.250 \cdot y_{soot}$	17	68	33	104	68
	$0.125 \cdot y_{soot}$	17	68	43	104	68

Table 5.7. Influence of input data on $ASET$ estimation for each tenability criterion (Y: tenability criterion is dependent on the input data; N: tenability criterion is not dependent on input data).

Input data	LLH	ULT	OD	FED_{toxic}	FED_{heat}
HRR_{peak}	N	N*	N	Y	Y
α_{HRR}	Y	Y	Y	Y	Y
ΔH_c	N	N	Y	Y	N
y_{CO}	N	N	N	Y	N
y_{soot}	N	N	Y	N	N

*If HRR_{peak} is low $ASET$ is not reached. However, if HRR_{peak} allows $ASET$ to be reached, it does not depend on HRR_{peak} value (see Figure 5.4(b)).

criteria. The change from ultrafast to a slow α_{HRR} implies a variation in $ASET$ from 300% to 600% (for the other input data the maximum variation is about 250%). HRR is therefore the most significant variable that has to be specified for $ASET$ calculation. This conclusion is supported by the findings of Babrauskas and Peacock (1992), who report that heat release rate is the most significant factor usable to predict fire hazards.

In order to achieve a simplification of the study of enclosure fires, it seems reasonable to adopt Group A tenability criteria (LLH and ULT), whose calculation requires less input data. Table 5.6 indicates that, among the five tenability criteria, $ASET$ is determined by LLH (refer to the *limiting hazard* concept, Section 4.2). In fact LLH reaches its threshold limit firstly in all cases but one. Furthermore, the $ASET$ calculation with LLH is comparable with that obtained with OD. By comparing Group A and Group B tenability criteria, it can be noticed that in both Groups the $ASET$ is firstly achieved for the criteria that refer to the smoke hazard (LLH and OD). Hence, referring to a pre-flashover fire in an enclosure, the smoke seems to be the first hazard faced by people.

Comparison between LLH and OD shows that LLH allows obtaining $ASET$ estimations with a safety margin which ranges from 1.0 to 2.5 (the value depends on the scenario studied). In one case ($0.125 \cdot \Delta H_c$) the LLH estimation is higher than OD estimation, but the difference is of about 2 s ($\approx 10\%$). This scenario is characterised by the presence of materials with low heat of combustion ($\Delta H_c \approx 6300$ kJ kg^{-1}). However, the majority of materials present in enclosure fires have a ΔH_c greater that this value and, in addition, they have a lower y_{CO} and y_{soot} than those adopted here (which are the maximum values found in the literature)(Tewarson, 2002; Karlsson and Quintiere, 2000). Therefore, this scenario is over-conservative and can be considered as a specific case of analysis.

In conclusion, LLH can be adopted for calculating $ASET$ in a simple way and the sole input data required for characterising the fire source is the HRR (specified through the fire-growth factor α_{HRR}). Moreover, $ASET$ estimation with LLH is comparable with that obtained by using more specific tenability criteria (OD). These results suggest that LLH and HRR are key elements usable to develop conceptual models (see Section 1.1) for estimating the standard times in PASS. This topic is addressed in Chapter 6.

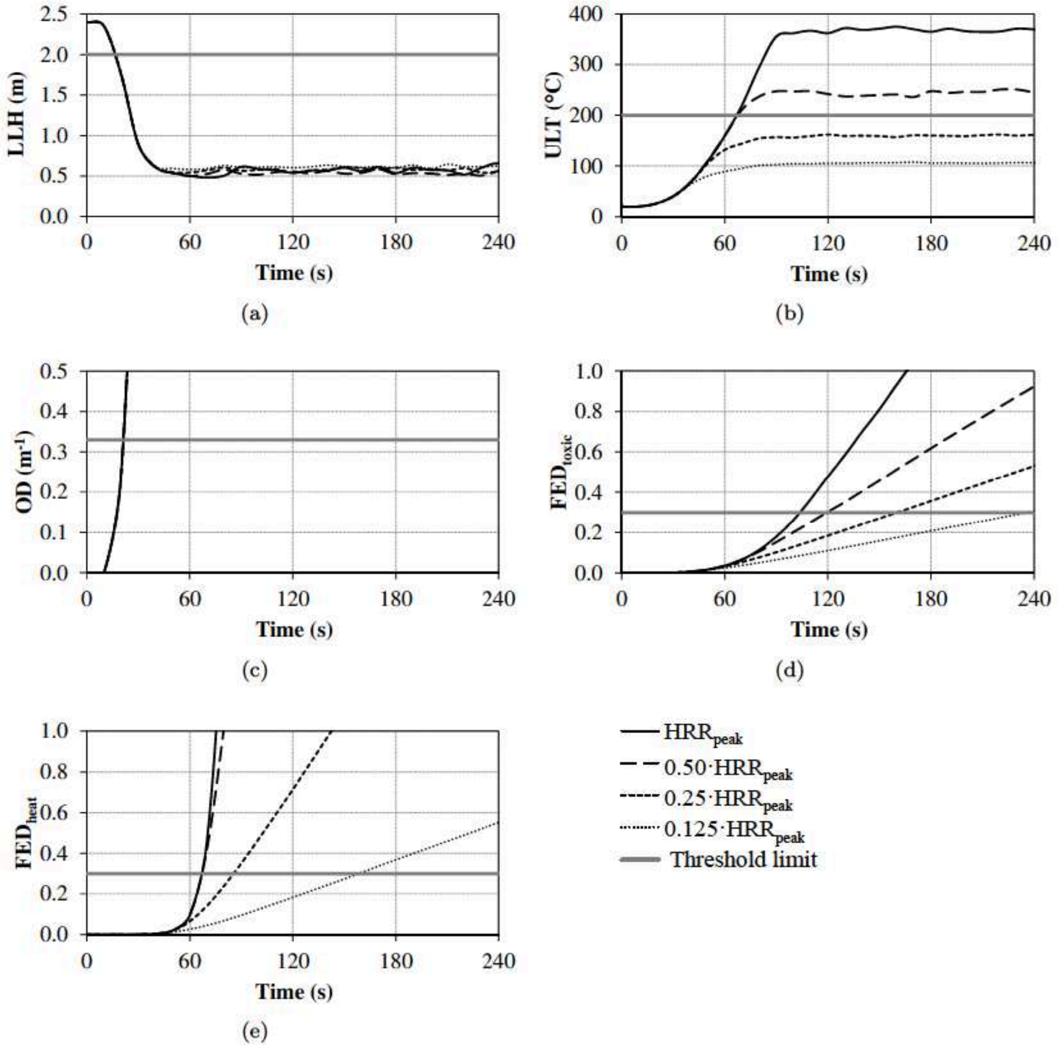


Figure 5.4. Trend of: (a) LLH, (b) ULT, (c) OD, (d) FED_{toxic}, (e) FED_{heat} as a function of the variation of HRR_{peak}.

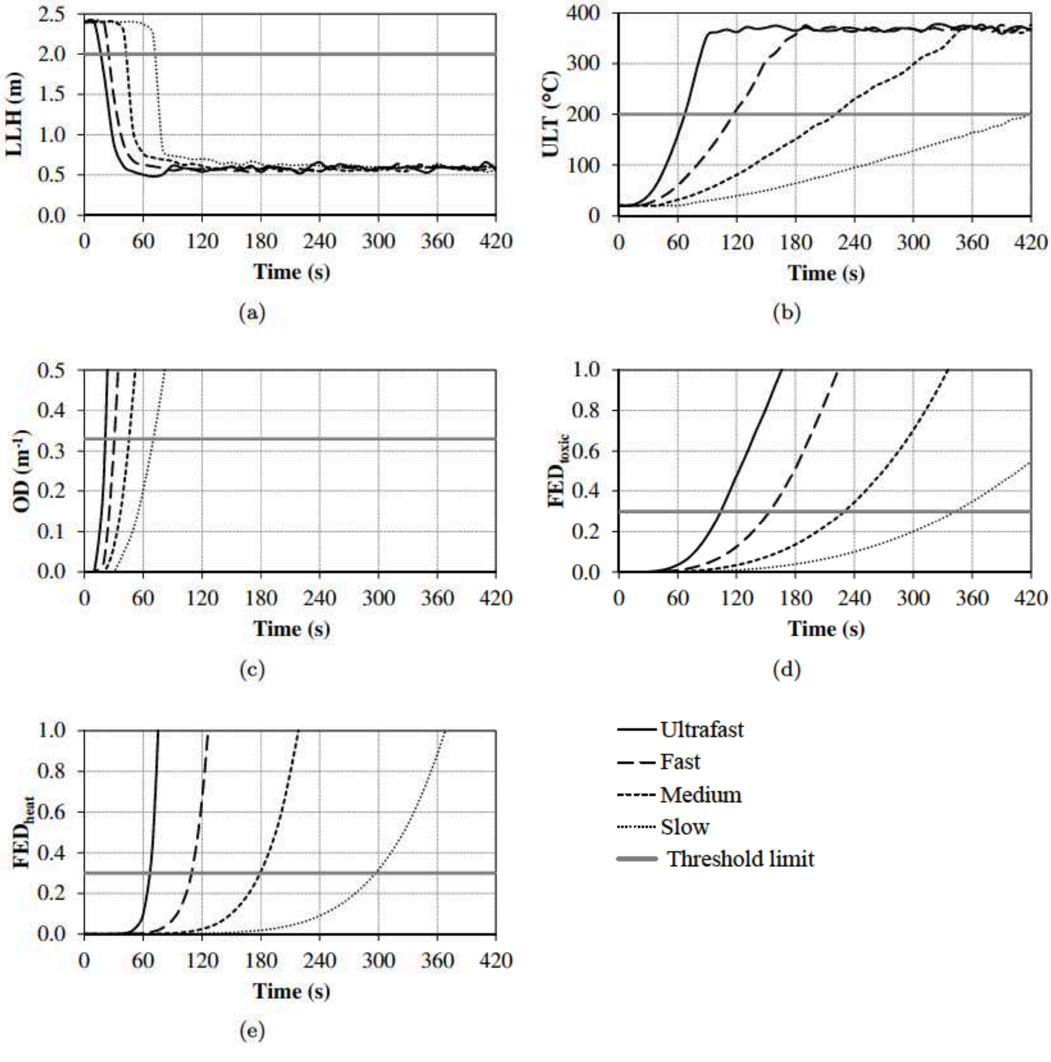


Figure 5.5. Trend of: (a) LLH, (b) ULT, (c) OD, (d) FED_{toxic}, (e) FED_{heat} as a function of the variation of α_{HRR}.

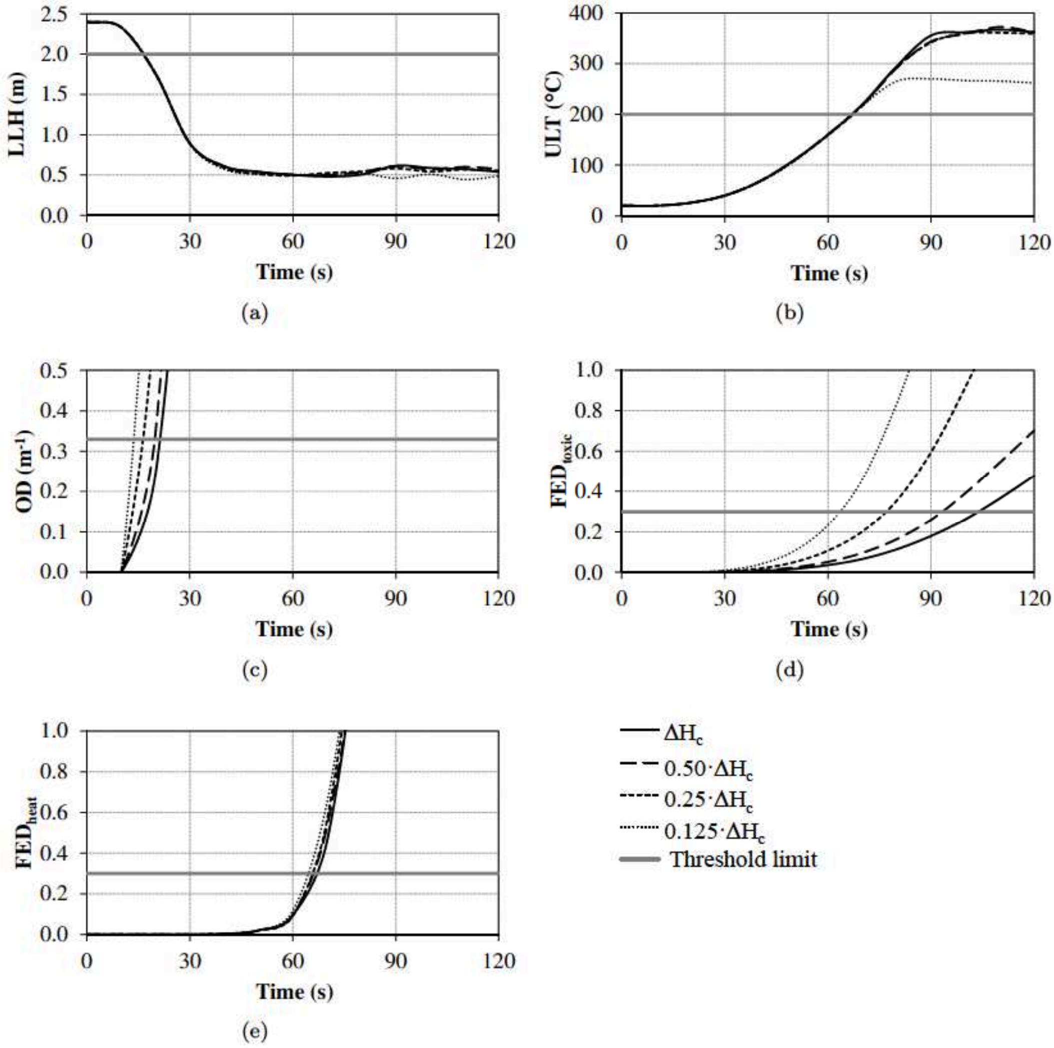


Figure 5.6. Trend of: (a) LLH, (b) ULT, (c) OD, (d) FED_{toxic}, (e) FED_{heat} as a function of the variation of ΔH_c.

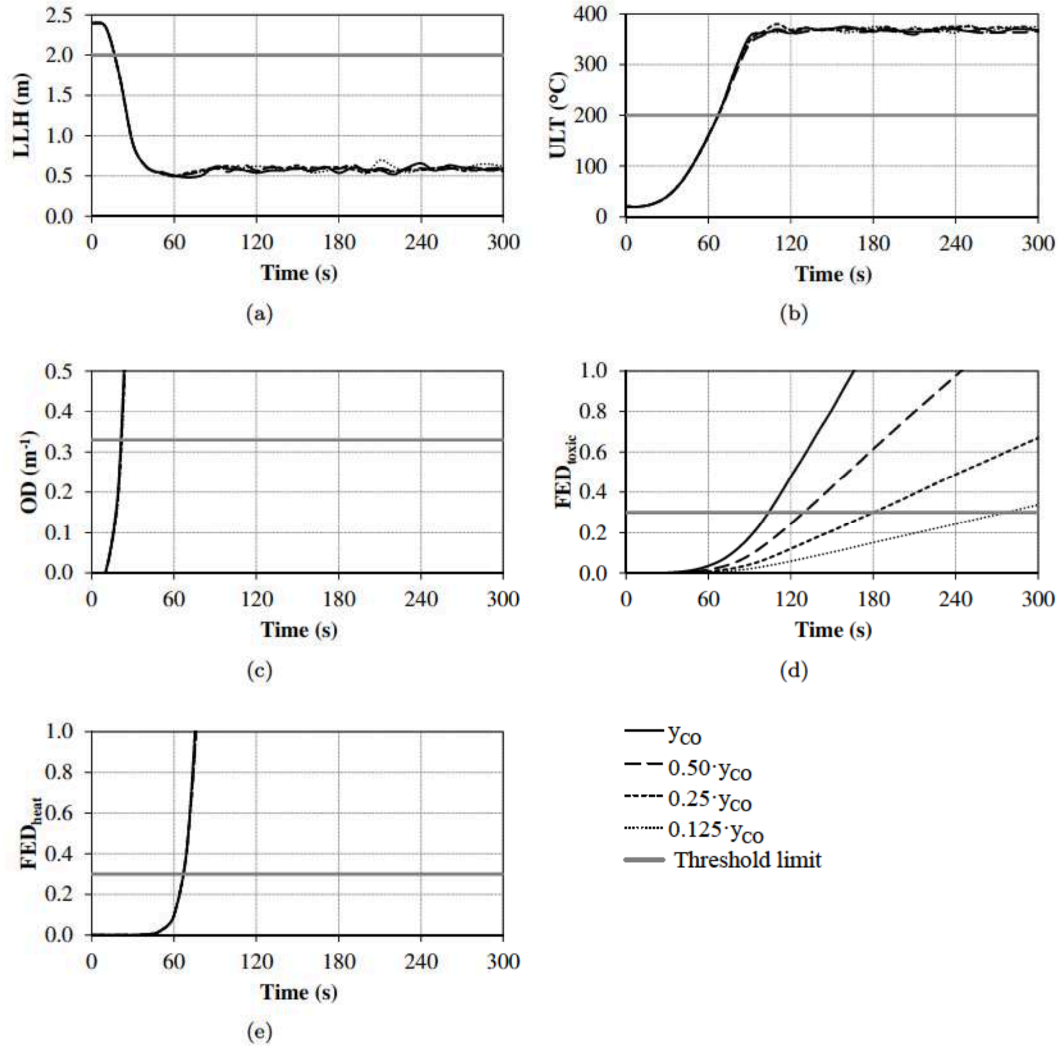


Figure 5.7. Trend of: (a) LLH, (b) ULT, (c) OD, (d) FED_{toxic}, (e) FED_{heat} as a function of the variation of y_{CO}.

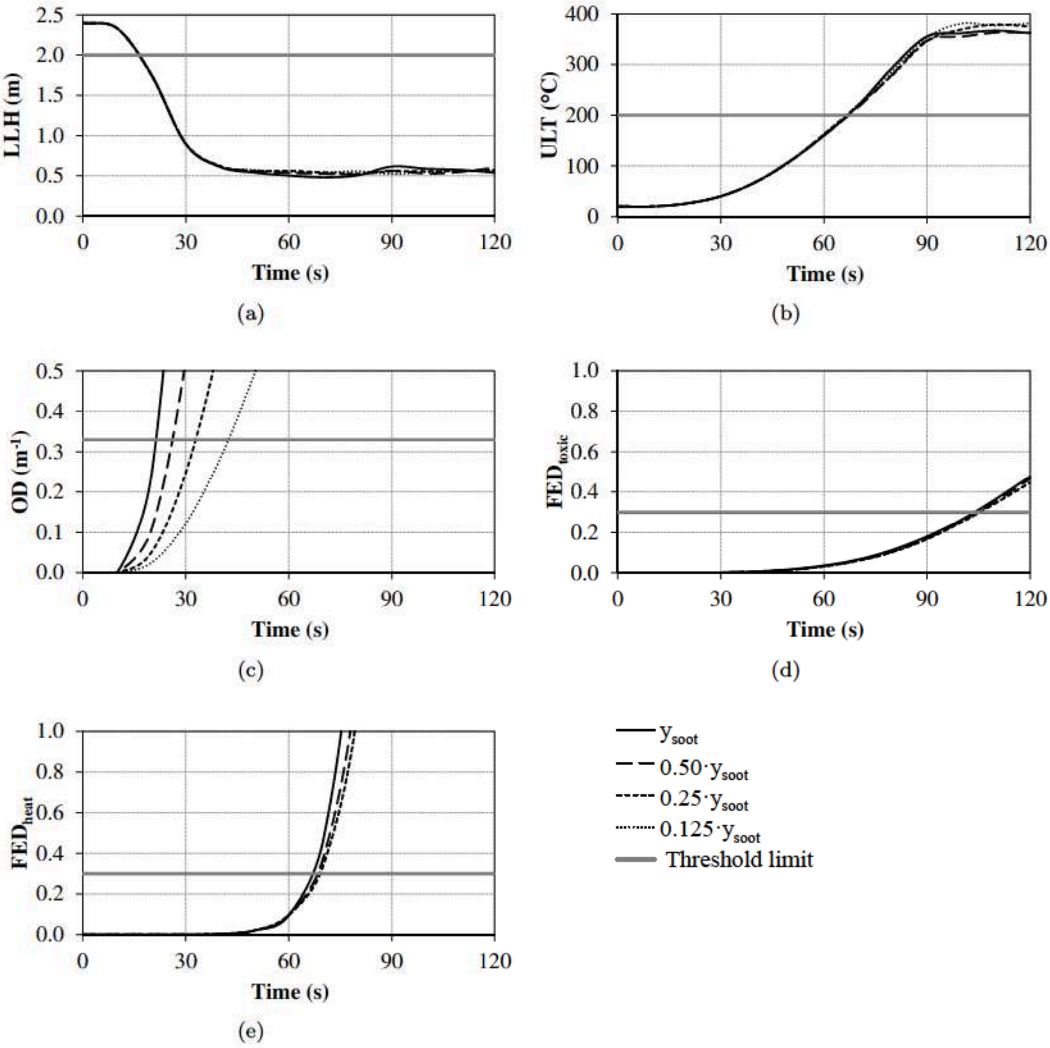


Figure 5.8. Trend of: (a) LLH, (b) ULT, (c) OD, (d) FED_{toxic}, (e) FED_{heat} as a function of the variation of y_{soot}.

6
Conceptual models

In Chapter 2 the *exodus-borders* conceptual model adopted in PASS for assessing the egress system performance was presented. In this conceptual model evacuation is conceived as the movement of people from the hot zone to safe or refuge zones. During their movement people pass through warm and/or temporary-cold zones, which are separated by barriers that offer different protection ratings against fire hazards. In order to succeed in evacuation, the egress system characteristics should allow people to move away from each zone within an established standard time. At each zone is then associated a standard time and these times are used in PASS in order to establish a reference level for the egress system performance assessment. Since standard times are fundamental for the PASS analysis, the need to set their values for each zone emerges.

Four times have then to be estimated (Figure 6.1), depending on the zone analysed:

1. ET_{GL}: maximum standard time for assessing the General Leaving of the system (GLs). This time is established for the whole egress system in the first level of analysis;
2. $T_{TC-ZONE}$: standard time for assessing whether people can escape from the temporary-cold zone (MA formulae, second level of analysis);
3. T_{w-zone}: standard time for assessing whether people can escape from the warm zone (MA formulae, second level of analysis);
4. T_{h-zone}: standard time for assessing if people can escape from the hot zone (PE formulae, third level of analysis).

PASS analysis if performed with a multilevel approach, from global to local, and then the standard times have to be defined accordingly. This means that time ET_{GL}, for example, has to be defined from global characteristics of the egress system while, on the contrary, T_{h-zone} has to be defined referring to specific aspects of the hot zone (height and surface of the zone, characteristics of combustible material present). This objective can be achieved once a conceptual model for estimating the standard times has been established.

Given this, two conceptual models for estimating the standard times in the hot and warm zones (T_{h-zone} and T_{w-zone}) were developed. Standard times in the temporary-cold zone ($T_{TC-ZONE}$) and for the global egress system (ET_{GL}) were established from

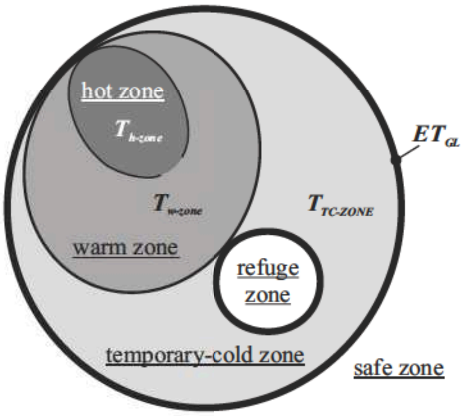


Figure 6.1. Standard times defined in PASS and corresponding zones.

general considerations on fire risk analysis with respect to people's safety, and referring to macroscopic characteristics of the egress system.

In Chapter 5 it was illustrated that, for rapid analyses of pre-flashover fires, the achievement of untenable conditions can be assessed by using the Lower Layer Height (LLH) tenability criterion. LLH is estimated with few input data (the fire-growth coefficient α_{HRR}) and the results obtained agree with those obtained from the other tenability criteria. Therefore, the results suggest that a simplified conceptual model for estimating PASS standard times can be developed by using the two zone approach, LLH as tenability criterion, and by characterising the hazards source (the fire) in terms of α_{HRR}.

This Chapter illustrates the general considerations adopted to establish ET_{GL} and $T_{TC-ZONE}$, and the framework conceived in order to estimate the reference times T_{h-zone} and T_{w-zone}. In Chapters 7 and 8 it is described how adopting this framework, simple tools for estimating the standard times T_{h-zone} and T_{w-zone} were developed.

6.1 Standard time ET_{GL}

Standard time ET_{GL} is included in the macroscopic analysis of PASS for assessing if people can safely leave the considered area of the building, and reach the safe or refuge zones before untenable conditions are achieved. The assessment is performed referring to elements which consider global characteristics of the egress system, such as its configuration (layout) and occupant characteristics. No additional details on the egress system are required. Therefore, accordingly with this macroscopic analysis, the standard time for the global leaving assessment has to be established referring to global characteristics of the building, or area of the building, analysed.

This time is established referring to the building risk profile, approach adopted also in FSRA series (2012).

Building risk profile can be determined referring to occupant characteristics and hazardous contents (BS 9999 (2008); FSRA series (2012)). Accordingly, occupants with standard mobility and familiarity with the building layout, low people densities, absence of hazardous contents are factors that determine a low risk profile. The building risk profile increases when people mobility decreases, people are unfamiliar, a high number of people occupy the building, and hazardous materials are present. Therefore, it is reasonable to conclude that in buildings, or part of a building, with a lower risk profile the available time for people to escape (say ET_{GL}) is greater than in buildings with a higher risk profile. According to these criteria, a set of risk classes can be developed for different combinations of people characteristics (expressed in terms of people mobility, density, alertness, familiarity with the building) and presence and characteristics of combustible contents within the analysed area (quantified by adopting the zone hazard level ZHL, see Chapter 2).

The flowchart reported in Figure 6.2 represents the logical framework developed in order to assign the building risk classes, and hence ET_{GL}. The considered factors are people characteristics (in terms of mobility, density and familiarity) and the hazardous contents in the building (ZHL).

As shown, the worse classes are assigned to people that are more vulnerable and, as second criterion, to areas with higher hazard levels ZHL. People with reduced or assisted mobility (residential homes for elderly, hospitals), or asleep (sleeping accommodation) are supposed to be the more vulnerable (Boyce et al., 1999; Gwynne et al., 2009a; Charters and Crowder, 2012). Therefore, buildings that accommodate these people's categories are assigned to the worse risk class, regardless of its hazardous contents. If people vulnerability decreases, more importance is given to the building hazardous contents. Hence, when people vulnerability is low, hazard is the most influencing factor for the risk class assignment.

Five building risk classes are adopted, which range from the lower risk class (I) to the higher risk class (V). At each risk class a standard egress time ET_{GL} is assigned. The minimum ET_{GL}, assigned to class V, is the time proposed in FSRA series (2012) for high risk buildings, set equal to 120 s. The maximum ET_{GL}, assigned to class I, is estimated by considering the ratio between the maximum and minimum travel distances for different buildings reported in FSRA series (2012). Due to the fact that this ratio is about 2.5, the maximum ET_{GL} is set equal to $120\,\mathrm{s} \cdot 2.5 = 300\,\mathrm{s}$ (this time is also adopted in the Italian fire regulation (Ministero dell'Interno, 1998) for low risk premises). At the building risk classes II, III, and IV, a ET_{GL} equal to 240, 180 and 150 s is assigned.

6.2 Standard time $T_{TC-ZONE}$

Standard time for the temporary-cold zone $T_{TC-ZONE}$ is included in PASS for assessing the egress system performance in the temporary-cold zone. By definition, the temporary-cold zone is the area adjacent to a warm zone from which it is separated by protection barriers that guarantee a protection rating against fire hazards for a specified period of time. If a temporary-cold zone is identified during the zoning process, for example when a fire compartment is present within a building, it is assumed that the designed protection rating of the barrier is maintained during a fire.

Therefore, $T_{TC-ZONE}$ is strictly connected with the designed protection rating of

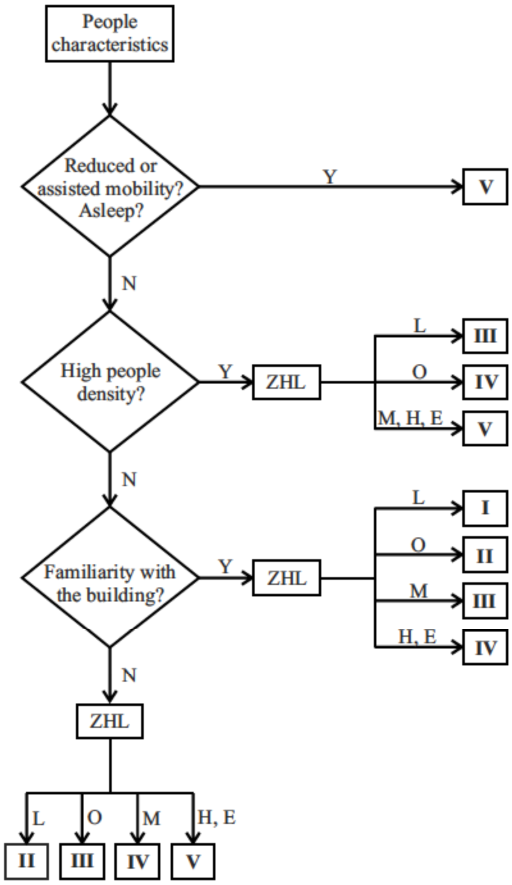


Figure 6.2. Criteria adopted in order to develop the building risk classes for setting ET_{GL} in PASS.

the barrier, and no conceptual models for estimating this time are adopted in PASS. Standards require a minimum fire protection rating equal to 15 minutes (see for example BS 9999 (2008); Coté (2000)). Therefore, people are not threatened by fire hazards if they move away from the temporary-cold zone in 15 minutes. In order to conservatively assess people's safety, and accordingly with the maximum standard time ET_{GL}, the standard time $T_{TC-ZONE}$ to move away from the temporary-cold zone is set equal to 300 s, namely one third of the minimum resistance time required for fire barriers.

6.3 Standard time T_{h-zone}: Cell Smoke Filling conceptual model

Standard time T_{h-zone} is included in the formulae adopted to test the primary escape in the hot zone. Hot zone is identified as the area where the fire hazards (smoke, heat, toxic gases) are generated. Referring to a building, the hot zone can be identified with the fire origin room. Performance in this zone is checked by evaluating if the characteristics of the egress system (layout, number and accessibility of gaps, presence of obstacles) allow people to escape within time T_{h-zone}. This time indirectly refers to the time taken to achieve untenable conditions.

The qualitative description of the fire dynamics and tenability criteria analysis results, show that the two zone approximation for fire dynamics can be used for a rapid estimation of the time taken to reach untenable conditions. Furthermore, α_{HRR} and LLH are the key elements for the engineering characterisation of the hazards source and smoke filling process. Given this, the Cell Smoke Filling (CSF) conceptual model for describing this process and quantifying T_{h-zone} was developed (Figure 6.3).

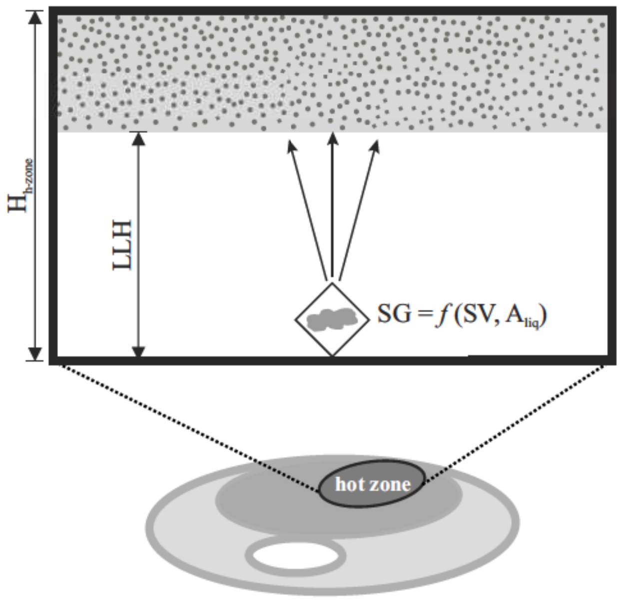


Figure 6.3. Cell Smoke Filling (CSF) conceptual model adopted to quantify T_{h-zone}.

The CSF conceptual model represents the process illustrated during the qualitative description of fire dynamics, but adopts some terms and key elements introduced in PASS to tackle in a simple way T_{h-zone} estimation.

In the hot zone the combustible materials are described as an unique source of fire hazards, the Smoke Generator (SG). Because we refer to the pre-flashover stage of an enclosure fire and from the results of Chapter 5, the principal hazard considered is smoke.

SG is characterised in terms of mass flow rates of smoke production, Smoke Velocity classes (SV), and surface of combustible materials exposed to air that can potentially burn. The SV class considers that slow fires release smoke with a slower mass flow rate than fast fires, and it can be represented in engineering terms by the fire-growth coefficient α_{HRR} (see Chapter 5).

The smoke generator surface takes into account the potential threat to people's safety due to flame spread across horizontal surfaces (like the floor). According to Drysdale (1999) surface flame spread velocity for combustible solids is of about 0.004 m s^{-1}, while the worst walking speed for disabled people is of about 0.2 m s^{-1}(Shi et al., 2009; ISO 16738, 2007; Boyce et al., 1999). Since people are expected to escape before they are overcome by fire flames, the surface flame spread for combustible horizontal solids does not constitute an hazard for people during the initial stages of a fire. For liquid combustibles, on the contrary, the maximum surface flame spread velocity is of about 1 m s^{-1}(Quintiere, 2002), higher than the worst people walking speed. Therefore, if liquids in contact with air (unconfined) are present and extend across the floor, they are a source of potential hazard for people's safety. The surface extension of liquid combustibles in contact with air (A_{liq}) is then included in the CSF conceptual model.

As the smoke generator releases smoke, hot zone stars to be filled from the ceiling. T_{h-zone} is calculated only for the hot zone and, working on the safe side, it is assumed that all the smoke produced is released inside the hot zone, and does not spread to adjacent zones or through windows. Hence, no openings are considered. The time taken to reach untenable conditions in the hot zone can then be quantified with the time taken by smoke to reach the threshold limit established for LLH (2 m). Since LLH depends only on the *HRR*, the smoke source can be described by specifying a fire-growth coefficient α_{HRR} as a function of the characteristics of the combustible contents of the enclosure.

Therefore, the key elements adopted by Cell Smoke Filling conceptual model for estimating T_{h-zone} are the characteristics of the combustible materials in the enclosure (α_{HRR} and, for liquids, A_{liq}) and the geometrical features of the enclosure (hot zone floor area, A_{h-zone}, and height, H_{h-zone}).

6.4 Standard time T_{w-zone}: Equivalent Smoke Generator conceptual model

Standard time T_{w-zone} is included in the tools adopted to check the egress system performance in the warm zone. In this zone fires are not present, but the fire hazards spread from the hot zone through gaps, if any. T_{w-zone} is adopted to establish the reference level of performance in the warm zone, namely to assess whether people can manage evacuation of the warm zone within T_{w-zone}.

If adopting the LLH tenability criterion and a two zone approach, T_{w-zone} is determined by estimating the time taken by smoke to fill the warm zone from the ceiling to an established height equal to LLH. The upper volume of the warm zone to be filled, V_{fill}, is equal to the surface of the warm zone by the difference between warm zone height H_{w-zone} and LLH. Therefore, if supposing the existence of a hot upper layer of smoke in the warm zone, T_{w-zone} is reached when a hot smoke volume equal to V_{fill} flows from the hot to the warm zone.

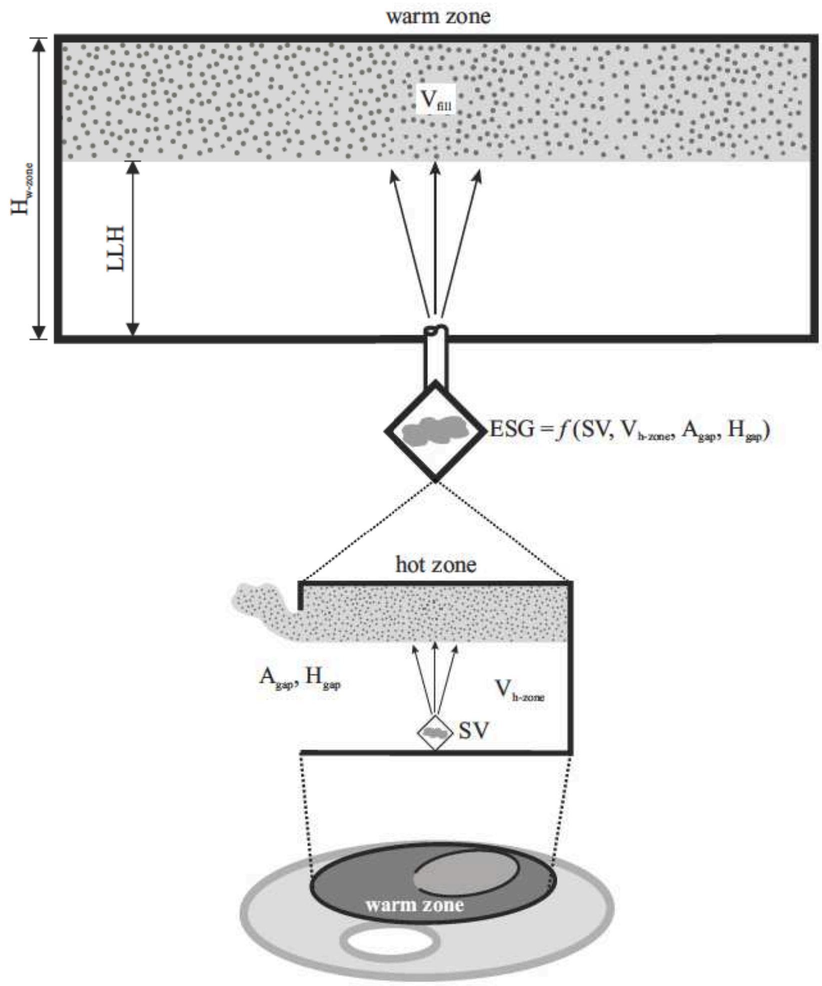


Figure 6.4. Equivalent Smoke Generator (ESG) conceptual model adopted to quantify T_{w-zone}.

The volume that flows through the gaps between hot and warm zone depends on the characteristics of the gaps (height and width) and on the density of the hot smoke (Emmons, 2002). The latter depends on the temperature of the smoke upper layer inside the hot zone and, considering the results on the variation of the tenability criteria (Chapter 5), it is influenced by α_{HRR}. Referring to the Cell Smoke Filling conceptual model, α_{HRR} can be represented in terms of Smoke Velocity classes SV. As shown in Chapter 7, the upper layer temperature depends also on the hot zone volume V_{h-zone}. In fact, given a α_{HRR}, the greater the hot zone volume is, the lower its ambient temperature is (Mowrer, 1999).

Given this, the Equivalent Smoke Generator (ESG) conceptual model for quantifying T_{w-zone} was developed (Figure 6.4).

Since fire hazards (smoke) are generated in the hot zone and they spread into the warm zone, the hot zone is considered as a source of smoke connected with the warm zone through one or more gaps. In the conceptual model the smoke source is represented with the Equivalent Smoke Generator, ESG, and depends on SV, V_{h-zone} and characteristics of the gaps between hot and warm zone. ESG introduces a volumetric flow rate of hot smoke into the warm zone, and causes this zone to be filled with smoke from the ceiling to the LLH (two zone approach). T_{w-zone} is defined as the time taken to fill a warm zone volume equal to V_{fill}.

Therefore, the key elements adopted by the ESG conceptual model are SV (or alternatively α_{HRR}), V_{h-zone}, characteristics of gaps between hot and warm zone and a threshold value for V_{fill}. The necessity of representing these elements in engineering terms for estimating T_{w-zone} then emerges. This aspect is addressed in Chapter 7.

7

Engineering methods for estimating PASS standard times

In this Chapter the Cell Smoke Filling and Equivalent Smoke Generator conceptual models developed in Chapter 6 are represented in engineering terms. This will allow developing simple tools for a rapid estimation of PASS standard times, as presented in Chapter 8.

7.1 Estimation of standard time T_{h-zone}

The Cell Smoke Filling (CSF) conceptual model attempts to represent in a schematic form the process of smoke filling in enclosure fires, as described in Section 6.3. In CSF conceptual model the hazards source is represented by the Smoke Generator (SG), described in terms of α_{HRR} and, for flammable liquids, also with surface area A_{liq}.

The tenability criteria analysis showed that, when referring to pre-flashover fires, the impact of fire hazards on people can be quantified in a simple way by adopting the Lower Layer Height as tenability criterion (Chapter 5). LLH, as the analysis demonstrated, is a tenability criterion that depends only on the fire-growth coefficient α_{HRR} and, reasonably, on the room dimensions. Therefore, a method that allows LLH estimation as a function of α_{HRR} and room dimensions has to be developed.

Karlsson and Quintiere (2000) proposed a simple method for calculating the smoke-filling time in a single enclosure based on a mass and energy conservation. The method can be used when:

- the formation of a hot upper layer and a smoke-free lower layer is supposed;
- the upper layer density is constant during the smoke-filling process;
- the heat exchange through the boundaries is negligible;
- the heat release rate (*HRR*) of the fire is low with respect to the enclosure volume.

These conditions apply well to the conceptual model, because it adopts a two zone approximation for pre-flashover fires, namely when the *HRR* produced is low with respect to the enclosure volume and the heat exchange through boundaries is low. Furthermore no mass exchange is supposes to occur, as the door of the enclosure during the initial stage of the fire is hypothesised to be closed. The method of Karlsson and Quintiere (2000) can then be rewritten referring to the Cell Smoke Filling conceptual model (Figure 7.1).

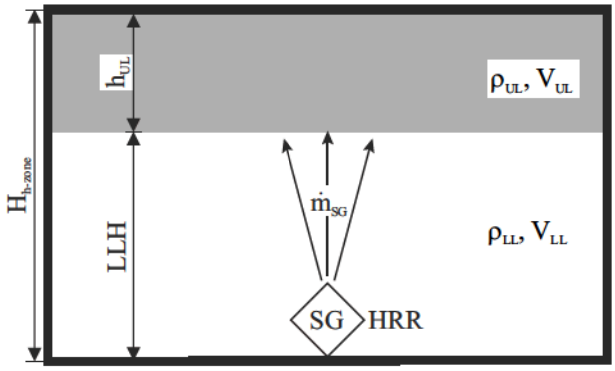


Figure 7.1. Two-zone scheme in the Cell Smoke Filling (CSF) conceptual model.

The conservation of mass is calculated for the upper volume of smoke, characterised by uniform gas density ρ_{UL} (kg m^{-3}) and temperature T_{UL} (K). The mass and energy transfer from the smoke generator to the upper layer is caused by the mass plume rate, here described in terms of mass smoke generator rate $\dot{m}_{SG}$ (kg s^{-1}). The conservation of mass applied to the upper layer is then:

$$\frac{d}{dt}\left(\rho_{UL}V_{UL}\right) - \dot{m}_{SG} = 0 \tag{7.1}$$

where

$$\dot{m}_{SG} = 0.21\left(\frac{\rho_{LL}^2 g}{c_p T_{LL}}\right) HRR^{1/3} \cdot LLH^{5/3} \tag{7.2}$$

The plume mass flow in Eq. (7.2) was proposed by Zukoski et al. (1980). ρ_{LL} is the uniform density of the lower volume (kg m^{-3}), T_{LL} is the temperature of the lower layer (K), c_p the specific heat (kJ kg^{-1} K^{-1}), g is the gravitational constant (m s^{-2}), HRR is the heat released by the fire (kW).

Assuming a constant average ρ_{UL}, ρ_{LL}, T_{UL}, T_{LL} and considering that $V_{UL} = A_{h-zone}\, h_{UL}$, the first term of Eq. (7.1) can be written as:

$$\frac{dh_{UL}}{dt}\rho_{UL}A_{h-zone} = -\frac{dLLH}{dt}\rho_{UL}A_{h-zone} \tag{7.3}$$

The mass balance for the upper layer is then:

$$\frac{dLLH}{dt}\rho_{UL}A_{h-zone} + 0.21\left(\frac{\rho_{LL}^2 g}{c_p T_{LL}}\right) HRR^{1/3} \cdot LLH^{5/3} = 0 \tag{7.4}$$

For a *t-squared* fire with $HRR = \alpha_{HRR} t^2$, Eq. (7.4) can be integrated from time 0 to t. This yields:

$$LLH = \left[\frac{0.21}{\rho_{UL}} \left(\frac{\rho_{LL}^2 g}{c_p T_{LL}} \right)^{1/3} \frac{2}{5} \frac{\alpha_{HRR}^{1/3} t^{5/3}}{A_{h-zone}} + H_{h-zone}^{-2/3} \right]^{-3/2} \tag{7.5}$$

Considering that for the initial stages of a fire T_{LL} can be set equal to 293 K and c_p equal to 1.0 kJ kg^{-1} K^{-1}, Eq. (7.5) can be solved once ρ_{UL} is determined. The energy balance for the upper volume allows determining ρ_{UL}. For the system adopted in the CSF conceptual model, the energy balance is:

$$\frac{d}{dt} \left(\rho_{UL} V_{UL} \right) c_p \left(T_{UL} - T_{LL} \right) = HRR \tag{7.6}$$

that, substituting HRR and V_{UL} and integrating from time 0 to t, can be written as:

$$\left(H_{h-zone} - LLH \right) \rho_{UL} A_{h-zone} c_p \left(T_{UL} - T_{LL} \right) = \frac{\alpha_{HRR} t^3}{3} \tag{7.7}$$

From the idel gas low $P\, M_w = \rho\, R T$, hence, considering air as an ideal gas with molecular weight M_w of 0.0289 kg mol^{-1}, atmospheric pressure P = 101325 Pa, $T_{UL} = \frac{353}{\rho_{UL}}$. Substituting in Eq. (7.6) it is found:

$$\rho_{UL} = \rho_{LL} \left[\frac{\alpha_{HRR}\, t^3}{3 \left(H_{h-zone} - LLH \right) \rho_{UL} A_{h-zone} c_p 353} \right] \tag{7.8}$$

Combining Eqs. (7.8) and (7.5), the time taken to reach the LLH threshold limit t_{LLH} (in seconds) can be estimated with the following equation:

$$t_{LLH} = \left[\frac{5}{2} \left(LLH^{-2/3} - H_{h-zone}^{-2/3} \right) \left(1 - \frac{\alpha_{HRR}\, t_{LLH}^3}{3 \left(H_{h-zone} - LLH \right) A_{h-zone} c_p 353} \right) \right]^{3/5} \cdot \left[\frac{A_{h-zone}\, \alpha_{HRR}^{-1/3} \rho_{LL}}{0.21 \left(\frac{\rho_{LL}^2 g}{c_p T_{LL}} \right)^{1/3}} \right]^{3/5} \tag{7.9}$$

t_{LLH} is then calculated by iteration of Eq. 7.9 once the geometrical characteristics of the hot zone (A_{h-zone} and H_{h-zone}), the characteristics of the combustible materials (α_{HRR}), and the threshold limit for LLH are set.

A preliminary comparison between the prediction of Eq. 7.9 and numerical results from FDS demonstrated that the Eq. 7.9 allows obtaining estimation of $ASET$ in good agreement with FDS (Tosolini et al., 2012a). However, in order to apply Eq. 7.9 for estimating t_{LLH} its range of validity has to be established.

Comparisons between simplified equations and experimental data were performed in several works. Mowrer (1999), for example, compared the equation derived by Karlsson and Quintiere (2000) and adopted in this work (Eq. 7.9) with experimental data of two different scenarios (5.62 × 5.62 × 6.15 m room with steady fire size of 186 kW and 720 m^2 by 26.3 m height room with steady fire of 1.3 MW). The results obtained showed a good agreement between calculated results (Eq. 7.9) and experimental data. Nonetheless, Mowrer did not report its range of validity in terms of maximum dimensions of the room. Delichatsios (2004) proposed a closed form approximate equation for calculating the smoke filling in enclosures by including also the heat exchange with walls. In that study, Delichatsios compared the predicted results with numerical results by using a two-zone model (CFAST). His results showed that for large enclosures (volumes greater than 5000 m^3) the critical tenability conditions occur because the upper layer temperature (ULT) reaches its threshold limit before the lower layer height (LLH) descends to its limit.

From the results of these studies two conclusions can be drawn:

a) the adopted analytical equation can predict the smoke filling with good agreement with experimental data (Mowrer, 1999), although its range of validity has not been fully investigated;

b) a limit of validity for the use of LLH as unique tenability criterion exists (Delichatsios, 2004).

Given this, in the next Section the study of the range of validity of Eq. (7.9), the analysis of its trend, margin of safety and sensitivity are performed in order to establish the scenarios in which it can be applied with good confidence (Tosolini et al., 2012b). The comparison is made with numerical data obtained by FDS. The adopted threshold limit for LLH is 2 m (see Table 5.1).

7.2 Analysis of t_{LLH}

The analysis of t_{LLH} calculated with Eq. (7.9) comprised 4 steps:

1. Study of the range of validity of Eq. (7.9) as a function of hot zone volume (V_{h-zone});
2. Study of the trend of Eq. (7.9) as a function of α_{HRR}, H_{h-zone}, and A_{h-zone};
3. Study of the safety margin obtained with Eq. (7.9);
4. Sensitivity analysis.

All the analyses were carried out with FDS (see Section 5.1). As demonstrated in Matheislová et al. (2010), FDS allows obtaining good agreement with experimental data of smoke filling predictions in compartment fires.

7.2.1 Range of validity for t_{LLH}

In order to establish the range of validity of Eq. (7.9) different simulations were performed by changing the volume of the enclosure. The results obtained for the greatest volume checked are summarised in Table 7.1. The *HRR* adopted was a *t-squared* fire and results

Table 7.1. Results obtained from the study of the range of validity for t_{LLH} predictions (H_{h-zone} = 12 m). Ultrafast *t-squared* fire.

Hot zone volume V_{h-zone} (m^3)	t_{LLH} (s) Eq. 7.9	FDS (LLH)	FDS (ULT)
4800	208	280	280
6000	228	316	308

are related to an ultrafast fire (which demonstrated to be the worst case, α_{HRR} = 0.192 kW s^{-2}).

Eq. (7.9) allows obtaining conservative estimations of t_{LLH} for hot zone volumes V_{h-zone} up to 6000 m^3. However, LLH can be adopted as unique tenability criterion for hot zone volumes lower or equal than 4800 m^3. For V_{h-zone} greater than 4800 m^3, in fact, the Upper Layer Temperature reaches its threshold limit before LLH drops to 2.0 m. This result agrees with the findings of Delichatsios (2004) who indicates that the volume at which ULT is reached before LLH is 5000 m^3. Therefore, Eq. (7.9) can be used for obtaining reliable results with V_{h-zone} up to 4800 m^3.

7.2.2 Trend of t_{LLH} as a function of α_{HRR}, H_{h-zone}, and A_{h-zone}

t_{LLH} estimated with Eq. (7.9) depends on the values of α_{HRR}, H_{h-zone}, and A_{h-zone}. An analysis within the range of validity of Eq. (7.9) for t_{LLH} trends as a function of variation of these input data was then performed and compared with FDS results. α_{HRR} was varied from slow to ultrafast *t-squared* fires, H_{h-zone} was varied from 3 to 12 m at constant A_{h-zone} = 25 m^2, and A_{h-zone} was varied from 25 to 400 m^2 at constant H_{h-zone} = 3 m. The floor shape was square.

t_{LLH} trend as a function of H_{h-zone} indicates that Eq. (7.9) underpredicts t_{LLH} as compared to FDS results (Figure 7.2(a)). Furthermore, as the hot zone height H_{h-zone} grows (hence the hot zone geometrical shape is comparable with a shaft), t_{LLH} calculated with Eq. (7.9) tends to stabilise to a constant value.

Analysis of the variation in percentage terms of t_{LLH} as a function of the variation of H_{h-zone} shows that for Eq. (7.9) there are no differences between the four α_{HRR} (Figure 7.2(b)) and confirms that t_{LLH} variation decreases as H_{h-zone} increases. Trend from FDS numerical results show a different behaviour, especially at higher H_{h-zone}. However, in the entire range checked, Eq. (7.9) predicts t_{LLH} with a good margin of safety.

t_{LLH} trend as a function of A_{h-zone} shows that, as the floor area of the hot zone increases (with constant height H_{h-zone} = 3 m), Eq. (7.9) tends to overpredict t_{LLH} if compared to FDS results (Figure 7.3(a)). This behaviour is enhanced for higher A_{h-zone}.

If analysing the variation of t_{LLH} as a function of A_{h-zone} variation (Figure 7.3(b)), it can be seen that for higher A_{h-zone} variations, Eq. (7.9) results change more for slow fires than for faster fires and, in general, its variation is greater than FDS variations (which seem to be less sensitive to α_{HRR}). From the results reported in Figure 7.3 it

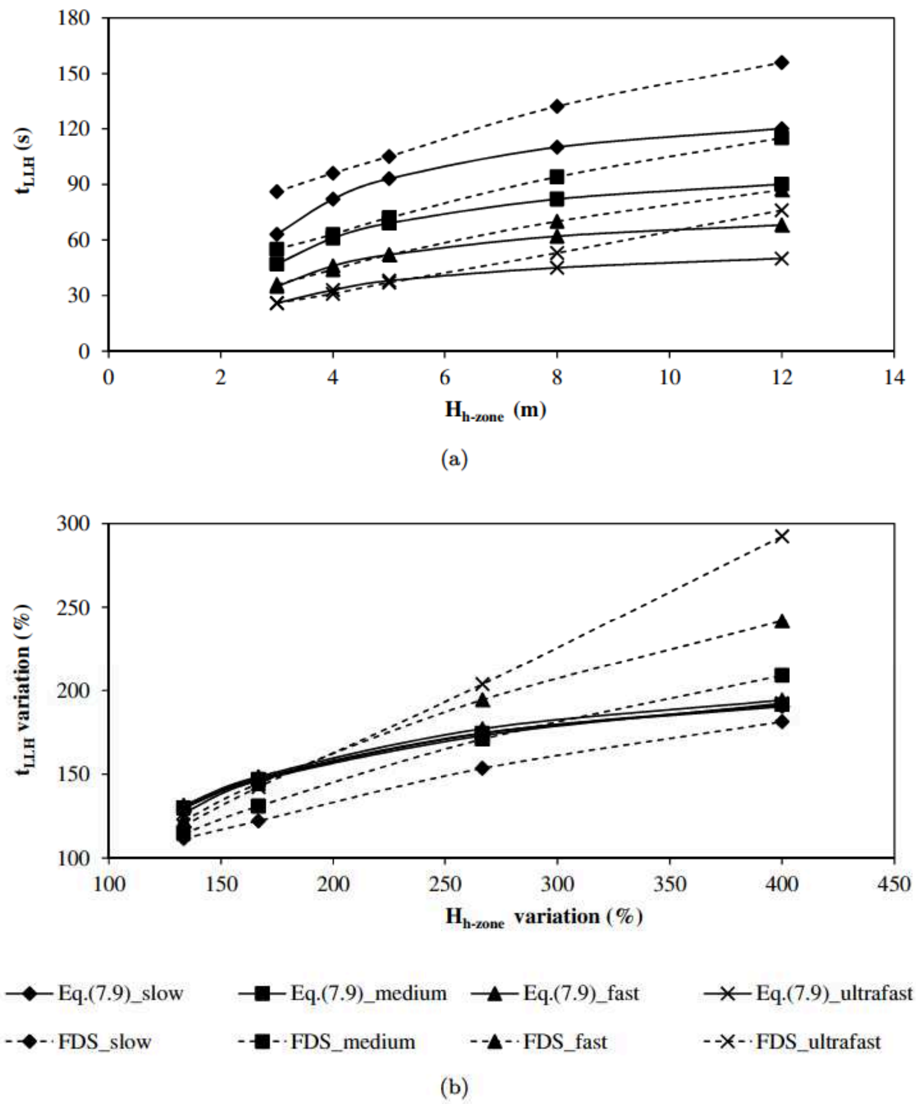
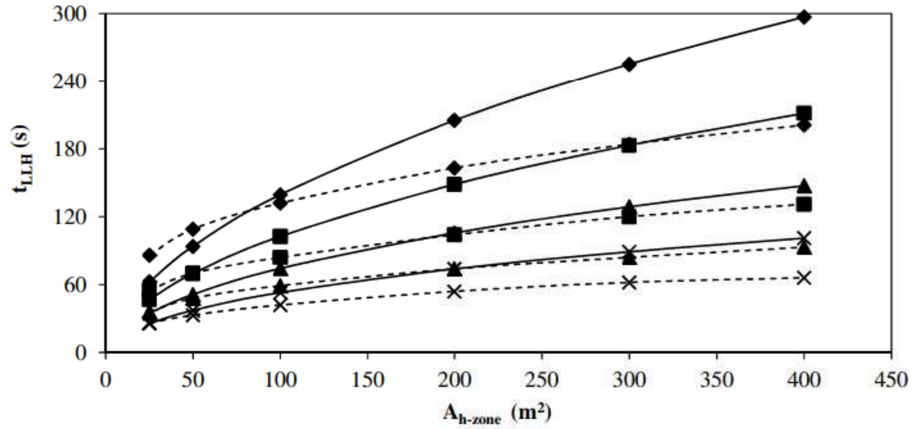
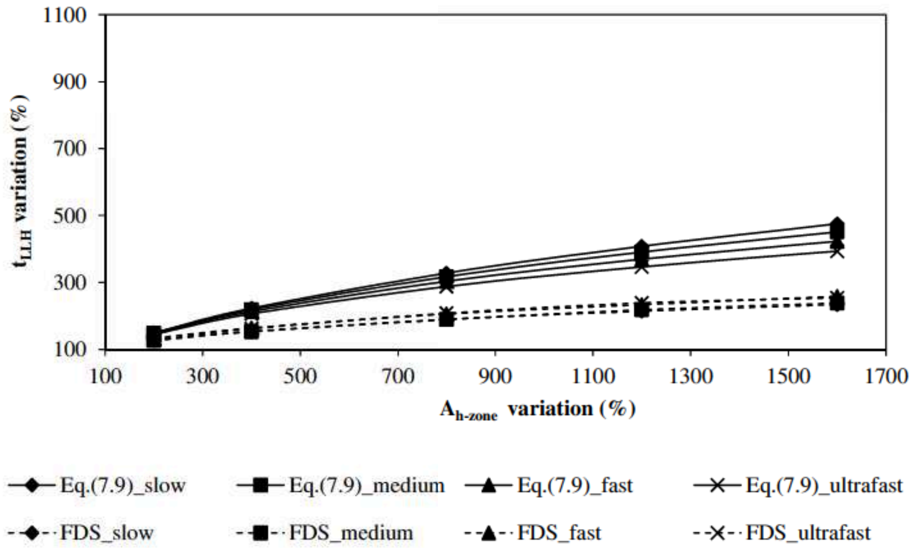


Figure 7.2. Comparison of t_{LLH} trends as a function H_{h-zone} ($A_{h-zone} = 25$ m^2) between Eq. (7.9) and numerical data. (a): Trend; (b): Variation in percentage terms.

emerges that a limit of validity of Eq. (7.9) exists. This limit has to be investigated in terms of H_{h-zone} to A_{h-zone} ratios within the hot zone volume of 4800 m^3. In the next section this aspect is explored.



(a)



(b)

Figure 7.3. Comparison of t_{LLH} trends as a function A_{h-zone} ($H_{h-zone} = 3$ m) between Eq. (7.9) and numerical data. (a): Trend; (b): Variation in percentage terms.

7.2.3 Safety margin of t_{LLH} predictions

In the analysis of trend variation of Eq. (7.9) as a function of α_{HRR}, H_{h-zone}, and A_{h-zone} it emerged that the correctness of t_{LLH} depends on the values of H_{h-zone} and A_{h-zone}. In order to establish the safety margin of Eq. (7.9) as a function of H_{h-zone}

and A_{h-zone} a safety factor SF is then defined:

$$SF = \frac{t_{LLH\ \mathrm{FDS}}}{t_{LLH\ \mathrm{Eq.\ (7.9)}}} \tag{7.10}$$

A SF value greater than 1 implies that Eq. (7.9) predicts t_{LLH} on the safe side (with a conservative safety margin). If SF is lesser than 1, Eq. (7.9) overpredicts t_{LLH}. Because t_{LLH} depends on both H_{h-zone} and A_{h-zone}, SF was calculated with respect to undimensional H_{h-zone} to $\sqrt{A_{h-zone}}$ ratios.

SF was calculated for all the scenarios analysed and the results are reported in Figure 7.4. As it can be seen, for H_{h-zone} to $\sqrt{A_{h-zone}}$ ratios greater than 0.6, Eq. (7.9) estimations are on the safe side. On the contrary, if the ratio is lesser than 0.6, in order to obtain reliable results it is necessary to adopt a suitable safety factor. When $\frac{H_{h-zone}}{\sqrt{A_{h-zone}}} < 0.6$ conservative results are then obtained by multiplying Eq. (7.9) by the SF related to the ratio adopted.

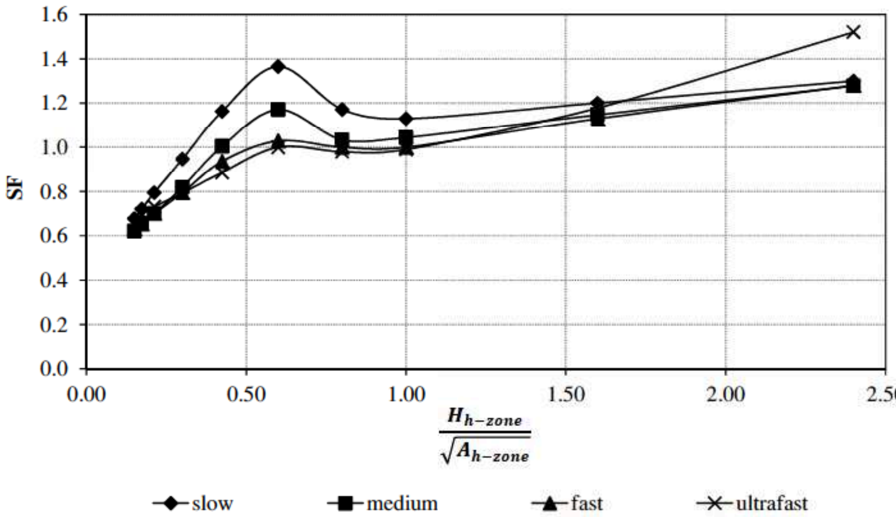


Figure 7.4. Safety margin of Eq. (7.9) as a function of H_{h-zone} to $\sqrt{A_{h-zone}}$ ratio.

7.2.4 Sensitivity analysis

A sensitivity analysis of Eq. (7.9) was performed in order to check how a slight change of input parameters (α_{HRR}, H_{h-zone}, and A_{h-zone}) affects t_{LLH}. Sensitivity analysis allows establishing whether the analytical equation is robust with respect to the different input parameters.

A generic physical system which may vary with time t can be defined as:

$$\frac{dy}{dx} = f(y, \phi, t) \qquad y(0) = y^i$$

where y is the independent time-dependent variable, ϕ is the vector of the m input parameters, f is continuous and continuously differentiable in all its arguments. Considering a small change of each input parameter ϕ_j : $\Delta\phi_j \rightarrow 0$, it can be demonstrated that (Varma et al., 2005):

$$s(y;\phi_j) = \frac{\partial y(t,\phi_j)}{\partial \phi_j} = \lim_{\Delta\phi_j \rightarrow 0} \frac{y(t,\phi_j + \Delta\phi_j) - y(t,\phi_j)}{\Delta\phi_j}$$

where s is defined as the local sensitivity of y with respect to ϕ_j, which may be normalized through the correlation:

$$S(y;\phi_j) = \frac{\phi_j}{y}\frac{\partial y}{\partial \phi_j} \tag{7.11}$$

S represents the sensitivity of y as a function of ϕ_j, namely the effects that small changes of input parameters (in the order of magnitude of 1%) have on the output y.

Referring to Eq. (7.9), Eq. (7.11) can be written as:

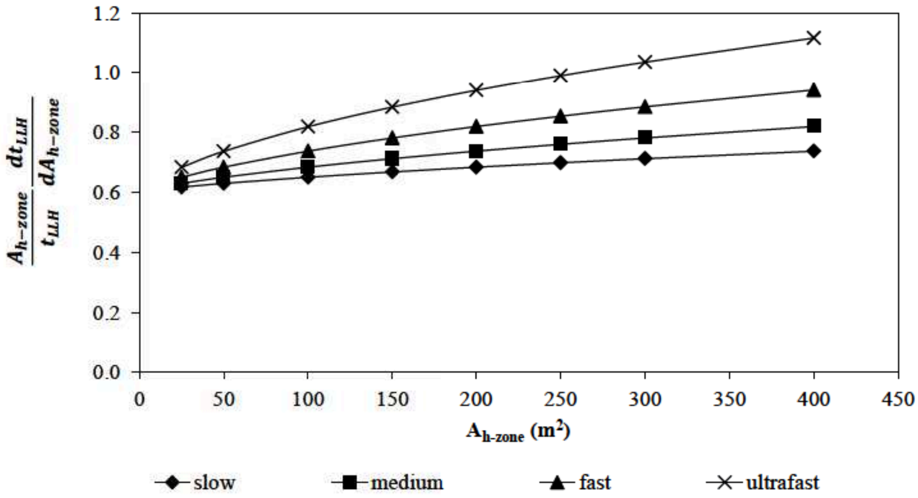
$$S(t_{LLH};\phi_j) = \frac{\phi_j}{t_{LLH}}\frac{\partial t_{LLH}}{\partial \phi_j} \qquad \phi = (\alpha_{HRR}, A_{h-zone}, H_{h-zone})$$

Figure 7.5(a) shows that $S(t_{LLH})$ increases consistently with the floor area A_{h-zone} for fast and ultrafast fires only. Therefore, small variations of the hot zone surface area affect t_{LLH} more for higher A_{h-zone} and for fast and ultrafast fires. On the other hand, Figure 7.5(b) shows that the $S(t_{LLH})$ decreases strongly with H_{h-zone} whatever the fire velocity. Hence, a small variation of H_{h-zone} implies a large variation of t_{LLH} for hot zones with a height less than 4 m, and that details on this parameter are essential for safety purposes. However, as emerges from the analysis of Figure 7.5, the t_{LLH} variation is small (maximum 1.6%), hence Eq. (7.9) is robust with respect to α_{HRR}, A_{h-zone} and H_{h-zone}.

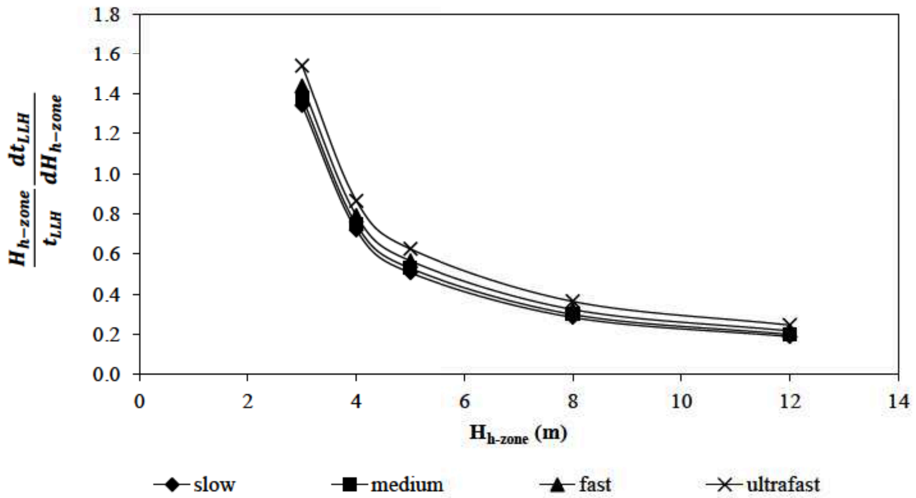
Summarising the findings of the previous analyses it can be concluded that:

- Referring to the CSF conceptual model (Figure 6.3), t_{LLH} can be easily estimated by iteration with Eq. (7.9) once α_{HRR}, H_{h-zone}, A_{h-zone}, and LLH are known;
- Eq. (7.9) presents limits of validity in terms of maximum hot zone volume and height to floor area ratios. These limits were established by using FDS;
- Within its validity range, Eq. (7.9) is robust with respect to α_{HRR}, H_{h-zone}, A_{h-zone}. Among the three input parameters, H_{h-zone} is the more sensitive input data, especially for a height less than 4 m;
- The analytical equation allows estimating t_{LLH} with few input data.

Although this equation is simpler than numerical simulations (CFD or two zone models), it can be solved only relying on iteration. Therefore, in order to be integrated in PASS it has to be represented in a form suitable to obtain rapidly t_{LLH} and to be usable



(a)



(b)

Figure 7.5. Results of sensitivity analysis of Eq. (7.9) (a) with respect to H_{h-zone}; (b) with respect to A_{h-zone}.

for a rapid screening of the egress system vulnerability. Furthermore, α_{HRR} is a fundamental input data (as also demonstrated in Chapter 5) and its value has to be linked with the characteristics of combustible materials present in the hot zone. A further step is then needed in order to integrate the analytical equation in PASS. Specifically, it is fundamental to link the fire-growth coefficient α_{HRR} for slow, medium, fast and ultrafast fires with the characteristics of the Smoke Generator. Once α_{HRR} is determined, Eq. (7.9) has to be represented in a simple form which allows a rapid estimation of t_{LLH}. This aspect is addressed in Chapter 8.

7.3 Estimation of standard time T_{w-zone}

The Equivalent Smoke Generator (ESG) conceptual model represents in a schematic form the process of smoke filling in the warm zone due to the smoke generated in the hot zone, as described in Section 6.4. In the ESG conceptual model, the smoke source is the Equivalent Smoke Generator (ESG), described in terms of α_{HRR}, volume of the hot zone V_{h-zone} and characteristics (width and height) of the gaps between hot and warm zone. The standard time for the warm zone, T_{w-zone}, was defined as the time taken for the smoke produced by the ESG to fill a volume of the warm zone equal to V_{fill}. Warm zone, by definition, is that area of a building enclosed by protection barriers that contains the hot zone and where fire hazards can spread. Therefore, no smoke spreading to temporary-cold or safe zones is considered (it is supposed that protection barriers prevent the fire spreading across zones). Because T_{w-zone} is quantified only for the warm zone, and considering its definition, V_{fill} is defined as:

$$V_{fill} = (V_{w-zone} - V_{h-zone}) - (A_{w-zone} - A_{h-zone})\, LLH \qquad (7.12)$$

where V_{w-zone} is the volume of the warm zone (m^3), V_{h-zone} is the volume of the hot zone (m^3), A_{w-zone} is the floor area of the warm zone (m^2) and A_{h-zone} is the floor area of the hot zone (m^2).

Given this, a method that allows estimating the time take to fill with smoke a V_{fill} can be introduced. Assuming that:

a) the hot zone has a uniform temperature distribution that differs from the warm zone temperature;

b) the hot smoke introduced in the warm zone stratifies due to buoyancy (two zone approach);

a simple expression for calculating the volume flow rate of smoke through a gap from the hot zone to the warm zone (Figure 7.6) can be developed, according to Karlsson and Quintiere (2000).

Assuming a uniform temperature distribution inside the hot zone (the hot zone is entirely filled with smoke), a pressure profile P_{h-zone} decreasing with height develops. A similar pressure profile is present in the warm zone, P_{w-zone}. However, warm zone temperature is lower that hot zone temperature and hence P_{w-zone} decreases more with height than in hot zone. This causes the two pressure profiles to cross at a certain height. At this point (neutral plane) the pressure difference between hot and warm zone is zero. Above this point, due to pressure differences, a flow of hot smoke $\dot{m}_{UL}$ from the hot zone to the warm zone exists. Below the neutral plane a flow of fresh air $\dot{m}_{LL}$ from the warm zone to the hot zone exists.

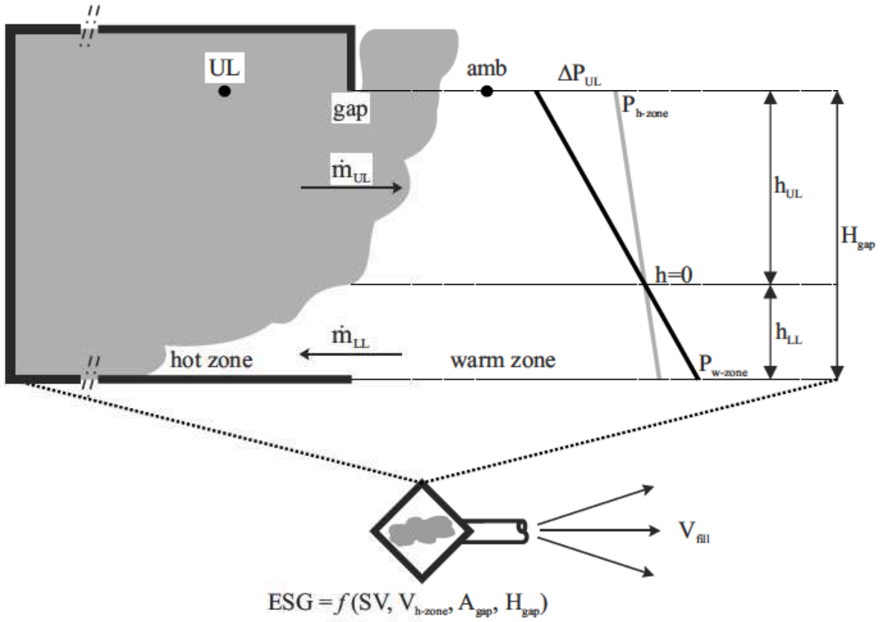


Figure 7.6. Smoke flow across a gap between hot and warm zones in the Equivalent Smoke Generator conceptual model. [Adapted from Karlsson and Quintiere (2000)).]

In order to quantify T_{w-zone}, the smoke flow $\dot{m}_{UL}$ has to be calculated. $\dot{m}_{UL}$ is defined as:

$$\dot{m}_{UL} = C_d \int_{A_{gap}} \rho_{UL}\, v_{UL}\, dA = C_d \rho_{UL} W_{gap} \int_{H_{gap}} v_{UL}(h)\, dh \tag{7.13}$$

where C_d is the flow coefficient for the vent (equal to 0.7 for doors), A_{gap} is the area of the gap (m^2), W_{gap} is the width of the gap (m), H_{gap} is the height of the gap (m), ρ_{UL} is the density of the hot smoke (kg m^{-3}) and $v_{UL}(h)$ is the smoke velocity of the hot smoke (m s^{-1}) as a function of the height h from the neutral plane.

$v_{UL}(h)$ is calculated applying Bernoulli equation between the hot zone and a point in proximity of the gap:

$$P_{h-zone} + \frac{1}{2}\rho_{h-zone} v_{h-zone}^2 + \rho_{h-zone} g\, h_{h-zone} = P_{gap} + \frac{1}{2}\rho_{gap} v_{gap}^2 + \rho_{gap} g\, h_{gap}$$

since $P_{h-zone} - P_{gap} = \Delta P_{UL}$, $v_{h-zone} = 0$, $\rho_{h-zone} = \rho_{gap} = \rho_{UL}$, $v_{gap} = v_{UL}$ and $h_{h-zone} = h_{gap} = h$:

$$v_{UL} = \sqrt{\frac{2\,\Delta P_{UL}}{\rho_{UL}}} \tag{7.14}$$

ΔP_{UL} is computed by applying Bernoulli equation between the hot zone and a point in the warm zone at ambient temperature T_{amb}:

$$P_{h-zone} + \frac{1}{2}\rho_{h-zone} v_{h-zone}^2 + \rho_{h-zone} g\, h_{h-zone} = P_{amb} + \frac{1}{2}\rho_{amb} v_{amb}^2 + \rho_{amb} g\, h_{amb}$$

since $P_{h-zone} - P_{amb} = \Delta P_{UL}$, $v_{h-zone} = v_{amb} = 0$, $\rho_{h-zone} = \rho_{UL}$, and $h_{h-zone} = h_{amb} = h$:

$$\Delta P_{UL} = h(\rho_{amb} - \rho_{UL})g \tag{7.15}$$

Combining Eq. (7.14) and Eq. (7.15), substituting in Eq. (7.13), and integrating from $h = 0$ to $h = h_{UL}$, $\dot{m}_{UL}$ is easily obtained:

$$\dot{m}_{UL} = \frac{2}{3} C_d\, W_{gap}\, \rho_{UL} \sqrt{\frac{2(\rho_{amb} - \rho_{UL})g}{\rho_{UL}}}\, h_{UL}^{3/2} \tag{7.16}$$

In a similar way the mass flow rate of cold air $\dot{m}_{LL}$ across the vent from the warm zone to the hot zone is obtained:

$$\dot{m}_{LL} = \frac{2}{3} C_d\, W_{gap}\, \rho_{amb} \sqrt{\frac{2(\rho_{amb} - \rho_{UL})g}{\rho_{amb}}}\, h_{LL}^{3/2} \tag{7.17}$$

Since the conservation of mass across the gap has to be respected, $\dot{m}_{UL} = \dot{m}_{LL}$. Combining Eq. (7.16) and Eq. (7.17), h_{UL} becomes:

$$h_{UL} = \frac{H_{gap}}{1 + \left(\frac{\rho_{UL}}{\rho_{amb}}\right)^{1/3}} \tag{7.18}$$

Substituting h_{UL} in Eq. (7.16):

$$\dot{m}_{UL} = \frac{2}{3} C_d\, W_{gap}\, \rho_{UL} \sqrt{\frac{2(\rho_{amb} - \rho_{UL})g}{\rho_{UL}}} \left[\frac{H_{gap}}{1 + \left(\frac{\rho_{UL}}{\rho_{amb}}\right)^{1/3}}\right]^{3/2} \tag{7.19}$$

The volumetric flow rate $\dot{v}_{UL}(t)$ (m^3 s^{-1}) at time t of hot smoke from the hot zone to the warm zone in obtained by dividing Eq. (7.16) by ρ_{UL}:

$$\dot{v}_{UL}(t) = \frac{2}{3} C_d\, W_{gap} \sqrt{\frac{2[\rho_{amb} - \rho_{UL}(t)]g}{\rho_{UL}(t)}} \left[\frac{H_{gap}}{1 + \left(\frac{\rho_{UL}(t)}{\rho_{amb}}\right)^{1/3}}\right]^{3/2} \tag{7.20}$$

ρ_{amb} is assumed constant with time and set equal to 1.2 (kg m^{-3}), while the density of the hot smoke $\rho_{UL}(t)$ depends on the temperature rise $T_{UL}(t)$ in the hot zone:

$$\rho_{UL}(t) = \frac{353}{T_{UL}(t)} \tag{7.21}$$

The temperature rise $T_{UL}(t)$, in absolute temperature, in the hot zone at time t with respect to ambient temperature T_{amb} and for *t-squared* fires can be estimated with the expression proposed by Mowrer (1999):

$$T_{UL}(t) = T_{amb} + \left\{ \exp\left[\frac{\alpha_{HRR}(1-\lambda)\, t^3}{3\, V_{h-zone}\, 353} \right] - 1 \right\} T_{amb} \tag{7.22}$$

where λ is the heat loss fraction coefficient. According to Mowrer (1992) a value of λ equal to 0.70 can be used.

From Equations (7.20), (7.21), and (7.22) a set of expressions usable for calculating the smoke volumetric flow rate from the hot zone to the warm zone at time t can be defined:

$$\begin{cases} \dot{v}_{UL}(t) & = & \frac{2}{3} C_d\, W_{gap} \sqrt{\frac{2[\rho_{amb}-\rho_{UL}(t)]g}{\rho_{UL}(t)}} \left[\frac{H_{gap}}{1+\left(\frac{\rho_{UL}(t)}{\rho_{amb}}\right)^{1/3}} \right]^{3/2} \\ \rho_{UL}(t) & = & \frac{353}{T_{amb}+\left\{\exp\left[\frac{\alpha_{HRR}(1-\lambda)\, t^3}{3\, V_{h-zone}\, 353}\right]-1\right\} T_{amb}} \end{cases} \tag{7.23}$$

T_{w-zone} is then calculated by numerical integration Eq. (7.23) once the value of V_{fill}, the hot zone volume V_{h-zone}, the characteristics of the fuel package (α_{HRR}), the gap height H_{gap} and width W_{gap} are set.

Eq. (7.23) represents the ESG conceptual model in engineering terms and allows T_{w-zone} to be estimated. However, before integrating it in PASS, the correctness of the methodology proposed to estimate T_{w-zone} has to be investigated. Eq. (7.23) was then compared with FDS numerical results. Different scenarios were developed and trends and margin of safety of Eq. (7.23) as a function V_{h-zone}, α_{HRR}, A_{gap}, V_{fill} and shape of the warm zone were analysed.

7.4 Analysis of T_{w-zone}

The operative tool for estimating T_{w-zone} in PASS analysis can be developed once the validity of Eq. (7.23) has been investigated. This can be fulfilled by comparing T_{w-zone} results from the analytical equation with FDS numerical results as a function of the input parameters required by Eq. (7.23).

The benchmark scenario used for this study consists in two 5 m × 5 m × 3 m equal rooms connected by a 1 m × 2 m gap (Figure 7.7). Starting from this configuration V_{h-zone}, A_{gap}, α_{HRR}, and shape of warm zone were then changed in order to check the effects of their variation on T_{w-zone}.

Figure 7.8 shows the effects of hot zone volume V_{h-zone} changes on T_{w-zone}. The values of V_{h-zone} checked were 75, 150, 300, and 600 m^3. The floor shape was maintained square. Gap and warm zone were maintained equal to the values of the reference scenario (Figure 7.7).

As it can be seen, T_{w-zone} increases as V_{h-zone} increases in both Eq. (7.23) and FDS results (Figure 7.8(a)). In fact, a higher hot zone volume causes a lower temperature in the hot zone (Eq. (7.22)) and hence a lower volumetric flow rate towards the warm zone.

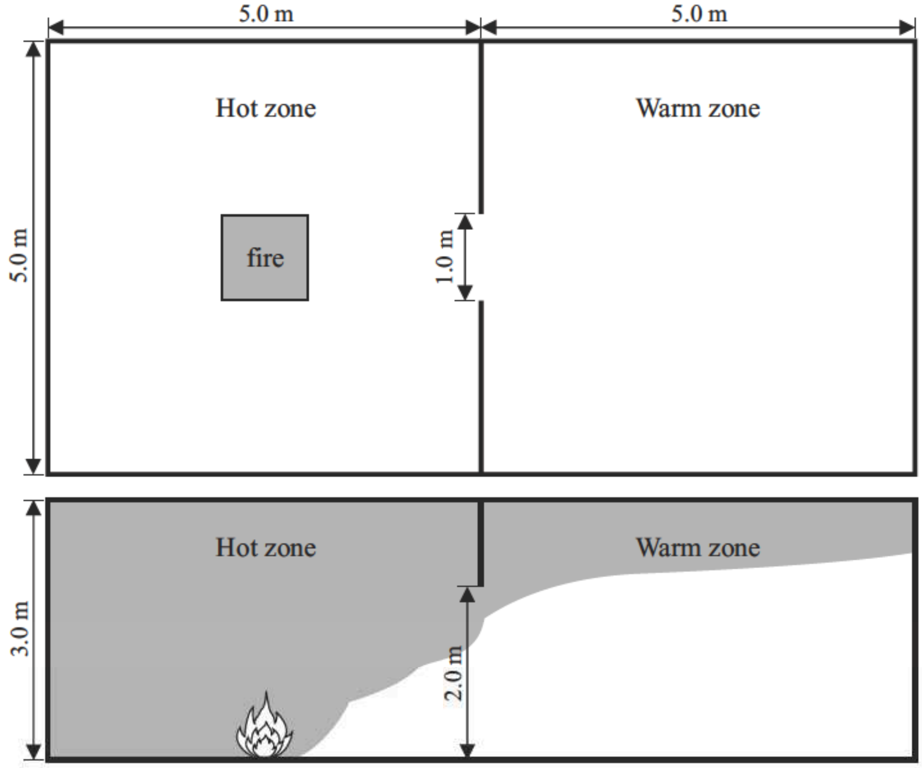


Figure 7.7. Reference scenario adopted for analysing Eq. (7.23).

Furthermore, starting from a volume of the hot zone greater than 400 m^3, Eq. (7.23) results are on the safe side for all α_{HRR}. The trend variation of T_{w-zone} changes constantly with α_{HRR} (Figure 7.8(b)). Although FDS seems to be more sensitive than Eq. (7.23) to α_{HRR} variations, trends are respected.

Figure 7.9 shows the effects of A_{gap} changes on T_{w-zone}. Hot and warm zones were equal to the reference scenario of (Figure 7.7). The values of gap areas checked were 2, 4, 6, and 8 m^2. As Figure 7.9(a) shows, T_{w-zone} decreases as the area of the gap increases and Eq. (7.23) results are on the safe side for gap areas greater than 4 m^2 for all α_{HRR}. As shown in Figure 7.9(b), although the analytical method is more sensitive to gap area variations than FDS, trend variation as a function of α_{HRR} is constant in both Eq. (7.23) and numerical results.

Figures 7.8 and 7.9 show that Eq. (7.23) overestimates T_{w-zone} with a configuration constituted by a V_{h-zone} equal to 75 m^3 and a gap area of 2 m^2. Since in this scenario T_{w-zone} predictions are not on the safe side, the analysis of T_{w-zone} estimation as a function of the warm zone shape is performed by adopting this configuration. This allows considering the worst case condition and to operate on the safe side.

T_{w-zone} for warm zone shapes similar to corridors is reported in Figure 7.10. Constant

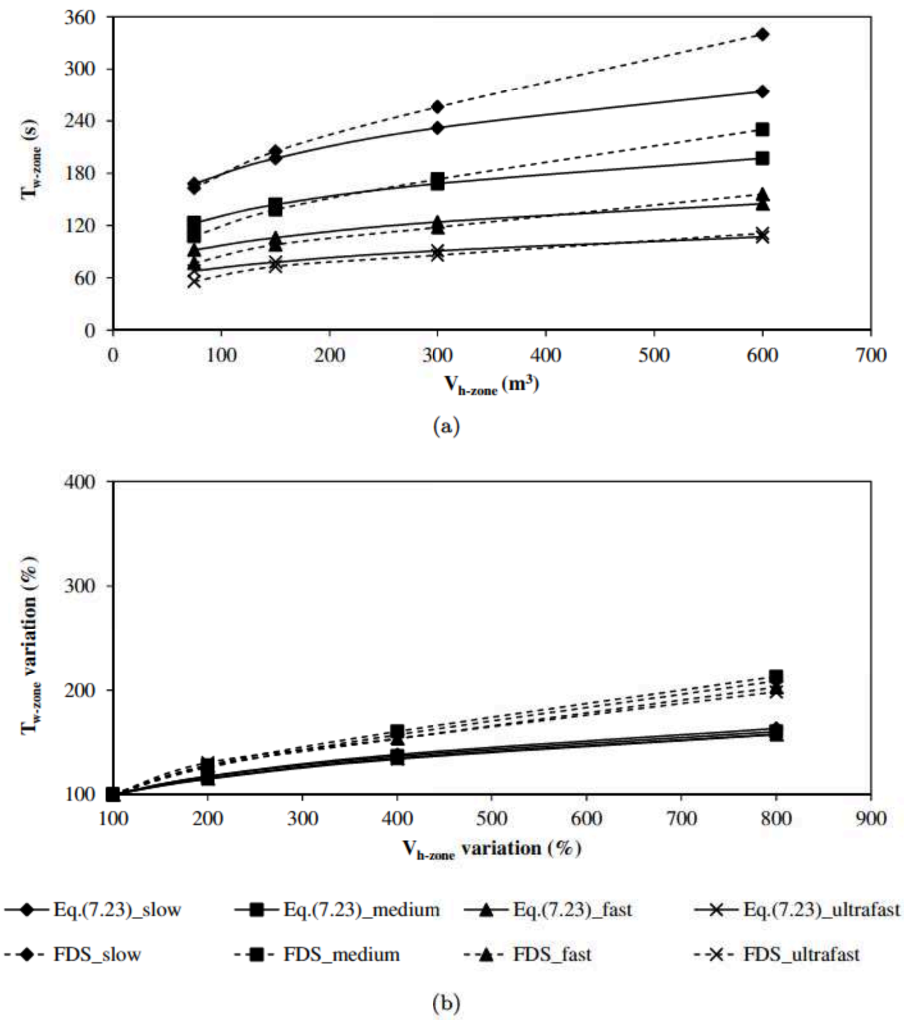


Figure 7.8. Comparison of T_{w-zone} as a function on V_{h-zone} between Eq. 7.23 and numerical results. (a): Trend; (b): Variation in percentage terms.

height equal to 3 m and width equal to 5 m were adopted. The checked length to width ratios of the warm zone were equal to 2, 4, and 8. This gives a V_{fill} equal to 50, 100, and 200 m^3 respectively. T_{w-zone} increases with V_{fill} in both Eq. (7.23) and FDS results (Figure 7.10(a)). However, although trend variations of FDS and Eq. (7.23) are similar (Figure 7.10(b)), Eq. (7.23) overestimates T_{w-zone} for all α_{HRR} and V_{fill}. Therefore, in order to obtain T_{w-zone} values on the safe side, it is necessary to adopt a suitable safety factor. Figure 7.12(a) reports the safety factor SF calculated with Eq. (7.10) as a function of V_{fill} for a corridor. A safety factor SF equal to 0.80 allows obtaining

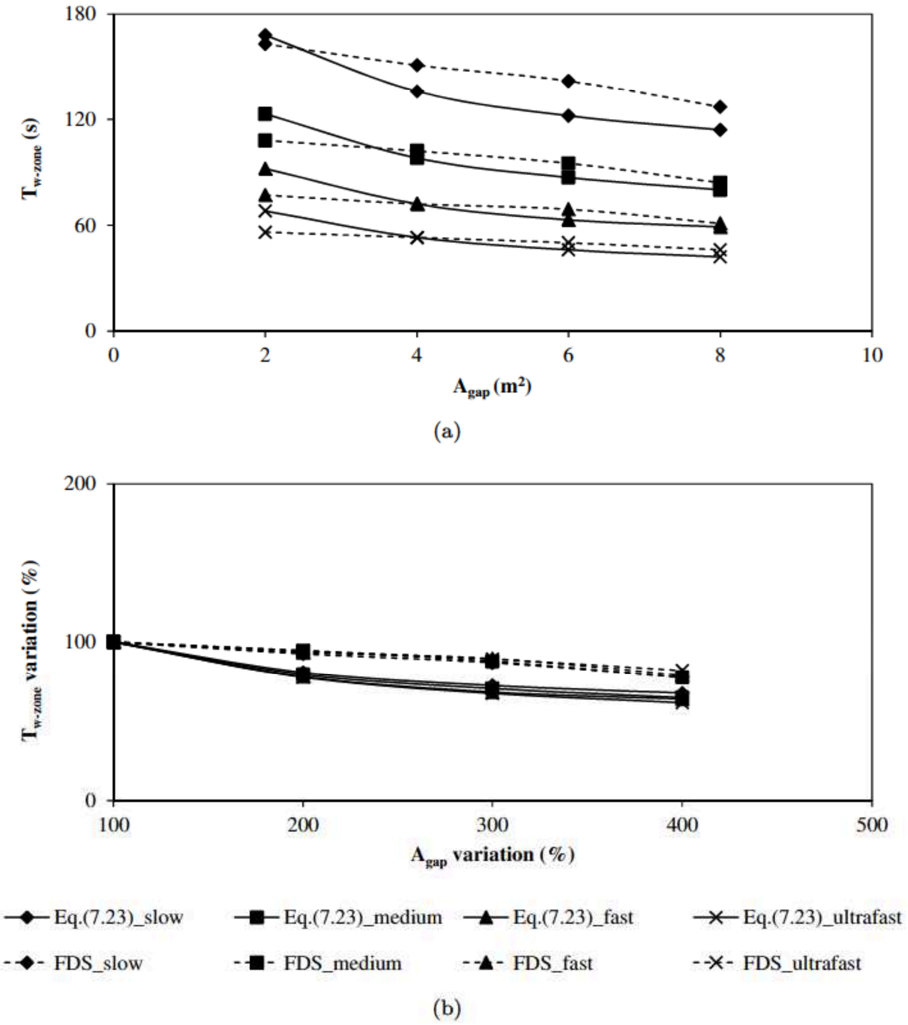
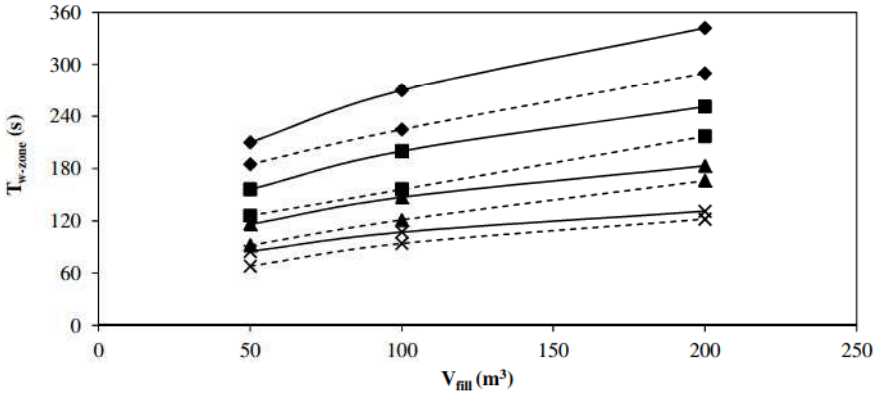


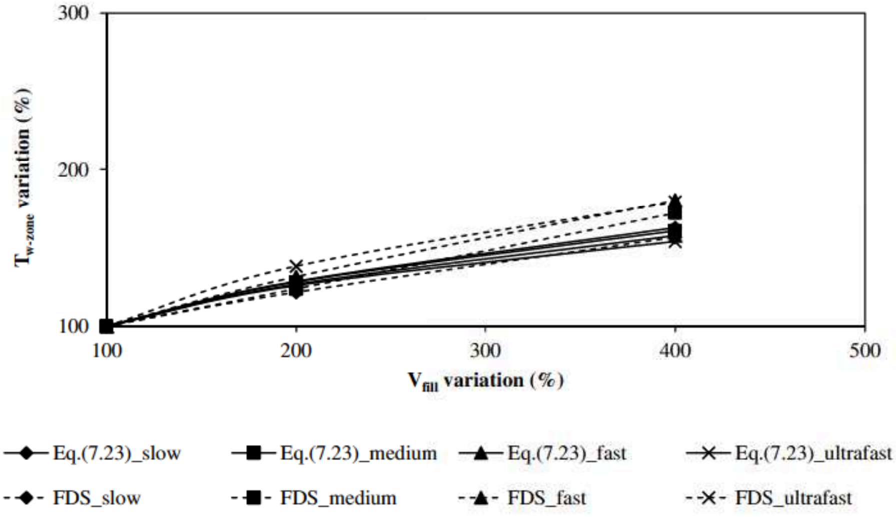
Figure 7.9. Comparison of T_{w-zone} as a function on A_{gap} between Eq. (7.23) and numerical results. (a): Trend; (b): Variation in percentage terms.

conservative T_{w-zone} in the V_{fill} range checked (from 50 to 200 m^3).

T_{w-zone} for warm zone shape similar to rooms is reported in Figure 7.11. Constant height equal to 3.6 m and width to length ratio equal to 1 were adopted. The checked warm zone floor area were equal to 32, 64 and 128 m^2. V_{fill} equal to 50, 100 and 200 m^3 respectively were then checked. T_{w-zone} increases constantly with V_{fill} in both Eq. (7.23) and FDS results (Figure 7.11(a)). Although trend variations of FDS and Eq. (7.23) are similar (Figure 7.11(b)), Eq. (7.23) overestimates T_{w-zone} for all α_{HRR} and V_{fill} also in the room shape. Therefore, a safety factor SF equal to 0.75 (Figure 7.12(b))



(a)



(b)

Figure 7.10. Comparison of T_{w-zone} as a function on V_{fill} between Eq. (7.23) and numerical results for corridor-like warm zone shapes. (a): Trend; (b): Variation in percentage terms.

has to be adopted in order to obtain T_{w-zone} values on the safe side in the V_{fill} range checked.

T_{w-zone} values for warm zone shape similar to shafts were not checked since in PASS a conservative assumption in order to deal with this geometrical configuration is adopted. This aspect is deepened in Chapter 8.

Summarising the findings of the previous analyses on T_{w-zone} trends it can be con-

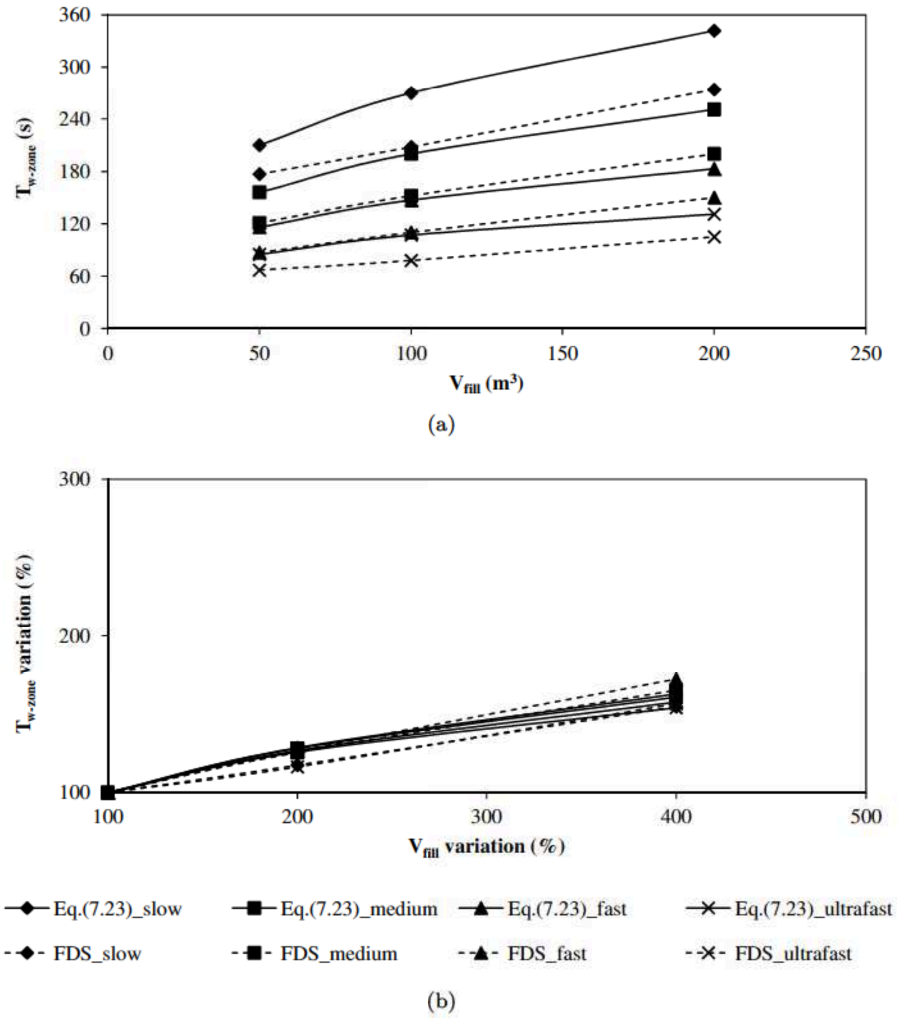
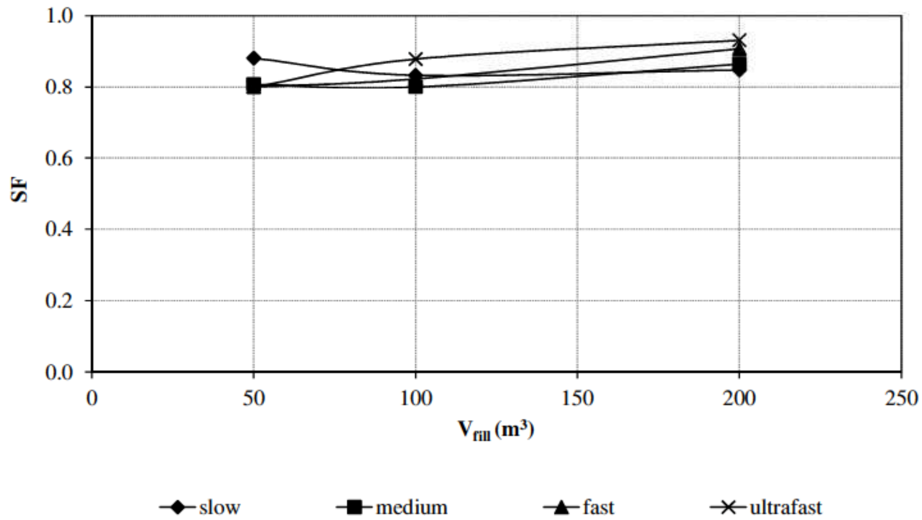


Figure 7.11. Comparison of T_{w-zone} as a function on V_{fill} between Eq. (7.23) and numerical results for room-like warm zone shapes. (a): Trend; (b): Variation in percentage terms.

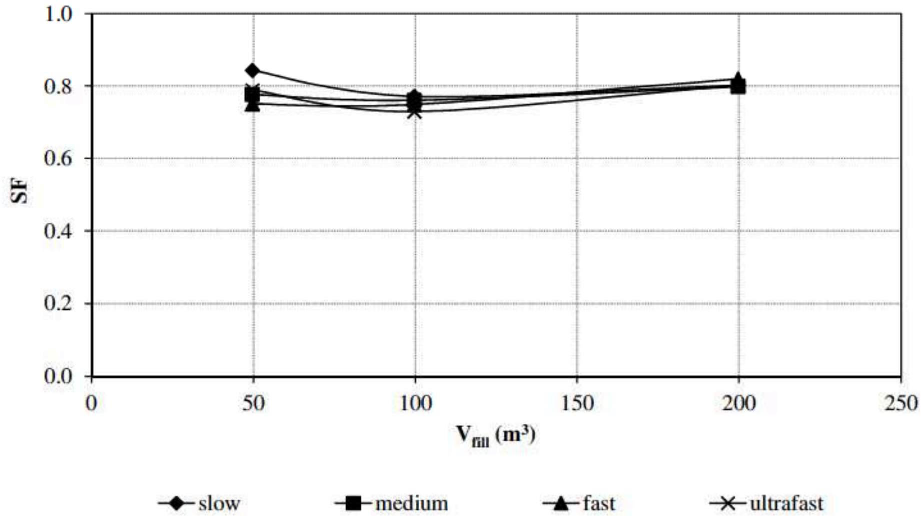
cluded that:

- Referring to the ESG conceptual model (Figure 6.4), T_{w-zone} can be easily estimated by numerical integration of Eq. 7.23 once V_{h-zone}, α_{HRR}, A_{gap}, and V_{fill} are known;

- The effects of the variation of input parameters of Eq. (7.23) are similar in both analytical equation and FDS;



(a)



(b)

Figure 7.12. Safety factor of Eq. (7.23) as a function on V_{fill} for (a) corridors and (b) rooms.

- Eq. (7.23) requires the adoption of two different safety factors SF for corridors and rooms in order to estimate conservatively T_{w-zone} in the range of V_{fill} checked (from 50 to 200 m^3);

- The analytical equation allows estimating T_{w-zone} with few input data.

Similar to the equation adopted for estimating t_{LLH}, although Eq. (7.23) equation is simpler than numerical simulations, it can be solved only relying on numerical integration. In order to be included in PASS, it has to be represented in a form suitable to be usable for rapid checks. A further step is then needed in order to represent Eq. (7.23) in a simple form which allows a rapid estimation of T_{w-zone} for corridors, rooms and shafts. This aspect is addressed in Chapter 8.

8

Operative tools for estimating PASS standard times

In this Chapter the conceptual models and engineering methods developed in Chapters 6 and 7 in order to estimate the PASS standard times are represented in the form of operative tools. This is necessary in order to achieve a rapid and simple estimation of the standard times ET_{GL}, $T_{TC-ZONE}$, T_{h-zone} and T_{w-zone}, and eventually to integrate them in PASS.

8.1 ET_{GL} and $T_{TC-ZONE}$

In Chapter 6 the criteria adopted for setting the building risk classes and ET_{GL} were presented. A set of ET_{GL} times which depend on the characteristics of occupants (familiarity, density, mobility) and on the building hazardous contents can then be introduced, as summarised in Table 8.1.

Table 8.1. Standard time ET_{GL}.

People's characteristics			ZHL^a			
			L	O	M	H or E
Standard mobility	Low density d ($d \leq 0.4\,\mathrm{p\,m^{-2}}$)	Familiar	300	240	180	120
		Unfamiliar	240	180	150	120
	High density d ($d > 0.4\,\mathrm{p\,m^{-2}}$)		180	150	120	120
Reduced or assisted mobility			120	120	120	120

[a] Refer to the worst case identified among the zones.

Since the temporary-cold zone guarantees tenability conditions for a time that depends on the characteristics of the protection rating of barriers against fire hazards, $T_{TC-ZONE}$ was set, conservatively and accordingly with the maximum ET_{GL}, equal to 300 s. This time is one third of the minimum protection time required for fire barriers (BS 9999, 2008; Coté, 2000).

8.2 Definition of the Smoke Velocity classes

In the Cell Smoke Filling and Equivalent Smoke Generator conceptual models, the Smoke Velocity classes (SV) are adopted in order to represent the hazards from the Smoke Generator and Equivalent Smoke Generator. SV class expresses the velocity at which the smoke is released in the environment. Considering pre-flashover fires (hence fuel-controlled combustion) it depends mainly on the characteristics of the combustible materials present in the enclosure. SV classes can be quantified with the fire-growth coefficient α_{HRR}, and four SV classes are defined accordingly. Table 8.2 reports the classification adopted.

Table 8.2. Smoke Velocity classes (SV).

α_{HRR} (kW s^{-2})	SV classes
0.003	S
0.012	M
0.047	F
0.192	UF

In order to use the SV classes for the egress system performance assessment, each class has to be associated with the characteristics of the combustible materials present in the hot zone. Namely, a fire-growth coefficient α_{HRR} has to be assigned to the different combustible materials, according to their combustion velocity. Slow fire-growth coefficients, for example, are appropriate for fuel packages constituted by thick and solid objects. Medium fires are typical for solid fuel packages of lower density, while fast fires for thin solids. Finally, ultrafast fires develop in presence of flammable liquids, dusty materials, highly flammable solids. An example of this categorisation is found in Nelson (1987), or ISO 13387-2 (1999) where several combustible materials are classified according to their form, arrangement and type of material.

Similarly, at each category of combustible contents, furnishings and interior finishes used in PASS for establishing the Cell and Zone Hazard Levels (CHL and ZHL, see Chapter 2 and Appendix B) a SV class was assigned.

In order to categorise these fuel packages in terms of SV classes through α_{HRR}, different references available in the literature were used. No experiments aimed at establishing in laboratory tests the HRR of each fuel package were made.

Categorisation of fuel packages along with their Smoke Velocity class and the bibliographic source adopted for their classification are reported in Table 8.3. In categorising the fuel packages, the presence of flame retardant materials, package surface size lower than 5% of total hot zone surface (floor+walls+ceiling), or fuel packages that are confined (sealed, closed in safety cabinets, in pipes) was considered. At these fuels the slowest Smoke Velocity class (S) was assigned, since during pre-flashover stages they constitute a low hazard for people's safety.

The correction factor γ_{ext} is assigned to flammable liquids to include in the assessment the surface flame spreading hazard (see Section 6.3). γ_{ext} considers the surface size A_{liq}

of flammable liquids exposed to air and is defined as:

$$\gamma_{ext} = \frac{A_{liq}}{A_{h-zone}}$$

where A_{h-zone} is the hot zone floor surface.

If flammable gases are present in the hot zone and are not confined, a value of γ_{exp} equal to 1 is assigned. In facts, if they ignite, they threaten immediately people's safety (namely the available time to escape from the hot zone T_{h-zone} is zero).

8.3 Standard time for the hot zone T_{h-zone}

In Chapter 7 an engineering method for estimating the time t_{LLH} taken to reach an established threshold limit for the lower layer height (LLH) was developed. Although the analytical equation proposed (Eq. 7.9) is useful for defining the standard time for the hot zone T_{h-zone}, it is solved relying on iteration. Therefore, in order to fulfil PASS aims and achieve a rapid estimation of T_{h-zone}, a set of pre-codified solution of Eq. (7.9) had to be developed.

The set of pre-codified solutions are reported in Figure 8.1, where t_{LLH} curves dependent on the Cell Smoke Filling classes (CSF) and as a function of the hot zone height H_{h-zone} were developed. Cell Smoke Filling classes (CSF) are defined in Table 8.4 considering Smoke Velocity class (SV) and hot zone floor area A_{h-zone} classes.

Since the curves reported in Figure 8.1 are solutions of Eq. (7.9) obtained by dividing in interval classes the range of A_{h-zone} (which is a continuous variable), approximations in the results are introduced. In order to compensate this approximation, and to ensure the validity of the results in the range of H_{h-zone} and A_{h-zone} reported in Figure 8.1, curves are plotted with a safety factor SF equal to 0.80 (see Section 7.2.3).

t_{LLH} is determined from Figure 8.1 once the Cell Smoke Filling (CSF) class is established (Table 8.4). Eventually, T_{h-zone} (s) is obtained considering the coefficient γ_{ext} (that incorporates the horizontal flame spread hazard for flammable liquids and gases, Table 8.3):

$$T_{h-zone} = (1 - \gamma_{ext})\, t_{LLH} \tag{8.1}$$

Therefore, for combustible solids T_{h-zone} is equal to t_{LLH}, for flammable liquids T_{h-zone} is lower than t_{LLH} as a function of the extension of the liquid surface A_{liq} exposed to air, for flammable gases in contact with air T_{h-zone} is zero.

The pre-codified solutions obtained with the proposed methodology were compared with FDS numerical results for different scenarios. The results are reported as points in Figure 8.1, where they are compared with the corresponding coloured curve, which is related to the simulated scenario. As emerges, with the methodology integrated in PASS it is possible to obtain results that agree well with numerical results. Some results are conservative, but this depends on the adoption of discrete classes to approximate the solution of Eq. (7.9). Thanks to this effective representation, PASS method provides results rapidly and with few input data, while FDS simulations need more input data and computational resource.

Table 8.3. Smoke Velocity classes SV according to the fuel package characteristics.

Fuel package	Characteristics		SV class	γ_{ext}	References
Combustible solids	Three-dimensional	wood furniture, wood, books, etc.	S	0	(Gann et al., 2001)
	Plastic furniture	bin, displays, stands, etc.	F/S[a]	0	(Gann et al., 2001)
	Thin solids	paper, fabrics, packing materials, etc.	UF/S[a]	0	(Bwalya et al., 2003)
	Electronic devices	computer, printer, power panel, etc.	S	0	(Babrauskas, 2002)
	Linear furnishings	carpets, curtains, generic coverings, etc.	F/S[a]	0	(Ahonen et al., 1984)
	Upholstered furniture	seat sofas, mattresses, etc.	M/S[a]	0	(Babrauskas, 2002)
	Termoplastics, high-toxic-emission-yield	non-fire resistant or melting plastics, foams, synthetic resins, etc.	UF/S[a]	0	(Morgan and Bundy, 2007)
	Pillows, bedding elements		S	0	(Babrauskas, 2002)
	Pallets		F/S[a]	0	(Karlsson and Quintiere, 2000)
	High flammable solids	matches, cellulosic material, phosphorus, etc.	UF/S[a]	0	(Karlsson and Quintiere, 2000)
	Dusty materials		UF/S[a]	0	(Karlsson and Quintiere, 2000)
	Reactive compounds		UF/S[a]	0	(Karlsson and Quintiere, 2000)
Flammable liquids			UF/S[a]	$\frac{A_{liq}}{A_{h-zone}}$	(Karlsson and Quintiere, 2000)
Flammable gases			UF/S[a]	$1/0^{a}$	

[a] If flame retardant material, or fuel package occupies a hot zone total surface (floor+walls+ceilings) lower than 5%, or is confined (sealed, closed in safety cabinets, in pipes, etc).

Table 8.4. Cell Smoke Filling classes (CSF) as a function of A_{h-zone} and SV classes.

Hot zone floor area	SV classes			
A_{h-zone} (m^2)	S	M	F	UF
$A_{h-zone} > 150$	CSF-1	CSF-4	CSF-7	CSF-9
$120 < A_{h-zone} \leq 150$	CSF-2	CSF-5	CSF-7	CSF-9
$100 < A_{h-zone} \leq 120$	CSF-3	CSF-6	CSF-8	CSF-10
$85 < A_{h-zone} \leq 100$	CSF-4	CSF-7	CSF-9	CSF-10
$70 < A_{h-zone} \leq 85$	CSF-5	CSF-7	CSF-9	CSF-11
$60 < A_{h-zone} \leq 70$	CSF-6	CSF-9	CSF-10	CSF-11
$50 < A_{h-zone} \leq 60$	CSF-7	CSF-9	CSF-10	CSF-12
$40 < A_{h-zone} \leq 50$	CSF-8	CSF-10	CSF-11	CSF-12
$30 < A_{h-zone} \leq 40$	CSF-8	CSF-10	CSF-11	CSF-12
$A_{h-zone} \leq 30$	CSF-8	CSF-10	CSF-12	CSF-12

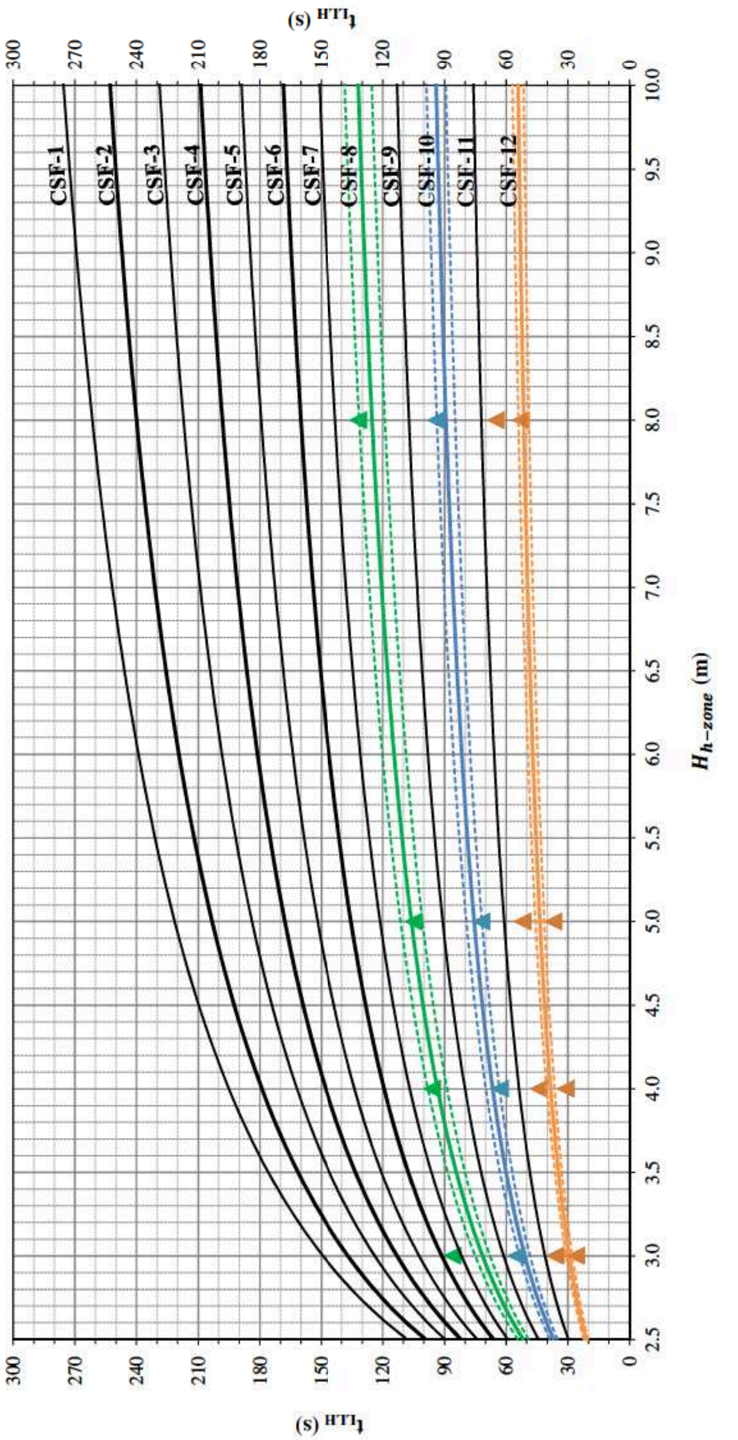


Figure 8.1. t_{LLH} (s) for the hot zone as a function of CSF classes. Dashed coloured line: 5% error line.

8.4 Standard time for the warm zone T_{w-zone}

In Chapter 7 an equation for calculating the standard time in the warm zone T_{w-zone} with few input data was proposed (Eq. 7.23). Once the volume of the hot zone V_{h-zone}, the Smoke Velocity class SV, the characteristics of the gaps between hot and warm zones (height H_{gap} and width W_{gap}), and the threshold limit for the maximum smoke volume in the warm zone V_{fill} are given, T_{w-zone} is easily calculated. However, although Eq. (7.23) is simpler and can be solved faster than numerical models, its solution still relies on numerical integration.

Therefore, similar to T_{h-zone}, in order to fulfil PASS aims and achieve a rapid estimation of T_{w-zone}, a set of pre-codified solutions of Eq. (7.23) had to be developed. Because T_{w-zone} depends on the shape of the warm zone, different solutions are developed for corridors, rooms and shafts (Section 7.4).

The set of pre-codified solutions for corridor- and room- like shapes are reported in Figures 8.2 and 8.3, where T_{w-zone} curves dependent on the Equivalent Smoke Generator classes (ESG) and as a function of the smoke filling volume V_{fill} are represented. Equivalent Smoke Generator classes (ESG) are defined in Tables 8.5 and 8.6 considering Smoke Velocity class (SV), classes of hot zone volume V_{h-zone}, and number of gaps between hot and warm zones. Gaps are represented in Table 8.6 as doors with height H_{gap} equal to 2.2 m and width W_{gap} equal to 0.9 m (1 door), 1.2 m (2 doors), 1.8 m (3 doors) and 2.4 (4 doors). According to the results of the T_{w-zone} analysis (Section 7.4), curves in Figures 8.2 and 8.3 are plotted by adopting a safety factor SF equal to 0.85 for corridors and 0.75 for rooms. In Section 7.4, a safety factor equal to 0.80 for corridors was proposed. However, the comparison between pre-codified solutions and numerical results showed that results are over-conservative if adopting this safety factor. Therefore, a SF equal to 0.85 is adopted here.

No curves are defined for warm zones with a shaft-like shape, but a set of conventional values that depend on ESG classes are introduced. Some assumption can be made for this scenario. Consider the worst case condition of a hot zone located in the lower level of a shaft (warm zone) and connected with the shaft by one or more gaps. Consider also that people have to escape from the warm zone by descending the shaft. This is the case, for example, of a multi storey building with several rooms connected to a staircase. Hot smoke flowing from the hot zone to the warm zone moves upwards and then threatens people that are descending the shaft. In this case the *zero-exposure* criterion, adopted to develop the tools for estimating PASS standard times, is not respected. According to the framework adopted in this work, people have to manage evacuation before they are exposed to fire hazards. Translating this concept for the case of the shaft, people descending the shaft have to move away from the warm zone before fire hazards spread from the hot to the warm zone (this is a conservative assumption). Referring to the ESG conceptual model, this time depends on SV, V_{h-zone}, and characteristics of the vent (hence on ESG class, Table 8.6) and it can be calculated considering a V_{fill} equal to 0 (alternatively a low value of V_{fill} can be adopted). Therefore, T_{w-zone} have to be set accordingly. A set of T_{w-zone} values were then calculated for a V_{fill} equal to 5 m^3(this value was adopted in order to prevent over-conservative estimations), as summarised in Table 8.7.

The pre-codified solutions for room and corridors were compared with FDS numerical results. The results are reported as points in Figures 8.2 and 8.3 where the numerical results are compared with T_{w-zone} curves. Each point is compared with the corresponding coloured curve, which is related to the simulated scenario. As emerges from the corridor-like shape (Figure 8.2) in 2 scenarios (green and red points at $V_{fill} = 200$ m^3) the results are over-conservative and on the safe side. However, the remaining points lie within the 5% error lines (dashed coloured lines).

In the room-like shape (Figure 8.3) in 3 scenarios the results are over-conservative (green and yellow points at $V_{fill} = 200$ m^3, yellow point at $V_{fill} = 50$ m^3) and the remaining point lie within the 5% error lines. Therefore, with the methodology proposed it is possible to obtain results on the safe side or with slight differences (of the order of 5%) if compared with numerical results. However, the pre-codified solutions allow estimating T_{w-zone} rapidly and with few input data. FDS, on the contrary, needs more input data and computational resource.

Table 8.5. Equivalent Smoke classes (es) as a function of V_{h-zone} and SV classes.

Hot zone volume	SV classes			
V_{h-zone} (m^3)	S	M	F	UF
$V_{h-zone} > 250$	es-1	es-3	es-5	es-7
$100 < V_{h-zone} \leq 250$	es-2	es-4	es-6	es-8
$50 < V_{h-zone} \leq 100$	es-3	es-5	es-7	es-9
$V_{h-zone} \leq 50$	es-4	es-6	es-8	es-9

Table 8.6. Equivalent Smoke Generator classes (ESG) as a function of equivalent smoke classes (es, Table 8.5) and number of doors between hot and warm zone.

equivalent smoke	Number of doors between hot and warm zone			
class (es) Table 8.5	1 door	2 doors	3 doors	4 doors
es-1	ESG-1	ESG-2	ESG-3	ESG-4
es-2	ESG-2	ESG-3	ESG-4	ESG-5
es-3	ESG-3	ESG-4	ESG-5	ESG-6
es-4	ESG-4	ESG-5	ESG-6	ESG-7
es-5	ESG-5	ESG-6	ESG-7	ESG-8
es-6	ESG-6	ESG-7	ESG-8	ESG-9
es-7	ESG-7	ESG-8	ESG-9	ESG-9
es-8	ESG-8	ESG-9	ESG-9	ESG-10
es-9	ESG-9	ESG-9	ESG-10	ESG-10

In this Chapter a set of rapid tools for estimating PASS standard times are illustrated. These tools were developed by introducing conservative assumptions on fire

Table 8.7. T_{w-zone} for shafts as a function of ESG classes.

ESG class	T_{w-zone} (s)
ESG-1	150
ESG-2	120
ESG-3	105
ESG-4	90
ESG-5	80
ESG-6	70
ESG-7	60
ESG-8	50
ESG-9	40
ESG-10	30

risk (ET_{GL} and $T_{TC-ZONE}$) and by engineering analyses of the smoke filling process (T_{h-zone} and T_{w-zone}).

Conceptual models that adopt the key elements usable to represent the smoke filling process were introduced and represented in engineering terms. This allowed introducing simple analytical equations for the estimation of T_{h-zone} and T_{w-zone}.

The correctness of these equations was checked by comparing their results with numerical results for a wide set of representative scenarios. Range of validity, trend analysis and safety factors for obtaining results on the safe side were then reported for each equation.

Because the solution of equations relies on numerical integration, diagrams with precodified solutions were developed, according to PASS approach. These constitute a set of rapid, simple and effective tools for estimating the standard times T_{h-zone} and T_{w-zone}. The comparison between standard times estimated with the simple tools and numerical results obtained by FDS showed a good agreement between the methods. Furthermore, it demonstrated that complex and sophisticated models can be used to develop simple but reliable operative tools. Eventually, the tools developed have been integrated in PASS.

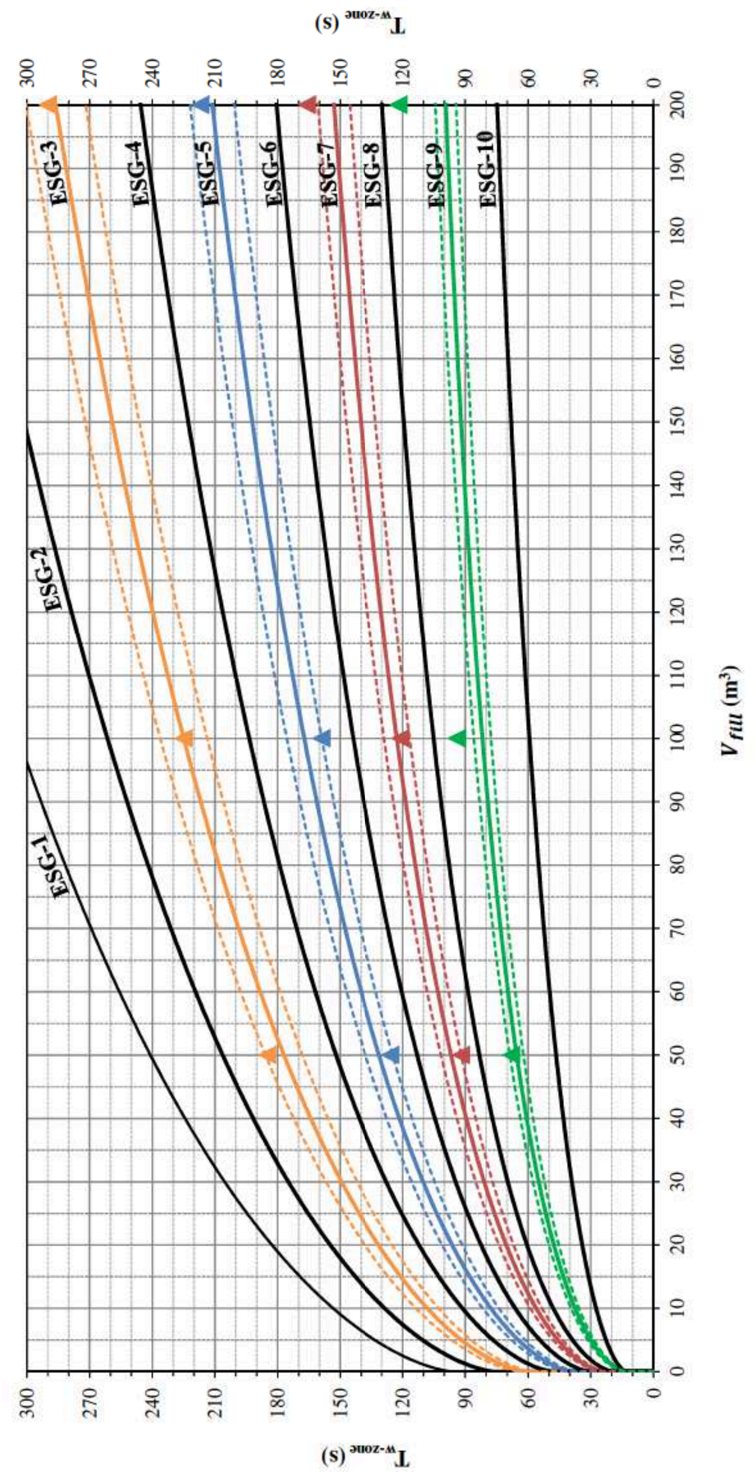


Figure 8.2. T_{w-zone} (s) for corridors as a function of ESG classes. Dashed coloured line: 5% error line.

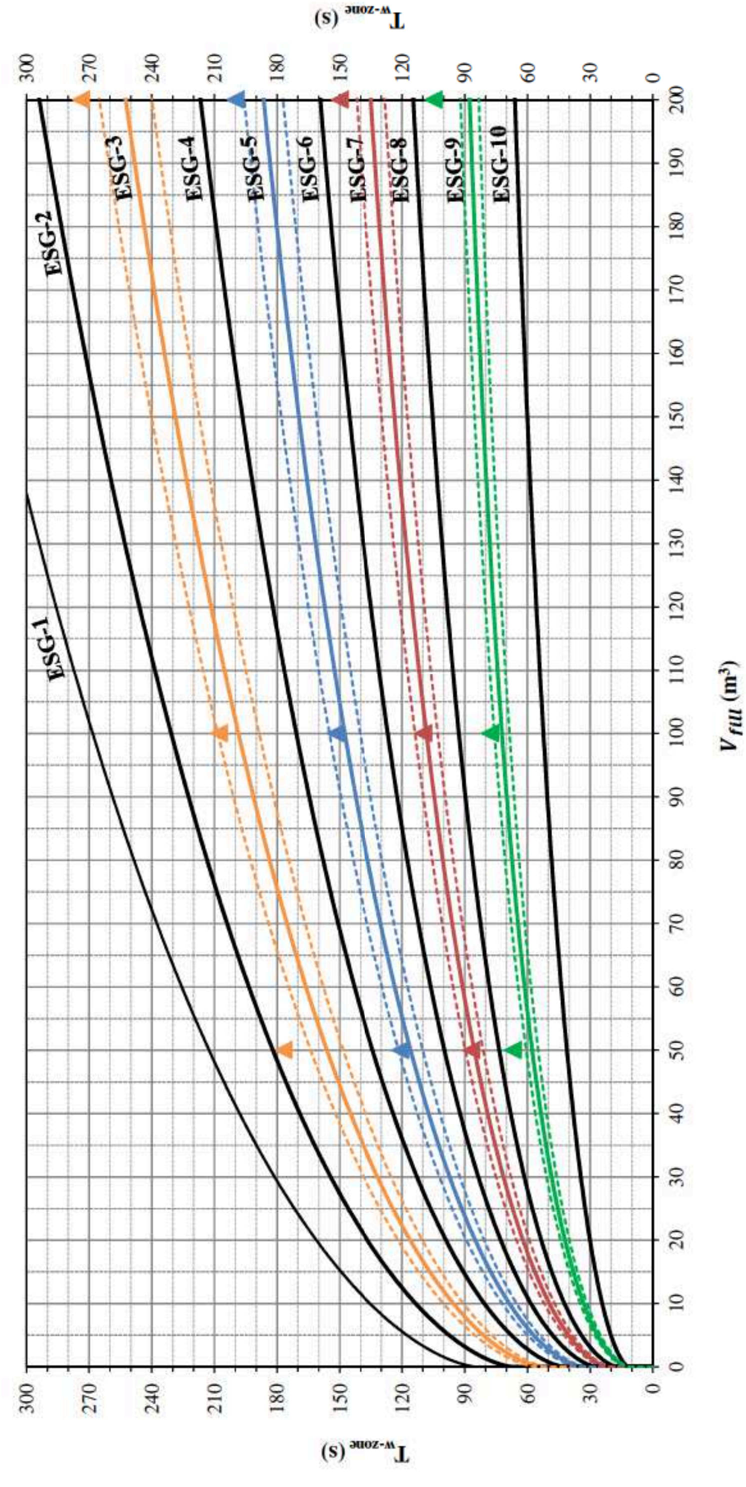


Figure 8.3. T_{w-zone} (s) for rooms as a function of ESG classes. Dashed coloured line: 5% error line.

III

LabCUBE$_{\text{egress}}$
A novel laboratory for studying human movement and behaviour during egress situations

9

Research background

Evacuation is a process strongly dependent on people-built environment-fire interrelationships. In PASS people-fire interrelationships are taken into account by adopting the *zero exposure* criterion and suitable hazards factor (see Part II).

People-built environment interrelationships are included in PASS by using appropriate factors, as reported in Chapter 2 (Figure 2.3). However, the need to develop a suitable approach, or methodology, for studying, quantifying in engineering terms and integrating in PASS these factors emerges (Chapter 3). Up to now, no suitable methodologies and data are available to achieve these goals.

$\text{LabCUBE}_{\text{egress}}$, a novel experimental laboratory, was conceived in order to accomplish these objectives, and it is presented in this thesis.

The research background on human behaviour and movement studies, fundamental to put in context $\text{LabCUBE}_{\text{egress}}$, is firstly described. Then, the characteristics of the laboratory are presented, and its capabilities are investigated through a set of experiments which allowed quantifying in engineering terms a factor adopted in PASS to include people's egress capabilities in the analysis. The calibrated factor was eventually included in PASS tools.

Finally, the application of PASS to a case study along with a comparison between PASS, evacuation models and experimental data are shown.

9.1 Human movement and behaviour: data collection methodologies

Evacuation in case of fire is that process during which people move away from a threatening zone and reach a place of safety. In order to preserve people's safety, evacuation has to be concluded before people are overcome by the fire effects (toxic gases, heat, oxygen depletion). Evacuation is then performed by people that, aware of the presence of a fire and of the necessity to escape from it, move within an environment through a designed egress system. A successful evacuation depends on the egress system performance.

When assessing the performance of the egress system it is fundamental to consider that evacuation is a complex process (Nilsson and Uhr, 2009) that not implies the sole geometrical features of a building. In fact also people, presence of fire and its effects, interrelationships between people themselves, environment in which they move and fire induced conditions have an important role in the evacuation process.

The concept of interrelationships was proposed by Sime (1991), when the thought that during an evacuation people move as a robot being only influenced by the geometrical features of the system (the so-called *ball-bearing* behaviour) was replaced with a more complex analysis of the evacuation process. Sime, in fact, gave a fundamental role to human behaviour and to people-people and people-environment interrelationships in evacuation. Currently, this concept is well established in the Fire Safety Engineering (FSE) field, and the importance of both human behaviour and interrelationships can be found in FSE guidelines (SFPE, 2003) and in contributions of many researchers (Gwynne et al., 1999; Kobes et al., 2009; Guanquan et al., 2012).

After recognising the importance of the interrelationships on the evacuation process, a lot of efforts have been made to study the evacuation process with a holistic perspective, focusing on these interrelationships and on the process of human behaviour in fire (see for example Kuligowski (2009)). However, the issue of integrating the engineering methodologies (which deal with static and dynamic objects, Sime (1995)) developed for analysing the egress system performance, with an interrelationships perspective (people think and behave, Sime (1995)) emerges (Sime, 1995; Meacham, 1999). Indeed, since both human behaviour and interrelationships strongly influence the evacuation process, they cannot be neglected when designing and assessing an egress system.

Quantification of human behaviour for engineering calculations allowed developing, for example, pre-movement time distributions (Purser and Bensilum, 2001; Gwynne et al., 2003; Gwynne and Boswell, 2009) which are currently integrated in engineering methods (ISO 16738, 2007). An advance in the integration of human behavioural factors into engineering analyses was recently made by Gwynne et al. (2012), who presented a method to identify real-word factors that influence evacuation, to understand their impact on human performance and eventually to represent them in engineering terms.

However, in order to include the human factors in engineering methods, such as analytical methodologies or evacuation simulation models (Kuligowski et al., 2010), it is necessary to collect the data which they need by studying and analysing people's movement and behaviour during egress situations. According to Fahy (2005), the required data for engineering methods are related to, for example, pre-movement times and activities, walking speeds on different types of surfaces and under different degrees of people density, movement capabilities and behaviour of a wide cross-section of society, actions and behaviour of people during evacuations, effects of obstruction in travel paths, exit choice decisions.

Several researches carried out studies on people's movement and behaviour during egress situations with different techniques. Fruin, for example, studied pedestrian movement in different contexts (buildings, transportation systems, urban environment) with empirical observations and provided relationships between walking speed-people density and between flow-people density (Fruin, 1987). With his analysis on tall building evacuations, Pauls (1977) introduced relationships between evacuation time, actual building population and available stair width. Proulx (1995) collected movement and behavioural data from dwelling evacuations by using video cameras and questionnaires. In order to validate a crowd dynamics model, Fang et al. (2008) carried out a survey on crowd movement during normal circulation in a railway station by using pre-installed video cameras. Liu and Lo (2011) attempted to investigate quantitatively the interrelationships between pre-evacuation responses and several impact factors (such as occupant characteristics, previous fire experiences, background of fire incident) by using post-fires questionnaires. In their small-scale tests on emergency door capacity, Daamen and Hoogendoorn (2012) studied the effects of the interrelationships between door with, presence of an open door, population composition and stress level on door capacity. Gwynne et al. (2009b) investigated the relationship between doorway width and achievable flow from video recordings during normal circulation. In order to integrate human factors in engineering analyses (evacuation models), Siddiqui and Gwynne (2012) employed pedestrian observations and investigated the relationships between individual actions and emergent conditions from video tapes, photographs, and human observations. Lawson et al. (2013) recently developed an approach for predicting human responses to emergency situations.

Those reported before are examples of works on people's movement and behaviour and further studies can be mentioned. However, what emerges is that these studies can be performed for different aims (development and validation of evacuation models, data collection, analysis of evacuation process, prediction of human behaviour), by using different techniques (video recordings, human observations, photographs) and that data can be derived from different sources which influence the methodology to collect them and the characteristics of the data collected. Gwynne (2010) classified the sources for deriving movement and behavioural data in:

- CCTV/security video footage;
- Full-scale experiments/trials;
- Small-scale component tests;
- Formal incident investigations;
- Surveys;
- Simulated data;
- Research of existing material/secondary resources.

Given a data source, data can be collected with different techniques and each technique has benefits and limitations (Fahy, 2012). Recalling the examples shown, and according to Gwynne (2010), data can be collected from:

- Video tapes;
- Still photograph;
- Human observers;
- Electronic sensors/automated measurement.

Methodologies and techniques adopted to study people's movement and behaviour during egress situations depend on the characteristics of the environment studied and on the research needs. For example, full-scale experiments (see evacuation drills) usually focus on the performance of the structure (Gwynne, 2010). The population involved in these studies could be representative only of the occupancy in which the experiments are performed and could be aware of the evacuation drill. Unless observers or video cameras are placed at specific points (transitions, staircases), the data collected during evacuation drills usually refer to the total evacuation time and to a single experiment. On the other hand, small-scale experiments allow focusing on particular aspects of human performance, as the layout investigated and the participants to involve in the study are selected. Furthermore, experiments can be repeated several times allowing specific data on people movement and behavioural patterns (data on merging flows, velocity on stair, specific flows) to be collected.

Therefore, when using the results of these studies for general considerations or as input data in engineering estimations, it is important to consider the hypotheses that underlie the experiments and the characteristics of the scenario studied (Gwynne, 2012). These aspects emerge clearly in a recent work of Hoskins and Milke (Hoskins and Milke, 2012) who demonstrated how different methods for calculating travel distance and area lead to significant differences in the results on people walking speeds in stairs by using the same data set.

In conclusion, when an experiment is performed in order to answer to a particular research need (Fahy (2005) gives an example of some open issues in the field of human behaviour in fire), it could be helpful to study a representative scenario (participant composition, for example, should be preferably heterogeneous and individuals not trained); to state clearly the conditions in which the experiments are carried out (in order to contextualise the data and to use them in a correct way); to repeat the experiments in the same conditions several times (this may allow collecting a sample of data statistically significant and reducing uncertainties); to record the experiments for their post-experiment analyses.

Aiming at deriving data on people-people and people-egress system interrelationships during egress situations with an approach that links different aspects of those mentioned before and at meeting PASS research needs, the LabCUBE$_{egress}$ laboratory has been conceived and designed (Tosolini et al., 2012c).

9.2 PASS research needs

In Chapter 2 it is described how the most important factors of human behaviour which influence the egress system performance are included in PASS. During a previous study aimed at a first application of PASS, the calibration of all factors by using only evacuation models or full-scale experiments was not possible (Tosolini, 2008). This because the factors used in PASS, on one hand, include some aspects of the human behaviour that cannot be predicted by using evacuation models and, on the other, the human behavioural patterns considered in PASS cannot be studied in full-scale experiments (such as evacuation drills).

Therefore, the necessity to develop a methodology for quantifying the factors related to the human behaviour emerged. Due to the lack of studies on human behaviour for the scenarios considered by PASS factors (for example the influence of exit signs on people's exit choice), in the preliminary study it was possible to guarantee only their global conservativity. The factors, when possible, were calibrated only for their minimum and maximum values.

LabCUBE$_{egress}$ laboratory has been conceived and designed in order to fill this gap, and to represent in engineering terms (quantitatively) the complete range of some factors adopted in PASS that are connected with the human behaviour. As presented in Section 9.1, data on human behaviour can be derived from different sources and adopting different techniques. For calibrating the PASS factors, several aspects have to be considered:

1. The data collected should be representative of the scenarios linked with the PASS factor studied. The laboratory then has to be flexible in order to be tailored to different scenarios (like small-scale experiments).

2. The experiment should be linked to real scenarios as much as possible. Usually the population involved in the experiments is homogeneous (in terms of physical characteristics, demographics, cultural background) and hence data could be not representative of a wide cross-section of society. This issue can be overcome by involving in the experiments common, heterogeneous and untrained individuals. Therefore, a portable laboratory placed in public places could aid in involving in the experiments participants with these characteristics.

3. The experiments should be repeated several times in order to quantify quantitatively the factor studied. This is guaranteed if a large number of participants take part to the experiments. Data can then be collected and analysed with a statistical approach (this is not easily accomplished in full-scale experiments).

4. Experiments should be optimised in order to allow deriving data for different factors during the same experiment. Because PASS adopts several factors linked to a large number of scenarios, it is fundamental to reduce the number of experiments to be performed (the laboratory layout should be rapidly re-configured).

5. Data have to be recorded in order to allow post-experiment analyses (the entire experiments have to be video recorded).

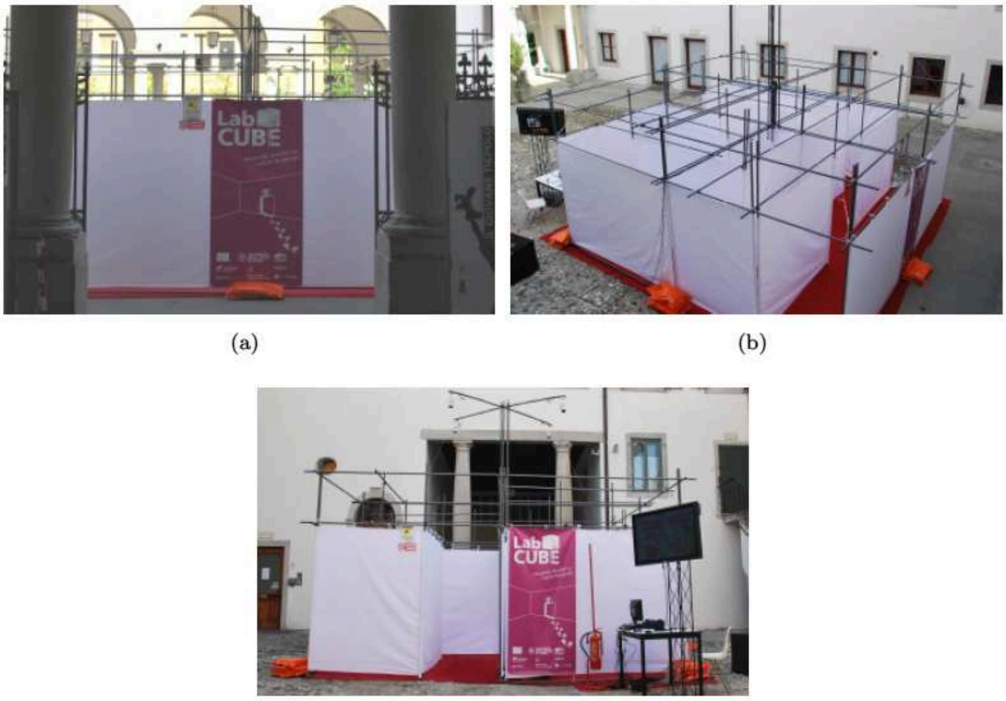
These requirements are fundamental in order to fulfil the calibration of PASS factors. LabCUBE$_{egress}$ is a laboratory conceived in order to study and quantify movement and behavioural factors which characteristics has been designed considering these requirements.

10

LabCUBE$_{egress}$

The main task for collecting and quantifying human behaviour data and eventually for integrating them in PASS was to conceive a laboratory with the characteristics reported in Section 9.2. Full-scale experiments, for example, are not suitable because the study of specific human factors is difficult to perform, especially in buildings where heterogeneous population is present (like public premises). Furthermore, they cannot be repeated in the same scenario in short times, and hence it is difficult to collect a quantity of data usable for a statistical analysis. Given this, small-scale experiments seem to be suitable for quantifying PASS factors. Small-scale experiments, in fact, allow studying in a systematic way specific aspects of human performance and, if correctly designed, can be carried out in different contexts where heterogeneous individuals can be involved in numerous experiments. Furthermore, the layout can be easily tailored to the aims of the study. Due to the fact that they are performed at small-scale, it is easy to video record all the experiments and to analyse them a-posteriori.

LabCUBE$_{egress}$ (Figure 10.1) is a laboratory conceived and designed in order to study the factors that characterize people-people and people-egress system interrelationships during egress situations considering these needs. It is composed by several cubes (each cube is built with a tube/coupler system and white fabric) and different configurations can be designed. The laboratory is then flexible, and numerous and different layouts are originated. This allows reproducing at a small-scale horizontal parts of an egress system with various degrees of complexity and characterised by the presence of critical aspects that can affect people movement (counter flows at exits, obstacles, decision points). Therefore, different scenarios can be studied. Thanks to its modularity, more than one factor can be studied during the same experiment (see Section 10.1). LabCUBE$_{egress}$ is also designed to be portable. It can be placed in different areas where a large number of individuals can be involved in the experiments (festivals, malls): generic or selected participants from a wide-cross section of society can take part to the experiments and data for both individuals and groups can be collected. The laboratory is equipped with CCTV video cameras that allow data recording.



(a) (b)

(c)

Figure 10.1. Images of LabCUBE$_{\text{egress}}$: (a) as people saw the entry; (b) an image taken from above; (c) exit side.

10.1 LabCUBE$_{\text{egress}}$ layout

LabCUBE$_{\text{egress}}$ is modular and flexible, hence a fixed layout is not defined. An example of layout designed in two different sets of experiments is shown in Figure 10.2. As it can be seen, three sections within the LabCUBE$_{\text{egress}}$ can be identified (see the coloured areas in the Figure 10.2) and in each section a specific factor of people-people and people-egress system interrelationships can be analysed during a single experiment. Experiments can be performed with both individuals and groups. As participants enter the LabCUBE$_{\text{egress}}$, they converge to the gap at the T-intersection. Here both the specific flow of people converging to the gap from opposite directions and people's choice behaviour at a decision point in presence and absence of exit signs can be analysed (people-people and people-egress system interrelationships). After the gap, people enter the section in which their movement (in terms of velocity) in paths with different widths is studied (people-egress system interrelationships). Finally, in the red area it is possible to check people's behaviour in presence of a dead end path (specifically here it is studied whether and how people's entering the dead end path communicate the presence of this critical point).

Because one task of this project is to develop a methodology for quantifying factors linked with the human behaviour, in what follows the results obtained from two set of experiments aimed at quantifying people's choice behaviour at a decision point (T-intersection, green area), with and without exit signs and for both individual and group participants will be presented. Finally, the integration of the obtained results in PASS is shown.

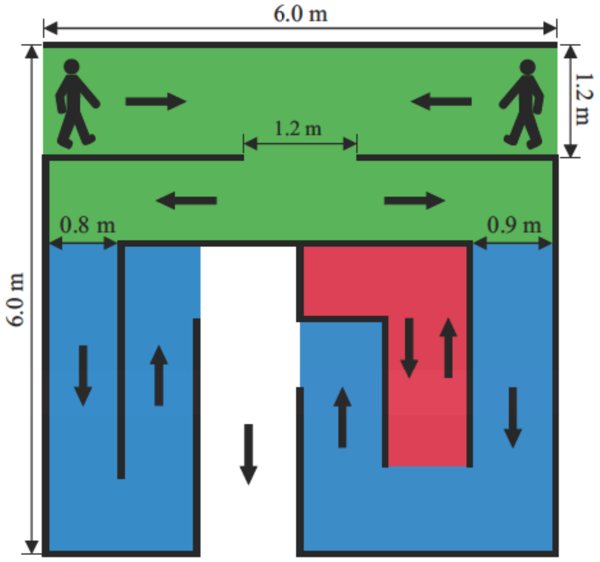


Figure 10.2. LabCUBE$_{egress}$ layout. Green area: study of people's choice behaviour at a decision point and specific flow of people converging to a gap. Blue area: study of people's movement in path with different widths. Red area: study of people's behaviour in presence of a dead end path.

10.2 Analysis of people's choice behaviour at a decision point

In this Section, after an overview on the current studies on people's choice behaviour in presence of exit signs, the experiments conducted in the LabCUBE$_{egress}$ (Figure 10.2) along with the results obtained are be presented and discussed. This study aimed at calibrating the egress capabilities factor *EC* adopted in MAr and PEr analyses of PASS (see Appendix D and E). As shown in Table 10.1, *EC* factor depends on people's movement capabilities (walking speed) and on their familiarity with the means of egress. In a previous study (Tosolini, 2008) this factor was calibrated only for the scenario related to people familiar with the means of egress and for the different movement capabilities.

The quantification of the scenarios related to unfamiliar people and the presence and absence of emergency signs have been an open issue. Two sets of experiments with the LabCUBE$_{egress}$ were then designed in order to fill this gap, and to calibrate the complete range of EC factor.

Table 10.1. Egress capabilities factor EC and scenarios analysed in the calibration study.

Familiarity with the means of egress	People's movement capabilities				
	Generic	Standard	Guided	Reduced	Assisted
Yes	–	1.00*	0.80*	0.75*	0.50*
No, exit signs are present and visible	G-ES	I-ES	G-ES	I-ES	G-ES
No, exit signs are not present	G-0	I-0	G-0	I-0	G-0

* These coefficients were calibrated in Tosolini (2008).

10.2.1 Studies on people's choice behaviour in presence of exit signs

The impact of exit signs on human performance and route selection behaviour during egress situations was investigated in few works. Xie et al. (2012) studied the likelihood that people faced with a route decision point perceive the emergency signs. That study was performed in a building sector, involving 68 individual participants (no groups were investigated), both familiar and unfamiliar with the building layout. The data were collected by using video cameras and post-questionnaires. That study revealed that among the unfamiliar population, 61% of individuals did not perceive a left exit sign at a symmetrical decision point (T-intersection), and 52% of the individuals who did not perceive the exit sign choose the route to the right. Carattin (2011) made a cognitive mapping test in which people had to recall emergency exits landmarks inside a supermarket and a single-storey shopping mall by using post-occupancy verbal interviews. A population of 260 individuals among clients and workers were involved in the study. Some results of the study showed that a maximum of 41% of individuals would look for signs in case of emergency and that approximately 80% of adults and elderly were unable to recall emergency exits. Veeraswamy et al. (2011) conducted an on-line survey with a map-based questionnaire in order to analyse wayfinding criteria from a building evacuation perspective. Their findings demonstrated that when people face a path choice, they are more likely to turn right, with a strong influence of handedness and a less influence of driving side. Heliövaara et al. (2012) investigated exit selection behaviour for groups when two exits are present in a corridor. Two set of controlled experiments were carried out in a building sector and the layout adopted was asymmetrical. Data of 102 undergraduate students (hence homogeneous population) were collected by using video cameras and post-questionnaires. From that study emerged that cooperative behaviour slows down egress (due to the lack of overtaking) and improves the self-organization. With individual tests performed during unannounced fire drills at night in a hotel, Kobes et al. Kobes et al. (2010) studied the influence of smoke and position of exit signs (ceiling and floor level) on wayfinding behaviour. Data of 83 generic participants were collected by using video cameras and post-questionnaires. The results showed that in normal conditions (no smoke and exit signs at ceiling level) about 56% of individuals used the exit signs (20 participants were involved in this test), in smoke conditions and exit signs at ceiling level about 82% of individuals used the exit signs (39 participants were involved in this test), while in smoke conditions and exit signs at floor level 75% of individuals used the exit signs (24 participants were involved in this test).

These works demonstrate that exit signs have their effectiveness, and hence it cannot be assumed that an exit signage system compliant with regulations is completely effective in conveying the designed information to evacuees and that they follow the information reported (Xie et al., 2012). Furthermore, except for the study of Heliövaara et al. (2012), the experiments involved only single individuals. However, the study of Heliövaara et al. (2012) makes evident that the presence of groups may influence the exit selection behaviour, and hence this aspect needs further investigation.

Experiments were conducted in the $\text{LabCUBE}_{\text{egress}}$ in order to explore these issues and investigate people's route choice behaviour with and without exit signs, the interaction between people and exit signs at a decision point for both groups and individuals, and eventually to use the data collected for the EC factor calibration.

10.2.2 Scenarios studied

Several scenarios are linked with the EC factor (Table 10.1) and they are function of both people's movement capabilities and people's familiarity with the means of egress. As concerns the classes of the first parameter, people's movement capabilities (generic, standard, guided, reduced, assisted) can be quantified by using different walking speeds, as reported in (Boyce et al., 1999; ISO 16738, 2007). On the contrary, up to now no studies are available to quantify the people's familiarity with the means of egress. With familiarity, here is intended the ability that people have to identify the most suitable way out within a building.

Familiar people with building layout and means of egress can identify the correct way out without the support of emergency signs. On the contrary, when people are unfamiliar with the building, in order to identify the way out they rely on the information conveyed by the exit signage system (if emergency staff is not present) or they exit the building by using the familiar route (Sime, 1985; Benthorn and Frantzich, 1999; Proulx, 2001).

In order to study people's choice behaviour during egress situations, a symmetrical decision point constituted by a T-intersection was identified as a critical point in an egress system. In fact, when facing a T-intersection people have to choose between two alternatives, the right or the left path. This point was designed in the $\text{LabCUBE}_{\text{egress}}$ layout adopted during the experiments (Figure 10.2). If people are familiar with the egress system layout (refer to the first line of Table 10.1), it reasonable to suppose that they will choose the correct path. Therefore, it can be assumed that their behaviour if effective in identifying the correct path (expressing this in terms of efficiency, the efficiency of their choice is equal to 1). On the contrary, if people are unfamiliar with the building layout (refer to lines 2 and 3 of Table 10.1), their choice can be affected by the presence of emergency signs and by the presence of other individuals (See Section 10.2.1). Currently, the efficiency of people's choice behaviour in these conditions is not completely known. In order to calibrate the *EC* factor adopted in PASS, these behaviours were investigated and quantified. Table 10.1 shows that four different scenarios linked with the *EC* factor can be defined:

- **I-ES**: unfamiliar individual that move within an egress system and exit signs are present and visible (for standard and reduced people's movement capabilities, no familiarity with the means of egress and presence of emergency signs);
- **I-0**: unfamiliar individual that move within an egress system and exit signs are not present (for standard and reduced people's movement capabilities, no familiarity with the means of egress and lack of emergency signs);
- **G-ES**: unfamiliar groups that move within an egress system and exit signs are present and visible (for guided and assisted people's movement capabilities, no familiarity with the means of egress and presence of emergency signs);
- **G-0**: unfamiliar groups that move within an egress system and exit signs are not present (for guided and assisted people's movement capabilities, no familiarity with the means of egress and lack of emergency signs).

These four scenarios were studied during the LabCUBE$_{egress}$ experiments.

10.2.3 Definition of the effectiveness of people's choice

Quantification of the differences between the four scenarios is possible once the effectiveness of people's choice at a decision point with and without exit signs and for both individuals and groups is defined. In this work this effectiveness is defined as a function of the number of people that selects the direction shown by an exit sign at a decision point. When all the participants select the direction shown by the emergency sign, the effectiveness can be assumed equal to 1. However, as shown in Section 10.2.1, for unfamiliar people this effectiveness is only theoretical. In order to represent in engineering terms this effectiveness, the following definition is adopted:

$$\eta_{scenario} = \frac{\%\ individuals\ that\ choose\ designed\ direction}{100} \tag{10.1}$$

where $\eta_{scenario}$ is people's choice effectiveness in the scenario studied.

The objective of LabCUBE$_{egress}$ experiments was to quantify $\eta_{scenario}$ for each of the four scenarios identified, as reported in Table 10.2.

From the studies of Xie et al. (2012), it is expected that without exit signs people that face a symmetrical decision point choose equally the right or the left. In order to estimate η_{I-0} and η_{G-0} it will be checked whether the choice between right and left is balanced. If it is balanced, η_{I-0} and η_{G-0} will be set equal to 0.5 (this means that when

Table 10.2. $\eta_{scenario}$ and scenarios studied.

Scenario ID	Description	$\eta_{scenario}$
I-ES	unfamiliar individuals; exit signs are present	η_{I-ES}
I-0	unfamiliar individuals; exit signs are not present	η_{I-0}
G-ES	groups; exit signs are present	η_{G-ES}
G-0	groups; exit signs are not present	η_{G-0}

people face a symmetrical decision point without exit signs, their chance of identifying the correct route is 0.5). The *EC* value for each scenario can be easily defined once the effectiveness $\eta_{scenario}$ is quantified, as summarised in Table 10.3.

Table 10.3. Definition of the *EC* factor as a function of $\eta_{scenario}$.

Familiarity with the means of egress	People's movement capabilities				
	Generic	Standard	Guided	Reduced	Assisted
Yes	–	1.00	0.80	0.75	0.50
No, exit signs are present and visible	$1.00\,\eta_{G-ES}$	$1.00\,\eta_{I-ES}$	$0.80\,\eta_{G-ES}$	$0.75\,\eta_{I-es}$	$0.50\,\eta_{G-ES}$
No, exit signs are not present	$1.00\,\eta_{G-0}$	$1.00\,\eta_{I-0}$	$0.80\,\eta_{G-0}$	$0.75\,\eta_{I-0}$	$0.50\,\eta_{G-0}$

10.2.4 LabCUBE$_{\mathbf{egress}}$ experiments

The experiments were carried out in the LabCUBE$_{egress}$ in order to study the effects of the presence of exit signs at a decision point on people's path choice. These effects were investigated in terms of statistical differences between people's choices in presence and absence of exit signs at a T-intersection. The layout adopted is sketched in Figure 10.3 and it is a section of the LabCUBE$_{egress}$ layout reported in Figure 10.2 (green area). The exit signs used (the green running man) complied with ISO standards (ISO 16096, 2004) and during the experiments with exit signs it was positioned at points P1, P2 and P3. Exit signs P2 and P3 were placed on a white background and participants approached all the signs with an angle of about 0°. The whole exit signage system (P1, P2 and P3) was intended to head people to the **left path** (referring to the results of Veeraswamy et al. (2011) this direction could be considered unnatural to the majority of people).

Experiments were carried out during the European Researchers' Night (September 2011) and during the *Festival della Sicurezza tra la Gente* (May 2012) in Udine (I). LabCUBE$_{egress}$ was placed in a public open square (Palazzo Morpurgo, Udine, Italy) and visibility conditions were constantly guaranteed during the experiments by natural

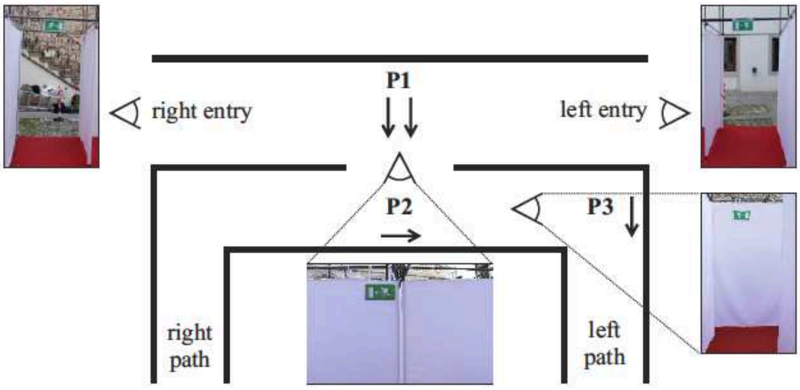


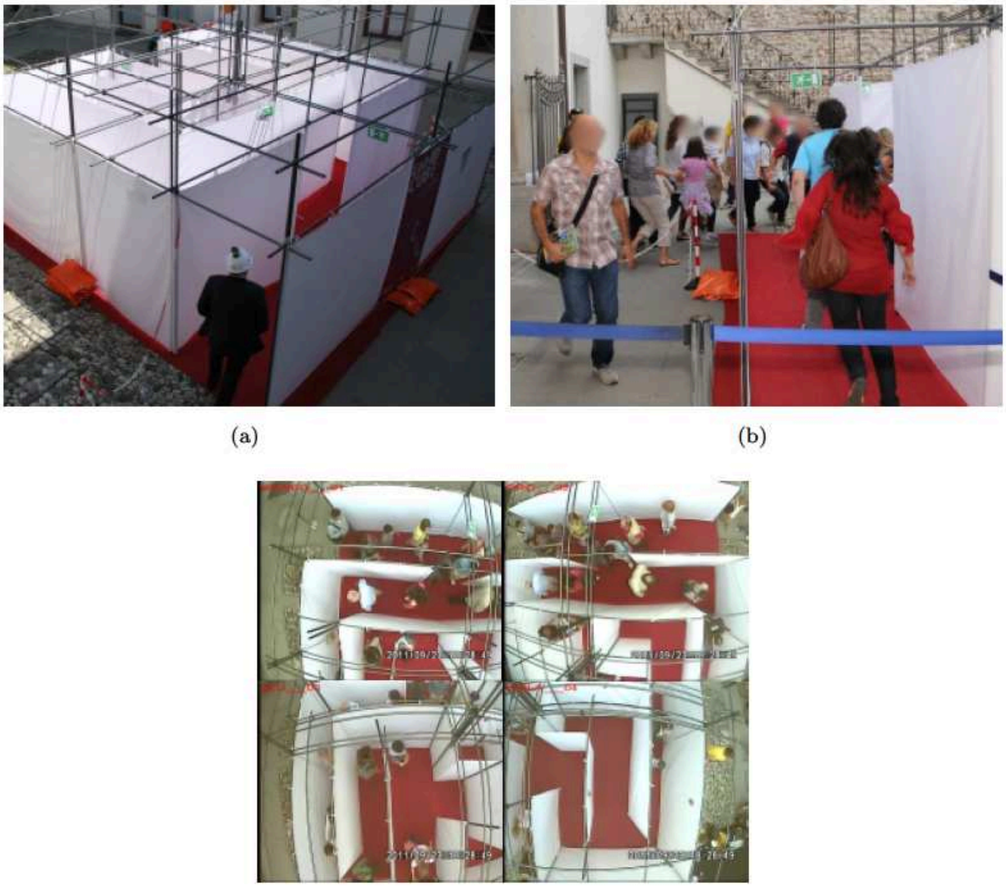
Figure 10.3. Details of the layout adopted for studying people's choice behaviour at a decision point.

and artificial light. All the experiments were recorded by using CCTV video cameras and the data analysis is based on these recordings (Figure 10.4). The population involved in the experiments was heterogeneous, untrained and representative of a wide cross-section of society.

The scenarios studied and compared are those described in Table 10.2. Scenarios G-0 and G-ES were studied during the European Researchers' Night, scenarios I-0 and I-ES were studied during the *Festival della Sicurezza tra la Gente*. Table 10.4 reports a summary of the characteristics of experiments. The data usable for the analyses are related to 56 participants in scenario I-0, 106 participants in scenario I-ES, 207 participants in scenario G-0 (13 experiments with a mean of 16 participants/experiment) and 97 participants in scenario G-ES (5 experiments with a mean of 19 participants/experiment). A total of 162 experiments were performed with individuals, 18 with groups. Each participant, unfamiliar with the LabCUBE$_{egress}$ configuration, took part in the experiment once. Information about gender and age was obtained by analysing the video recordings in order to characterise the population involved in the experiments and not to associate specific data at each gender and age category.

Table 10.4. Characteristics of each scenario studied during the experiments

Scenario	Persons/ exp. (mean)	Exit signs	Total pop.	Gender		Age		
				M	F	Child	Adult	Elderly
I-0	1	No	56	50.0%	50.0%	3.6%	96.4%	0.0%
I-ES	1	Yes	106	50.9%	49.1%	1.0%	96.2%	2.8%
G-0	16	No	207	48.3%	51.7%	6.7%	88.3%	5.0%
G-ES	19	Yes	97	45.4%	54.6%	8.3%	90.7%	1.0%



(a) (b) (c)

Figure 10.4. Images of $\text{LabCUBE}_{\text{egress}}$ experiments: (a) individual; (b) groups; (c) CCTV video recordings.

Experiments started outside the $\text{LabCUBE}_{\text{egress}}$, where people were invited to take part in a generic study on people's movement. Once participants accepted to take part in the experiments, they were told to behave as they had to move away from a threatening situation and to reach a safe area, situated at the exit of the $\text{LabCUBE}_{\text{egress}}$. To ensure safety they were told not to run and no emergency was simulated. No information about the $\text{LabCUBE}_{\text{egress}}$ configuration and about the presence of exit signs was provided. At the end of each experiment, a short debriefing with the participants was carried out in order to explain the real aims of the study and to sensitise people to safety issues. During the debriefing session additional information about participants' behaviour was collected.

10.2.5 Results and discussion

People's choice effectiveness $\eta_{scenario}$ was quantified by counting in the video recordings the number of people that choose the right and left paths, and the effects that the presence of exit signs have on people's choice were studied. Because CCTV system allowed recording the entire LabCUBE$_{egress}$ layout, each participant were tracked during the whole experiment, and both the entry side and path choices were detected. Gender and age category (child, adult, elderly), entry choice and path choice of each participant were entered into a spreadsheet. Hence, all the relevant data were available for the analysis. Distribution of people's choice (goodness of fit test) was tested with the χ^2 test, since data are related to one categorical variable (left and right) and are supposed to not follow a particular distribution. The results obtained are reported in Table 10.5.

Table 10.5. Results obtained from the experiments aimed at studying people's choice effectiveness at a T-intersection.

Scenario	People							
	from **left entry**		from **right entry**		to **left path**		to **right path**	
I-0	28	(50.0%)	28	(50.0%)	**26**	**(46.4%)**	**30**	**(53.6%)**
I-ES	40	(37.7%)	66	(62.3%)	**74**	**(69.8%)**	**32**	**(30.2%)**
G-0	111	(53.6%)	96	(46.4%)	**97**	**(46.9%)**	**110**	**(53.1%)**
G-ES	50	(51.5%)	47	(48.5%)	**59**	**(60.8%)**	**38**	**(39.2%)**

As concerns the **entry choice** (Figure 10.5), in scenario I-0 an equal proportion of people entering LabCUBE$_{egress}$ from left and right is observed (50.0% and 50.0% respectively). In scenario I-ES the proportions of participant entering from left and right are statistically different (from left 40 participants (37.7%), from right 66 (62.3%), $\chi^2 = 6.38,\ p = 0.01 < 0.05$). For the scenarios involving groups, in scenario G-0, 53.6% (111) of participants choose to enter the LabCUBE$_{egress}$ from the left and 46.4% (96) participants from the right. No preference for a particular entry side is suggested ($\chi^2 = 1.09,\ p = 0.30 > 0.05$). In scenario G-ES, 51.5% (50) of participants selected the left entry and 48.5% (47) the right. No evidence of a preferred entry is observed ($\chi^2 = 0.09,\ p = 0.76 > 0.05$). If considering the whole set of G scenarios (group experiments) no preference for a specific entry is observed ($\chi^2 = 1.07,\ p = 0.30 > 0.05$), while in I scenarios (individuals) a slight preference for the right entry emerges (58.0%, $\chi^2 = 4.17, p = 0.04 < 0.05$). It is important to point out that participants were told to enter the LabCUBE$_{egress}$ without showing the entry, and that the section of the laboratory used in these analyses has a symmetrical configuration.

The analysis of the results of the **path choice** (point P2 in Figure 10.3) shows a significant difference between the experiments with and without the exit signs, in both I and G scenarios (Figure 10.6). In scenario I-0 (individuals and no exit signs), 46.4% (26) of participants selected the left path and 53.6% (30) of participants selected the right path. The same behaviour is observed in scenario G-0 (groups and no exit signs), where 46.9% (97) of participants selected the left path, and 53.1% (110) the right. Without

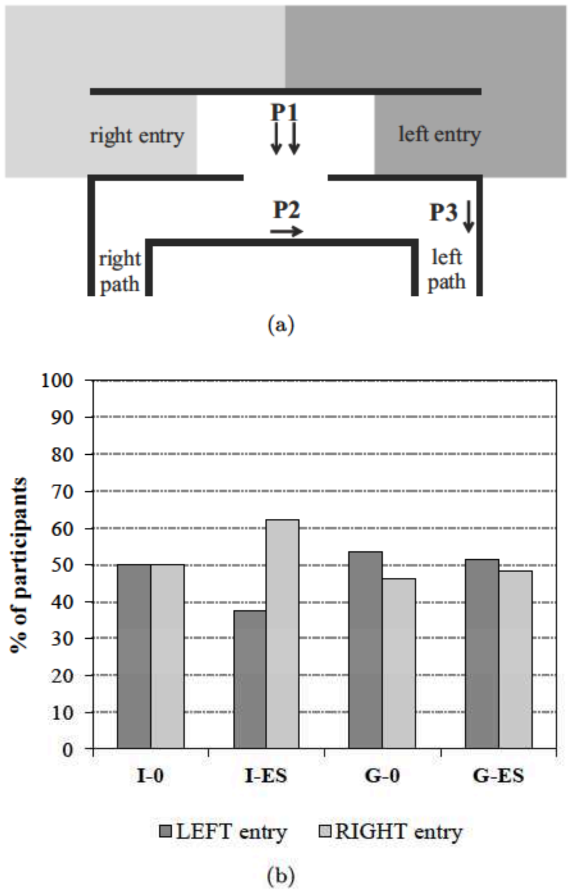


Figure 10.5. People's **entry** choice. (a) sketch of the LabCUBE$_{egress}$ section checked; (b) results.

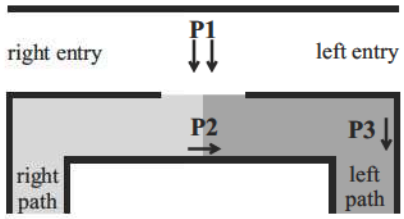
exit signs a slight preference for the right path emerges, although this conclusion cannot be confirmed by statistical results (I-0: $\chi^2 = 0.29$, $p = 0.59 > 0.05$; G-0: $\chi^2 = 0.82$, $p = 0.37 > 0.05$). The results for scenario I, however, agree with the findings of Xie et al. (2012) who reported that 52% of unfamiliar individuals who did not see a route sign at a symmetrical T-intersection choose the path to the right (in this study the percentage is 53.6%). Although the context of the experiments of Xie et al. is different, the results are related to the same scenario (unfamiliar individuals and no emergency signs). The results seem also to confirm the findings of Veeraswamy et al. (2011) who suggest that, without exit signage system at a symmetrical T-intersection, people with right handedness and driving to the right side (as the majority of the participants in this study is supposed to be) prefer the right path. Due to the lack of suitable references, no comparison with existing studies among groups (G-0 scenario) is possible.

When the exit signs P1, P2 and P3 were present (the exit signage system prompted to select the left path) a different behaviour is observed. In scenario I-ES (individuals and exit signs), 69.8% (74) of participants selected the left path and 30.2% (32) the path to right (I-ES: $\chi^2 = 16.64$, $p = 0.00005 < 0.05$). In scenario G-ES (groups and exit signs), 60.8% (59) of participants selected the left path and 39.2% (38) the path to right (G-ES: $\chi^2 = 4.55$, $p = 0.03 < 0.05$). Although no information regarding the actual detection of exit signs by participants is available, form a statistical perspective the difference between experiments without exit signs and experiments with exit signs emerges (test of independence between I-0 and I-ES: $\chi^2 = 8.48$, $p = 0.004 < 0.05$; independence between G-0 and G-ES: $\chi^2 = 5.16$, $p = 0.02 < 0.05$). In fact, the proportion of population that choose the left path increases from 46.4% to 69.8% in individual experiments and from 46.9% to 60.8% in group experiments. Figure 10.6 shows that the left exit signage system prompts people to select the left path and this behaviour is stronger when people face individually the decision point (I-0 scenario). As indicated, in individual experiments the proportion of people that selected the left path increases by 50%, while in group experiments by about 30%. This difference can be explained in terms of herding behaviour that arises when people move in groups. In fact, it is reasonable to believe that a proportion of participants during group experiments at the decision point did not look for information by seeking exit signs, but simply followed the flow, which in absence of exit signs is slightly biased to the right. The tendency to follow the flow emerged also during the debriefing session, when several participants referred that at the T-intersection (point P2) they followed other participants. This behaviour is reported here only as general information, since currently specific data are not available to demonstrate it.

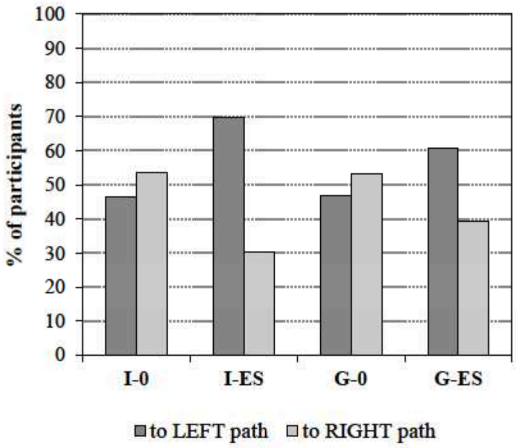
However, the initial idea of differences in the choice behaviour between groups and individuals is confirmed by these experiments and these differences, although from a macroscopic perspective, were quantified.

The effects of exit signs on people's choice can also be studied by checking how many people changed their first decision (to select the entry) at the T-intersection (where they had to select the path). Table 10.6 reports a summary of this behaviour. The effects of the presence of exit signs are evident if in presence of exit signs, the proportion of people entering from right and selecting the left path increases (Figure 10.7(a)), and if the proportion of people entering from left and selecting the right path decreases (Figure 10.7(b)). In fact, in the first case the adopted exit signage system prompts people to change their initial decision (and, referring to Veeraswamy et al. (2011), to choose an unnatural direction - the left). In the second case the exit signs reinforce the first decision (to head towards the left).

As concerns the proportion of people that entered from right and selected the left path in presence of exit signs, in individual experiments it increased from 57.1% to 72.2% and in group experiments from 27.1% to 34.0% (Figure 10.8(a)). On the contrary, the proportion of people that entered from left and selected the path to the right (with the presence of exit signs), in individual experiments decreased from 64.3% to 35.0% and in group experiments from 36.0% to 14.0% (Figure 10.8(b)). Therefore, in both cases the influence of the exit signage system on people's path choice at the T-intersection is evident.



(a)



(b)

Figure 10.6. People's **path** choice with (I-ES and G-ES scenarios) and without (I-0 and G-0 scenarios) the left exit signs. (a) sketch of the LabCUBE$_{egress}$ section checked; (b) results.

It is worthwhile highlighting that, although involving unfamiliar and untrained individuals, these experiment were carried out in ideal conditions: no emergency was simulated, the visibility was good, the exit signs were placed on a white background and the overload of environmental cues was limited. Furthermore, the study was performed by using a left exit signage system. Therefore, the results obtained are related to this scenario, which can constitute a benchmark scenario for further research on this topic. For example, different behaviours may be observed by adopting a different exit signage system and in different environmental conditions.

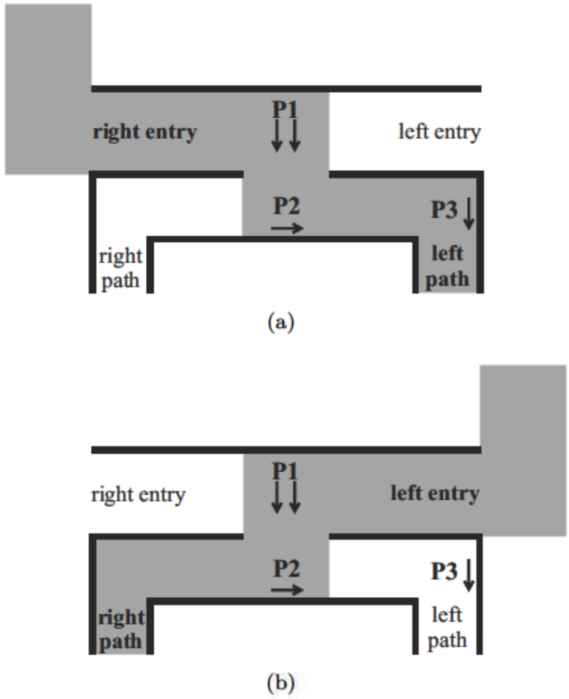


Figure 10.7. People's route choice from entry to path. (a) from right entry to left path; (b) from left entry to right path.

Table 10.6. Results obtained from LabCUBE$_{egress}$ experiments expressed in terms of relationships between first choice (select the entry) and second choice (select the path at the decision point).

Scenario	People			
	from **right entry** to **left path** (Figure 10.7(a))		from **left entry** to **right path** (Figure 10.7(b))	
I-0	16	(57.1%)	18	(64.3%)
I-ES	48	(72.2%)	17	(35.0%)
G-0	26	(27.1%)	40	(36.0%)
G-ES	16	(34.0%)	7	(14.0%)

10.3 Estimation of $\eta_{scenario}$ and calibration of EC factor

The results obtained in Section 10.2.5 show that the exit signs affect people's behaviour at a decision point, and that people's choice effectiveness is different when single individuals or groups face the decision point. Although the first aspect emerged also from

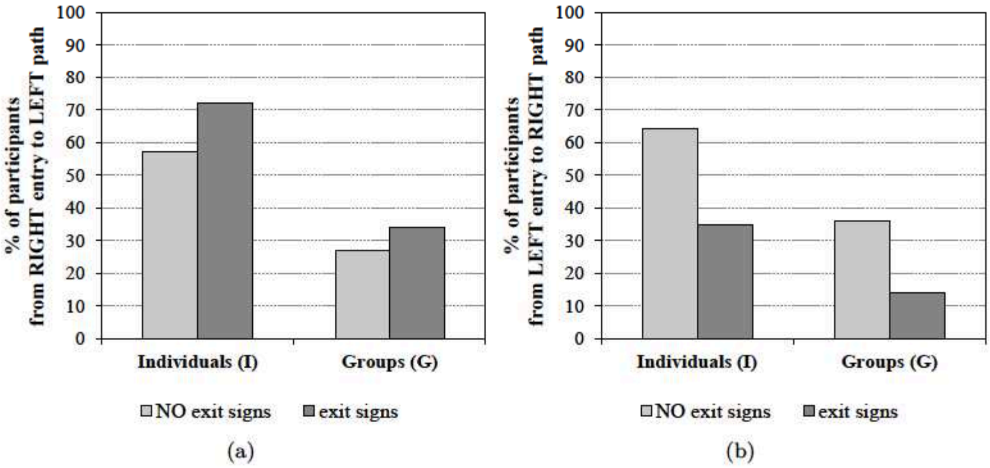


Figure 10.8. Results of people's route choice from entry to path. (a) from right entry to left path; (b) from left entry to right path.

other studies (see Section 10.2.1), the available data were no sufficient to represent in engineering terms all the scenarios linked with the factor EC adopted in PASS. No studies are available on the differences between group and individual behaviour at a decision point, with and without exit signs. Furthermore, the only possible comparison with existing data shows an agreement with the results obtained in this study (although in ideal conditions), and this enforces the thought that the approach proposed can be used for quantifying human behavioural factors (due to the differences between the studies only the comparison of one scenario was feasible).

EC factor can be calibrated once the effectiveness of people's choice $\eta_{scenario}$ is estimated, according to Eq. (10.1). Table 10.3 summarises how EC can be calibrated. As shown, η_{I-ES}, η_{I-0}, η_{G-ES}, and η_{G-0} have to be estimated.

From the results of the path selection reported in Table 10.5 and from the analysis that followed, a preferred path not was statistically evident when exit signs were not present (I-0 and G-0 scenarios). Reasonably, it can be assumed that people when no exit signs are present choose either the right or the left, with no evidence of preference in both individual and group experiments. Since the proportion of people leading to left and right is of about 50%, from Eq. (10.1), $\eta_{I-0} = \eta_{G-0} = 0.5$.

As regards the behaviour of unfamiliar people when exit signs are present, for individuals the percentage of people that selected the left path (due to the fact that left exit signs were adopted, the data used are those referring to the left) is 69.8%, while for groups it is 60.8%. According to Eq. (10.1), $\eta_{I-ES} = 0.698 \approx 0.7$ and $\eta_{G-ES} = 0.608 \approx 0.6$. The results for $\eta_{scenario}$ are summarised in Table 10.7.

From the values reported in Table 10.7, and recalling Table 10.3, the whole set of the EC factors can be easily estimated. The results are reported in Table 10.8. Then, the calibrated factor can be integrated in PASS.

Table 10.7. $\eta_{scenario}$ calculated with Eq. (10.1).

$\eta_{scenario}$	Value
η_{I-ES}	0.70
η_{I-0}	0.50
η_{G-ES}	0.60
η_{G-0}	0.50

Table 10.8. EC factor.

Familiarity with the means of egress	People movement capabilities				
	Generic	Standard	Guided	Reduced	Assisted
Yes	–	1.00	0.80	0.75	0.50
No, exit signs are present and visible	0.60	0.70	0.50	0.50	0.30
No, exit signs are not present	0.50	0.50	0.40	0.35	0.25

These experiments allowed studying the four different scenarios linked with the egress capabilities factor EC. LabCUBE$_{egress}$ layout was designed in order to collect data on the effects of exit sign on people's choice at a critical point. During the experiments, although performed in normal conditions and with left exit signs, data on both individual and groups were measured. As more than 400 persons were involved in the experiments, the data could be statistically treated. From a statistical analysis at a macroscopic level, the results showed a difference in the people's choices with and without exit signs, in both individual and group experiments. By adopting a cause-effect approach for studying the effects of exit signs on people's choice, the effectiveness of people's choice was estimated for the four scenarios. This allowed calibrating the whole EC factor, and integrating it in PASS.

LabCUBE$_{egress}$, therefore, demonstrated itself as a suitable laboratory for studying and calibrating the factors used in PASS for including aspects of human behaviour in the analysis. Given this, its fully capabilities may be used in future research on this topic.

Thanks to the results obtained in Part II and from LabCUBE$_{egress}$ experiments, PASS was applied to a case study. Egress system performance was checked, and the obtained results were compared with evacuation models and data collected from an evacuation drill (Chapter 11).

11

Application of PASS to a case study

The results obtained in Parts II and III allowed integrating PASS with a simple methodology for estimating with a scenario-dependent approach the standard times. In addition, the experiments performed with LabCUBE$_{\text{egress}}$ allowed calibrating the people's egress capabilities factor EC.

However, for exploring PASS capabilities to assess rapidly the egress system vulnerability its application to a case study is needed. In this Chapter an application of PASS is reported and compared with the results obtained from numerical simulations and an evacuation drill. The complete set of tools used for the PASS multilevel analysis is reported in Appendix.

11.1 Characteristics of the scenario studied

The studied egress system is a section of a secondary school (San Vito al Tagliamento, Pordenone, Italy) occupied by students with normal movement capabilities and with age ranging from 15 to 19 (Figure 11.1). It is composed of 3 classrooms located at the same level (first floor), 1 corridor, 1 emergency exit, and 1 stairway that connects the first floor with the ground floor.

Referring to the terms adopted in PASS (Table B.1), the actual egress system is composed by 3 cells (C1, C2, C3), 5 gaps (G1, G2, G3, G4, G5), 1 horizontal path and 1 vertical path (Figure 11.2). 21 students populate cell C1, 19 cell C2, and 20 cell C3. The total population that occupies this building area is then 60 occupants. Because combustible materials are present only in the cells, 3 hot zones, 1 warm zone and 1 temporary-cold zone are identified. The safe zone is identified as that area at the end of the vertical path, beyond gap G5. Therefore, 3 conventional scenarios have to be assessed. However, as the 3 cells are equal, only the worst scenario in which the most populated cell (C1) is the hot zone can be considered.

No internal coverings and combustible contents are presents, except for desks and chairs in the hot zone. The cell hazard level CHL is then 0, and consequently the zone hazard level ZHL is low (L) (see Appendix B).

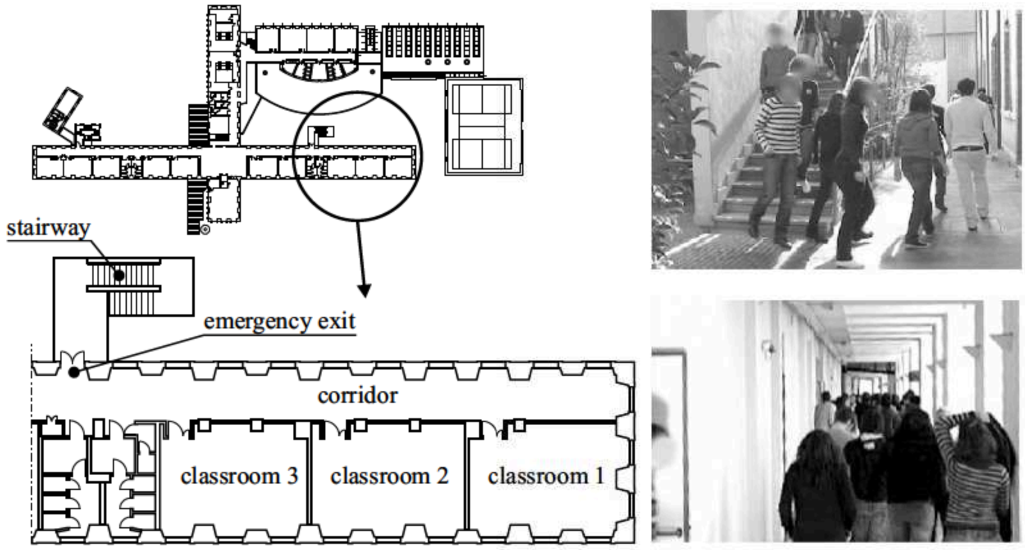


Figure 11.1. Sketch of the analysed egress system. [Adapted from Grimaz and Tosolini (2011).]

Following the process reported in Figure 2.4, PASS can be used for checking the egress system performance.

11.2 PASS performance assessment

11.2.1 GLs analysis

GLs analysis (see Appendix C) is carried out for the entire egress system. The longest path identified is from cell C1 to gap G5 (EP_{max} = 57 m). This gap is also the only gap that connects temporary-cold zone with safe zone and has an effective width W_{eff} equal to 110 cm. ET_{GL} is equal to 300 s, as the worst zone hazard level is low (L), people density is low and people are familiar with the building. The total population P_{tot} is 60 occupants. Egress system has a tree configuration ($ES_{config} = 0.60$). Because of emergency plans are present, people have standard mobility and familiarity with the building (accessed mainly by students), a safety factor SF_{GLs} equal to 1.25 can be adopted. Referring to this scenario, the condition required by Eq. (C.1):

$$\max\left[\frac{57\cdot 1.25}{0.7}, \left(\frac{60\cdot 350\cdot 1.25}{110\cdot 0.60}\right)^{\frac{1}{1.37}}\right] \leq 300$$

gives $101 \leq 300$. The check is passed, and no weaknesses at the first level of analysis emerge.

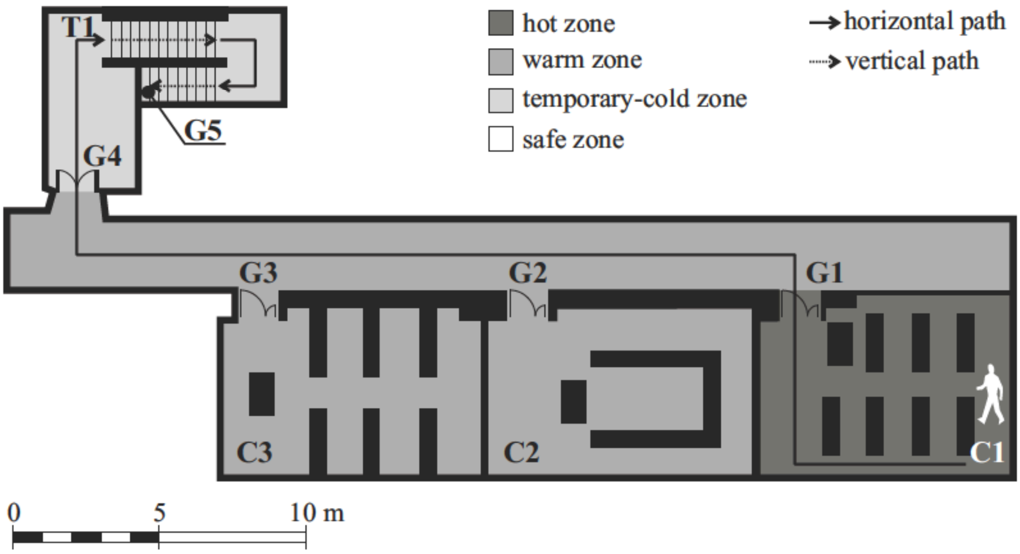


Figure 11.2. Schematic form of the egress system and scenario assessed.

11.2.2 MA analysis

The Move Away analysis (see Appendix D) is performed in both temporary-cold and warm zones to check if occupants can move away safely from these zones, and to identify potential system weaknesses.

MA analysis for the temporary-cold zone

As reported in Figure 11.2, temporary-cold zone is identified with the area beyond gap G4. MAr analysis is carried out considering the presence of horizontal paths (PL_{max} = 10.5 m) and vertical paths (PL_{max} = 8 m). $T_{TC-ZONE}$ is equal to 300 s. People have standard movement capabilities and are familiar with the building ($EC = 1.00$). The exposure factor EX is equal to 0, as $CHL = 0$ and there is no explosion risk. Hazards factor HZ_{MAr} is 1.80 ($ZHL = L$; open area; MAa analysis not passed). As only a single flow is present $PI = 1.00$. Safety factor SF_{MAr} is equal to 1.5 (emergency plans are present). The condition required by Eq. (D.1):

$$\frac{10.5 \cdot 0}{0.90 \cdot 0.80} + \frac{8.0 \cdot 0}{0.90 \cdot 0.80} \leq \frac{0.7 \cdot 300 \cdot 1.00}{1.5}$$

gives $0 \leq 140$. The check is passed.

MAc analysis is made at transition T1, the section where the path narrows (W_{eff} = 110 cm) and changes from horizontal to vertical. At this point 60 occupants have to be considered ($p^{MAc} = 60$) . The hazard factor HZ_{MAc} is equal to 1.2 (ZHL is low); the merging path factor MP is 1.00 (single flow); the safety factor SF_{MAc} is 1.6. As the path leads to a uniform stair (raiser 16.5 cm, tread 30.0 cm), the path flow factor PF is equal to $1.00 \times 0.75 \times 1.00 \times 0.90 \times 0.85 = 0.57$. The condition required by Eq. D.2:

$$60 \leq \frac{110 \cdot 300^{1.37} \cdot 1.2 \cdot 0.57 \cdot 1.00}{1.6 \cdot 350}$$

gives $60 \leq 330$. The check is passed.

Therefore MA analysis in the temporary-cold zone is passed. No weaknesses emerge.

MA analysis for the warm zone

The identified warm zone is highlighted in Figure 11.2. The length of its path PL_{max} is 38 m (measured from point C1 to G4). T_{w-zone} is 290 s, as obtained from Figure D.2 for a $V_{fill} = 140$ m^3 and a ESG class equal to ESG-2 (Smoke Velocity class: S; $V_{h-zone} \approx 120$ m^3; 1 door). People's egress capabilities factor EC is equal to 1.00; the exposure factor EX is equal to 0; hazards factor HZ_{MAr} is 0.80 ($ZHL = L$; no protection systems; MAa analysis not passed). As the main flow in the path merges with secondary flows from cells, $PI = 0.90$. Safety factor SF is equal to 1.5 (emergency plans are present). The condition required for MAr analysis by Eq. (D.1):

$$\frac{38 \cdot 0}{0.90 \cdot 0.80} \leq \frac{0.7 \cdot 290 \cdot 1.00}{1.5}$$

gives $0 \leq 135$. The check is passed.

MAc analysis is made for gap G4 ($W_{eff} = 110$ cm) and referring to a total population p^{MAc} of 60 students. The hazard factor HZ_{MAc} is equal to 1.2 (ZHL is low); the merging path factor MP to 1.00 (single flow); the safety factor SF_{MAc} to 1.6. As the path leads to a uniform horizontal path, the path flow factor is equal to $1.00 \times 1.00 \times 1.00 \times 1.00 \times 1.00 = 1.00$. For a T_{w-zone} equal to 290 s, the conditions required for MAc analysis by Eq. D.2:

$$60 \leq \frac{110 \cdot 290^{1.37} \cdot 1.2 \cdot 1.00 \cdot 1.00}{1.6 \cdot 350}$$

gives $60 \leq 550$. The check is passed.

Also in the warm zone MA analysis is passed, and no weaknesses emerge.

11.2.3 PE analysis

PE analysis (see Appendix E) focuses on the hot zone, and checks whether occupants can escape and reach the warm zone safely. 3 hot zones can be identified (cells C1, C2, C3) but, as these zones are similar, the analysis is carried out for cell C1 in which the highest number of students is present ($p^{PEc} = 21$). The length of the longest path towards the gap G1 (PL_{max}) is equal to 12 m. People's egress capabilities factor EC is 1.00, like in MA analysis. Hazard factor HZ_{PEr} is equal to 1.33 ($CHL = 0$ and no protection systems). Factor OP is equal to 0.67, as people density is low and movable obstacles are present (desks and chairs). The safety factor SF_{PEr} adopted is equal to 1.7 (multiple and symmetrical paths to reach the gap are present). T_{h-zone} is equal to 70 s and it is obtained from Figure E.3 for a hot zone height $H_{h-zone} = 3.0$ and a CSF class equal to CSF-8 (Smoke Velocity class: S; $A_{h-zone} \approx 48$ m^2). The condition required for PEr analysis by Eq. (E.1):

$$12 \leq \frac{0.7 \cdot 70 \cdot 1.00 \cdot 1.33}{0.67 \cdot 1.7}$$

gives $12 \leq 57$. The check is passed.

Only one gap is present in the cell (G1) and it has a nominal width W_{nom} equal to 85 cm. PEc analysis is then performed at gap G1. People are generic and their body width W_{body} is 55 cm. This gives only one potential line at the gap, $nL = 1$, and a line interaction factor $LI = 0.90$ ($W_{net} = 30$ cm). The gap is horizontal and the door swing direction is outward: GF factor is then equal to 1.0. The hazard factor HZ_{PEc} is equal to 1.2 ($CHL = 0$) and the safety factor SF_{PEc} is 3.0 (only one gap is present). The condition required for PEc analysis by Eq. (E.2):

$$21 \leq \frac{1.4 \cdot 1 \cdot 1.0 \cdot 0.90 \cdot 70 \cdot 1.2}{3.0}$$

gives $21 \leq 35$. The check is passed.

PEa analysis is not made as the maximum length of the cell is less than 15 m.

Because all the conditions required by the PASS multilevel analysis are met, no critical points (or weaknesses) in the egress system emerged. Therefore, it can be reasonably concluded that its actual performance guarantees a safe evacuation for people. However, in order to explore whether the PASS assessment is correct, a comparison between PASS, evacuation models, and data collected during an evacuation drill was made.

11.3 Comparison between PASS, evacuation drill and evacuation models

In Section 11.2, a rapid screening of the egress system performance was made with PASS tools. In that case study no weaknesses, or critical points, emerged. In order to deepen the analysis of PASS capabilities, and in particular to investigate whether PASS assessment is acceptable, an additional analysis was carried out. Referring to the same egress system (Figure 11.1), a comparison between the results obtained from PASS, an evacuation drill and two evacuation simulation models was made.

Experimental data were collected from an announced evacuation drill performed in the section of the analysed egress system on 17 February 2009 (11:00 local time). 60 occupants among teachers and students took part to the experiment. 4 cameras and 5 operators registered exit times at points G1, G2, G3, G4, P1 and G5. The evacuation was also modelled with the evacuation simulation models STEPS and FDS+Evac (v.2.3.1).

STEPS (Mott MacDonald Simulation Group) (Simulation of Transient Evacuation and Pedestrian movementS), is a model developed by Mott MacDonald Simulation Group. It can simulate movement of individuals in normal and emergency conditions in any type of building by calculating the path to the exit through a grid. It is a movement/partial behaviour model. Occupants are assumed to have the same size of the grid cell that they occupy. The grid is also used to model the building geometry. People move towards exits by following a potential map that is updated recursively by considering the presence of other occupants, obstacles, queues at exits. The model can import fire data from external sources and it is validated against codes, fire drills and literature on past experiments. STEPS was used in a wide range of scenarios. Capote et al. (2012), for example, used STEPS for exploring the impact that crew procedures have on evacuating two high-speed trains under different fire scenarios. Ronchi et al. (2013) tested its applicability in road tunnel evacuations scenarios.

FDS+Evac (Korhonen and Hostikka, 2010) is the evacuation module of the Fire Dynamics Simulator (FDS) (McGrattan et al., 2010a). It is a partial behaviour model that simulates individual movement in a continuous network by adopting the Helbing's social force model (Helbing and Molnar, 1995). People are guided towards exits by an evacuation flow field map and during their movement they maintain a minimum distance from the other occupants, obstacles, building elements. FDS+Evac allows modelling simultaneously fire and evacuation, and considering the effects of fire hazards on people's movement and decisions. It is validated against fire drills, literature on past experiments, and other models. In addition, Lei et al. (2013) used FDS+Evac to investigate the evacuation process in a dormitory and compared numerical results with data collected from evacuation drills. Ronchi et al. (2012) explored FDS+Evac capabilities in modelling the impact of different emergency exit signs during tunnel evacuations.

The evacuation drill was announced and operators reported that people started evacuating immediately after the alarm. Therefore, pre-movement time is assumed to be zero and in both STEPS and FDS+Evac simulations it was not modelled. In STEPS the density-velocity curve of Nelson and Mowrer (2002) was adopted with a maximum walking speed equal to 1.19 m $s^{-1}$and a grid size of 0.50 m. In FDS+Evac simulations the default values for adults, the anisotropy parameter $\lambda_i = 0.3$ and a grid size of 0.20 m were used. Fire dynamics were not included in both simulations because of the evacuation drill was carried out in normal conditions.

PASS is not a simulation model, but a suite of tools that allow checking the egress system vulnerability and identifying its weaknesses. Therefore, it is not possible to compare directly PASS results with simulation models. These models, in fact, analyse the egress system with a time based approach, PASS by checking the level for the three performance indicators. Therefore, in order to compare PASS results with simulation models and experimental results the standard times ET_{GL}, T_{w-zone}, $T_{TC-ZONE}$ and T_{h-zone} are calculated for the factor values adopted during the multilevel analysis. By comparing calculated PASS standard times with numerical simulations and experimental results it is possible to check if PASS estimates correctly the actual performance of the egress system. PASS estimations can be considered correct if the calculated standard times are comparable with experimental and numerical results.

During the evacuation drill exit times at the classrooms exits (point G1, G2, and G3), at the emergency exit (G4) at the stairway entrance (T1) and the total evacuation time (G5) were collected. Therefore, the evacuation times at the same points were calculated with PASS formulae (GLs, MAc, PEc) and evacuation models. Times at points G1, G2, G3, G4 and T1 indicate the time needed to cross the gaps. Total evacuation time indicates the time needed for the last occupant to reach gap G5 and it is measured from the instant when the alarm sounded.

Measured and calculated evacuation times are reported in Figure 11.3. The times calculated from STEPS and FDS+Evac are the mean from 50 simulations. PASS standard times are calculated with and without safety factors (the results obtained with the safety factors are reported with the dashed positive variation line).

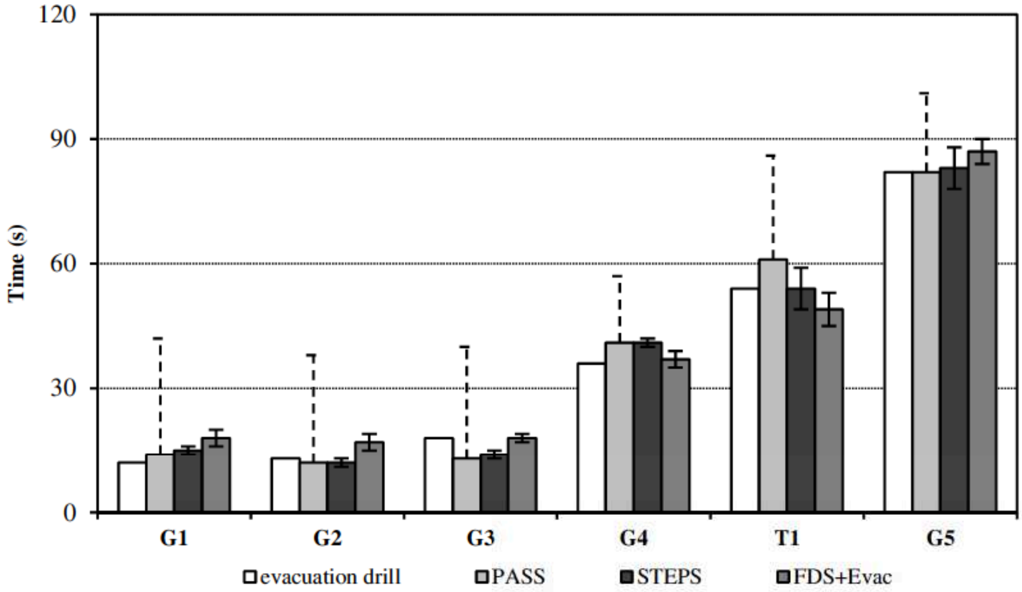


Figure 11.3. Results obtained in the comparison between evacuation drill, PASS, STEPS, FDS+Evac.

A good agreement between evacuation drill, PASS and STEPS is observed for the total evacuation time (point G5), while FDS+Evac results are slightly conservative. Referring to the positive standard deviation, it can be seen that evacuation models and PASS assess total evacuation time with a good margin of safety (+23% for PASS, +7% for STEPS, +9% for FDS+Evac).

Results have a different trend if focusing on the other parts of the egress system. At the stairway entrance (point T1), where 60 people queue and where the egress route narrows and changes slope (from horizontal to vertical), different results between the tools used are observed. FDS+Evac predicts a lower time required to cross the gap if compared with STEPS results and evacuation drill. This may be related to the different approach used to model the space (continuous in FDS+Evac and fine network in STEPS) and to the different flow rate achieved at this transition (FDS+Evac specific flow rate is 1.22 p s^{-1}, and 1.11 p s^{-1} for STEPS). However, if considering the results of the positive standard deviation, FDS+Evac results are equal to those from the evacuation drill. STEPS results are equal to experimental results and, considering the positive standard deviation, on the safe side (+10%). PASS estimations are on the safe side, also without the safety factor (+13% without safety factor).

The same behaviour between FDS+Evac and STEPS is observed at point G4 (emergency exit). Also at this transition people queue (this behaviour is also observed in video recordings), because the exit route narrows although its slope does not change. FDS+Evac specific flow rate at point G4 is 1.62 p s^{-1} and 1.46 p s^{-1} in STEPS. These values are higher than those achieved at the stairway entrance, and this indicates that more the transition is irregular, lower the flow rate is. PASS considers this aspect in its analysis by adopting different values for the path flow factor PF (see Appendix MAc test). All the calculated results are on the safe side (the safety margins are +14% for PASS, +14% for STEPS, +3% for FDS+Evac).

If analysing the results of exit times at gaps G1, G2, G3 it can be seen that FDS+Evac results are constant and conservative. STEPS estimates lower exit times (hence higher specific flow rates), however, except for gap G3, its results are on the safe side. PASS estimations (without safety factors) are comparable with STEPS results, while the results with safety factors are over-conservative because for this scenario (presence of only one gap) a safety factor equal to 3 is used in order to penalise a layout with only one gap (i.e. no alternatives are present). If considering the experimental results, exit times at G1 and G2 are similar. At G3 the exit time is higher, 18 s against 12 s (gap G1) and 13 s (gap G2). As observed in video recordings, these differences may be related to the presence of people in the corridor that had already exited rooms C1 and C2 and slowed down evacuation from room C3 (interference among flows).

As shown, the results obtained with PASS for this scenario are coherent with both measured and numerical data, and on the safe side if its safety factors are used. These conclusions are certainly valid for this case study, but when applying PASS to other scenarios the results obtained have to be carefully judged and, preferably, compared with other well validated tools.

The application of PASS demonstrated that its use allows getting in a rapid and simple way results comparable with traditional tools (evacuation models) and with measured data. However, significant differences are related to the time required for the analysis: PASS application took approximately one hour, the application of STEPS and FDS+Evac a day. Hence, the tools included in PASS can be used to perform rapid checks of egress system performance and to identify its weaknesses. Suitable strategies can then be developed by solving, for example, the weaknesses linked to those factors that affect significantly the egress system performance. As a pre-design tool complementary to evacuation models, PASS can provide quickly a validation check on computer simulations and a useful rapid estimation of evacuation performance. This may allow solving egress system critical points, if any, before the use of evacuation models, and hence their focused use.

Conclusions

PASS (Preliminary Assessment of the egress System Safety) is a method for assessing the egress system vulnerability and constitutes the basis for the work presented in this thesis. It comprises simple tools that, with a multilevel analysis approach, allow a rapid check of the egress system performance without simulating the evacuation process. Instead, it compares the egress system actual performance with a standard performance required to guarantee people's safety. The actual performance is assessed by checking the possibility that evacuees have to reach and to cross the gaps, along with the presence of alternative routes. The standard performance is established through standard times, which indirectly express the time within untenable conditions are achieved in case of fire.

Due to the importance of estimating the standard times with a scenario-dependent approach, a simple but effective methodology was developed and integrated in PASS. An initial analysis of the variation of tenability criteria adopted for estimating the $ASET$ as a function of the variation of several input data demonstrated that, in case of an enclosure fire, people's safety can be assessed in terms of smoke-free layer height above the floor. The most important input data for its estimation is the rate at which energy is released by the fire (HRR, Heat Release Rate).

Starting from these results, key elements for representing in a simple form both the smoke filling process in a fire origin room, and the smoke spreading through vents were identified. These elements allowed developing the Cell Smoke Filling conceptual model, CSF (it schematises the smoke filling process), and the Equivalent Smoke Generator conceptual model, ESG (it schematises the smoke spreading through vents).

CSF and ESG conceptual models were represented in engineering terms through the use of analytical equations, which allow estimating the PASS standard times once the geometrical features of a room and the characteristics of the combustible contents are specified. Range of validity, trend analysis and safety factors for getting results on the safe side were obtained for different scenarios by comparing the equations with the computational fluid dynamics model FDS. According to PASS approach, pre-codified solutions were developed and represented in tables and diagrams. These solutions constitute a set of rapid, simple but effective tools for estimating the PASS standard times. A final comparison between pre-codified solutions and FDS numerical results showed a good agreement between the two methods for the considered scenarios.

In addition to fire dynamics, human factors have a fundamental role in the evacuation process and a comprehensive egress system assessment should include these factors. PASS meets this requirement by adopting a set of factors that take into account people-people and people-egress system interrelationships. In order to quantify quantitatively the key human behavioural aspects and to calibrate the associated PASS factors, the laboratory LabCUBE$_{\text{egress}}$ was conceived and realised.

LabCUBE$_{\text{egress}}$ is a movable structure with a flexible configuration which can be customised to create several layouts and to reproduce different parts of an egress system. A wide cross-section of population (more than 400 participants) was involved in a set of experiments aimed at quantifying the effects of exit signs on people's choice at a critical point (T-intersection). The results allowed quantifying the effectiveness of people's choice in this configuration, and revealed that the effects of exits signs are statistically different between groups and individual participants: with a left exit sign only 70% of individuals choose the shown direction, and this value drops to 60% for groups. The results obtained allowed calibrating a PASS factor associated with this behavioural factor.

The method PASS was finally applied to a case study. Results were compared with data collected during an announced evacuation drill and numerical data obtained from evacuation models STEPS and FDS+Evac. The comparison showed that PASS results are comparable with experimental and numerical data, and on the safe side if the suitable safety factors provided by PASS are adopted. In addition, PASS results were obtained faster than numerical results (the time ratio for the considered case study between the two approaches is 1:24).

Some limitations of the study should be acknowledged and the opportunities for future research identified.

The evaluation of PASS standard times obtained with CSF and ESG conceptual models was carried out with FDS, and no comparison with real scale experiments, or available experimental data, was made. However, FDS is a well validated model for studying compartment fires, and it can be considered a valid reference tool for checking the analytical results. In addition, the correctness of the solutions obtained with the CSF and ESG conceptual models were verified and demonstrated for a set of standard scenarios. Every extrapolation from the original context should be judged carefully. Future research on this topic is recommended in order to extend the range of application of the proposed simplified tools.

Experiments with the $\text{LabCUBE}_{\text{egress}}$ were carried out in a controlled environment, in a specific layout, with good visibility and limited environmental cues, but involving participants untrained, unfamiliar and representative of a wide cross-section of society. The results are then valid for this scenario, and different people's behaviour can be expected in other contexts and with other $\text{LabCUBE}_{\text{egress}}$ layouts. As this simple novel approach proposed for studying human behaviour and representing it in engineering terms demonstrated its validity, future research should address this topic, proceed with the calibration of the whole set of PASS behavioural factors, and compare the results obtained in this work (which can constitute a benchmark scenario) with those obtained in other configurations. Furthermore, the collection of more specific data (at individual level) could allow improving the knowledge of particular behavioural patterns.

Finally, the application of PASS to a case study confirmed its capabilities for checking rapidly the egress system vulnerability. PASS results are comparable with those obtained from traditional tools (evacuation models), but the validity of PASS was checked only in a specific scenario (a high school with standard population and in normal conditions). When applying PASS to different scenarios, the assessment outcomes have to be carefully judged and, preferably, compared with other validated tools. For extending PASS range of validity, future research should test PASS in different scenarios.

Thanks to the results achieved and the opportunities for future research, PASS can be proposed as a stand-alone tool for the egress system vulnerability assessment. Because it is a simple, pre-codified and rapid method, PASS can be used when a rapid performance assessment and identification of safety solutions are required, for example during a preliminary design phase or for managing the safety of existing egress systems. Due to the necessity of providing solutions in dynamic scenarios and with few input data, in these contexts the use of sophisticated numerical tools can be difficult. Differently than traditional simulation tools, PASS adopts a novel approach for assessing egress system safety without simulating the evacuation process. It allows a fast identification of the egress system critical points and to tailor the safety solutions necessary to improve its performance.

A
PASS flowchart

A.1 Flowchart for the PASS multilevel analysis

The multilevel analysis proposed in PASS can be accomplished by following the steps reported in Figure A.1.

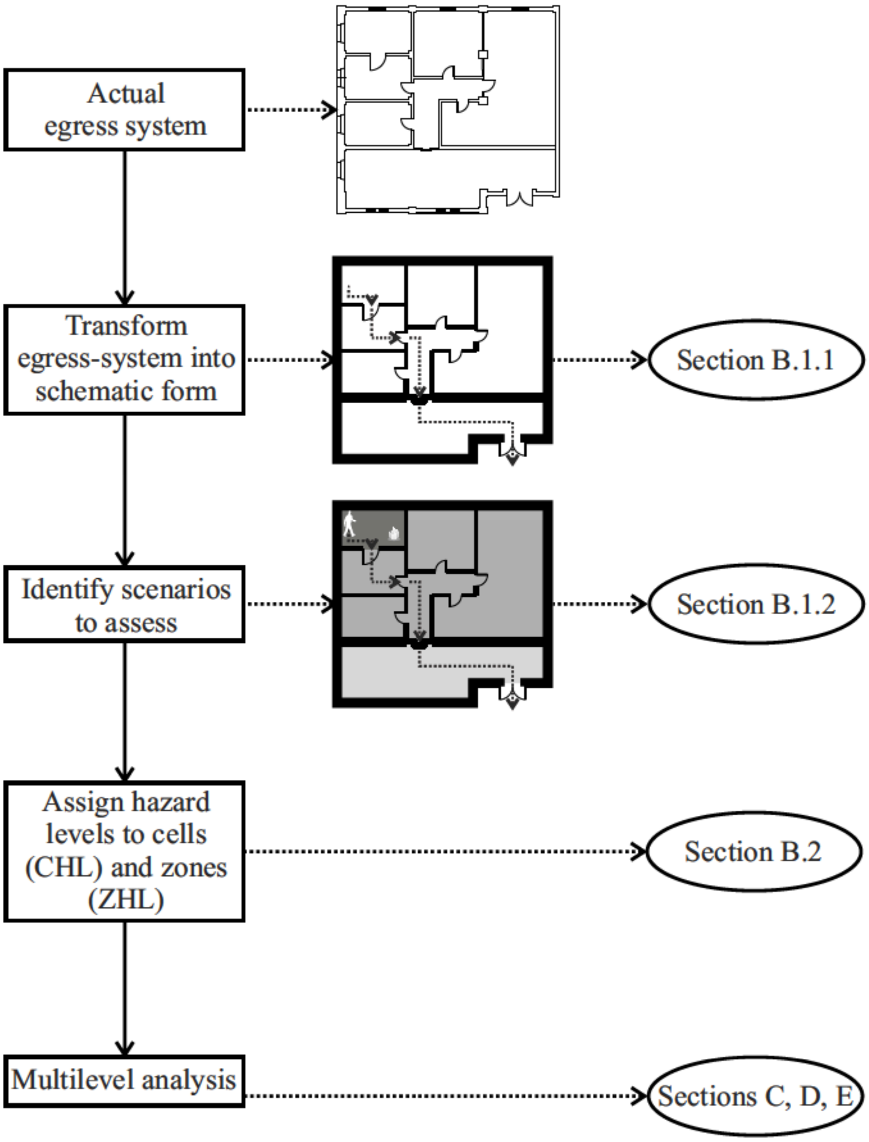


Figure A.1. Steps for achieving the PASS multilevel analysis.

B

Preliminary analysis: schematic egress system, scenarios, hazard levels

B.1 Schematic egress system and scenarios for the analysis

B.1.1 Schematic egress system

The multilevel analysis proposed in PASS is performed on a schematic form of the egress system. It is set up considering the exodus-borders conceptual model and by using the elements that it adopts (see Table B.1 for definitions). The egress system is then a set of cells, gaps, paths, barriers and zones. Figure B.1 shows an example of how the actual egress system is transformed into the schematic form.

Table B.1. Elements adopted in PASS in order to schematise the egress system.

Term	Definition	Example
Barrier	A physical element with different protection ratings against hazards (smoke, heat, etc.)	wall
Cell	A volume enclosed by barriers with at least one gap that people can pass through	room
Gap	An opening in the barriers that allows people to enter in or exit from a cell or zone	doorway
Path	Horizontal or vertical route that connects different gaps, cells or zones	corridor, stairway
Standard time	Maximum time available to people in order to leave a zone	
Hot zone	Area in a building where hazards are generated and that has to be evacuated rapidly	fire origin room
Warm zone	Area enclosed by protection barriers that contain the hot zone and where hazards can spread	fire compartment
Temporary-cold zone	Area adjacent the warm zone separated by protection barriers which guarantee a defined protection rating against hazards	area adjacent a fire compartment
Refuge zone	Area in the temporary-cold zone where tenability conditions are guaranteed, and that can be safely leaved thanks to the intervention of rescue teams	area of refuge
Safe zone	Area where tenability conditions are guaranteed	area outside a building

B.1.2 Identification of the scenarios for the analysis

The scenarios to assess during the multilevel analysis are identified referring to the schematic form of the egress system as follows:

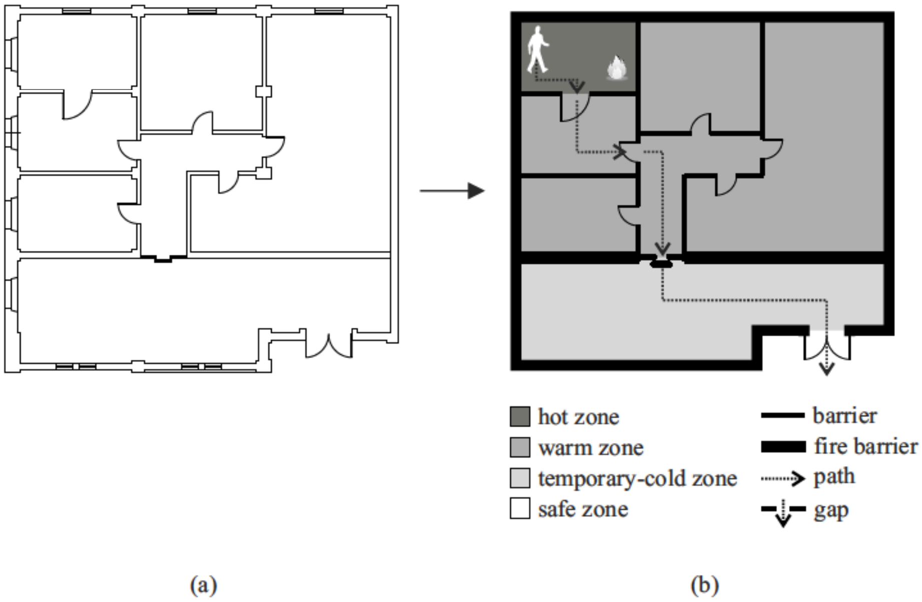


Figure B.1. (a) Actual egress system; (b) Scenario on which the PASS analysis will be performed.

1. the hot zone is defined by setting a fire in a cell containing combustible materials;
2. the warm zone is defined as that area enclosed by fire barriers and including the hot zone;
3. the temporary-cold zone is defined as that area outside the fire barriers (the hot zone is not included);
4. the safe and/or refuge zone are defined as that areas where tenability conditions are guaranteed.

It is worthwhile highlighting that the hot zone is defined only in cells containing combustible materials and that the temporary-cold zone is not identified if fire barriers are not present. The set of scenarios is developed by repeating the previous procedure for each cell of the schematic egress system. Therefore, the difference among the scenarios is due to the distribution of the zones across the egress system assessed. The multilevel analysis is applied to the set of the scenarios identified with the procedure or, alternatively, to the worst scenario identified. Figure B.1 (b) shows a typical scenario to assess.

B.2 Hazard levels CHL and ZHL

PASS tests are performed once the hazard levels for each cell and zone within the schematic egress system are set. Both cell hazard level (CHL) and zone hazard level (ZHL) depend on the characteristics of the combustible contents, furnishings and interior finishes present in the cells.

Firstly, the hazard level for each cell CHL is identified as summarised in Tables B.4 and B.5. The CHL for the analysed cell is the worst level identified between the Tables. The zone hazard level ZHL is then assigned as described in Table B.3. ZHL is a function of the hazard level of the n cells within the zone, and it is defined by adopting the Mean Hazard Index MHI:

$$MHI = \frac{\sum_{n=1}^{n.cells} chl_n \cdot A_{floor_n}}{\sum_{n=1}^{n.cells} A_{floor_n}}$$

where:

n	=	number of the cells within the zone;
chl_n	=	see Table B.2;
A_{floor_n}	=	floor area of the cell (m^2).

Table B.2. *chl* parameter.

CHL	*chl*
0	1
I	2
II	4
III	8
IV	16

Table B.3. Zone Hazard Level (ZHL).

MHI	ZHL
$1.0 < MHI \leq 1.5$	L
$1.5 < MHI \leq 3.5$	O
$3.5 < MHI \leq 7.5$	M
$7.5 < MHI \leq 14.0$	H
$MHI > 14$	E

Table B.4. Cell Hazard Level CHL. Combustible contents and furnishings.

Combustible contents and furnishings	Not present	Present
Plastic furniture or combustible carpets	0	I
Pillows or bedding elements	0	I/0[a]
Upholstered furniture or mattresses	0	II/I[a]
Electronic devices	0	II
Highly flammable solids or dusty materials	0	III/II[b]
Flammable liquids	0	III/II[b]
Flammable gases	0	III/II[b]/I[c]
Reactive compounds	0	III/I[b]
Radioactive materials	0	III/II[b]
Explosives	0	IV

[a] If may ignite but not sustain a flame and give off slight volume of smoke.
[b] If sealed or stored in safety cabinets.
[c] If present in pipes or spray.

Table B.5. Cell Hazard Level CHL. Interior finishes characteristics.

Interior finishes	Contribution to fire spread and smoke generation[a]	Not present	Present[b]			
			$A < 5\%$	$5 < A \leq 25\%$	$25 < A \leq 50\%$	$A > 50\%$
Generic coverings	low	0	0	0	0	I
	ordinary-high	0	II	II	II	II
Wood coverings	low	0	I	I	I	I
	ordinary-high	0	II	II	II	II
Curtains	low	0	I	I	I	I
	ordinary-high	0	II	II	III	III
Thin solid coverings	low	0	II	II	III	III
	ordinary-high	0	III	III	III	III
Thermoplastics/ high-toxic-emission-yield	low	0	I	II	III	III
	ordinary-high	0	IV	IV	IV	IV

[a] low: may ignite but not sustain a flame and give off slight volume of smoke;
ordinary-high: ignite, sustain a flame and give off considerable volume of smoke.

[b] percentage of cell area A is computed considering the area of floors+walls+ceiling. For curtains the total area is computed considering only walls.

C

GLs Analysis

C.1 GLs analysis

The General Leaving of system analysis (GLs) checks whether the population inside the considered area of the building (P_{tot}) can reach a safe or refuge zone within the maximum standard time ET_{GL}. GLs analysis assesses both the maximum egress route length and the maximum flow rate achievable at the gaps.

GLs is passed if:

$$\max\left\{\frac{EP_{max}\cdot SF_{GLs}}{v_{max}},\left[\frac{P_{tot}\cdot 350\cdot SF_{GLs}}{\left(\sum_{i=1}^{n.\,safety\,gaps}W_{eff_i}\right)ES_{config}}\right]^{\frac{1}{1.37}}\right\}\leq ET_{GL} \qquad \text{(C.1)}$$

where:

EP_{max}	=	length of the longest egress path that people have to cover in order to reach a refuge or safe zone (m);
SF_{GLs}	=	safety factor (Table C.3);
v_{max}	=	standard travel speed (set equal to 0.7 m s^{-1});
P_{tot}	=	number of persons that populate the considered area of the building;
W_{eff}	=	effective width (cm) of the gaps towards the refuge or safe zone (Figure C.1);
ES_{config}	=	egress system configuration factor (Table C.2);
ET_{GL}	=	maximum standard time available to reach a refuge or safe zone (Table C.1).

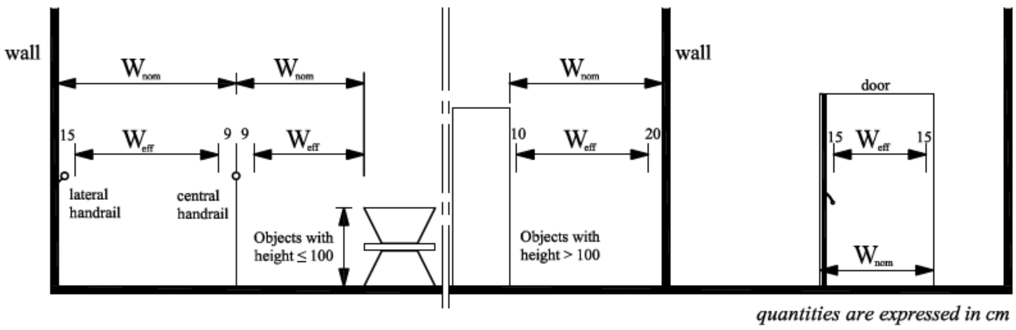


Figure C.1. Effective width (in cm) of the refuge or safety gaps (W_{eff}).

Table C.1. GLs analysis: maximum standard time (in seconds) available to reach a refuge or safe zone (ET_{GL}).

People's characteristics			ZHL (refer to the worst case)			
			L	O	M	H or E
Standard mobility	Low density d ($d \leq 0.4$ p m^{-2})	Familiar with the building	300	240	180	120
		Unfamiliar with the building	240	180	150	120
	High density d ($d > 0.4$ p m^{-2})		180	150	120	120
Reduced or assisted mobility, asleep			120	120	120	120

Table C.2. GLs analysis: egress system configuration factor (ES_{config}).

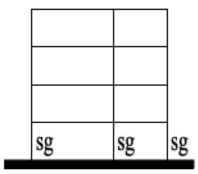
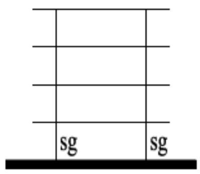
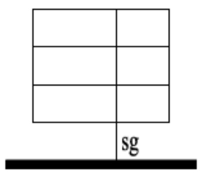
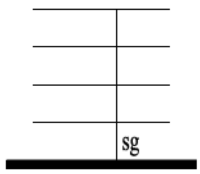
ES_{config}			
1.00	0.80	0.67	0.60
Fully connected configuration with multiple safety gaps (sg)	*Partially connected configuration with multiple safety gaps (sg)*	*Fully connected configuration with single safety gap (sg)*	*Tree configuration*
			
Every path of the egress system has at least two alternatives and multiple safety gaps are present.	The egress system has dead-end paths but multiple safety gaps are present.	Every path of the egress system has at least two alternatives but only one safety gap is present.	The egress system has dead-end paths and only one safety gap is present.

Table C.3. GLs analysis: safety factor (SF_{GLs}).

SF_{GLs}		
Occupancy use	**Emergency plan present**	**Emergency plan NOT present**
Activities with predominance of people with reduced mobility and not familiar with the building	2.50	5.00
Activities with predominance of public	2.00	4.00
Activities with public access	1.50	3.00
Activities with private access to people with reduced mobility and not familiar with the building	1.50	2.50
Activities with private access to people with standard mobility and familiar with the building	1.25	2.00

D
MA Analysis

D.1 MAr analysis

The Move Away reaching gap analysis (MAr) checks whether the population can escape from both the warm and temporary-cold zones within a standard time.

When performed in the **warm zone**, MAr analysis checks if people can reach the gaps that connect the warm zone with temporary-cold or refuge zones (when present). When performed in the **temporary-cold zone**, it checks if people can reach the gaps that connect the temporary cold zone with safe or refuge zones.

MAr analysis assesses the length of the longest path towards the gap that has to be reached to move away from the zone analysed and it is passed if:

$$\sum_{i=1}^{n.uniform\ paths} \frac{PL_{max_i} \cdot EX_i}{PI_i \cdot HZ_{MAr_i}} \leq \frac{v_{max} \cdot T_{std} \cdot EC}{SF_{MAr}} \tag{D.1}$$

where:

PL_{max_i}	=	length of the longest uniform path i (m) towards the gap that has to be reached to move away from the warm/temporary-cold zone. A path i is uniform when EX_i, PI_i, and HZ_{MAr_i} are constant;
EX_i	=	exposure factor (Table D.3);
PI_i	=	people's interaction factor (Table D.5);
HZ_{MAr_i}	=	hazards factor (Table D.4);
v_{max}	=	standard travel speed (set equal to 0.7 m s^{-1});
T_{std}	=	standard time (s) available to pass the transition checked. When the test is performed in the **warm zone** it is equal to T_{w-zone} (Section D.4). For the **temporary-cold zone** it is set equal to $T_{TC-ZONE}$= 300 s;
EC	=	egress capabilities factor (Tables D.1 and D.2);
SF_{MA_r}	=	safety factor (Table D.6).

Table D.1. MAr analysis: egress capabilities factor EC. The people's movement capabilities are defined as a function of people's mobility and age (see Table D.2).

			People's movement capabilities				
			GN	S	G	R	A
Familiarity with the building	Yes		1.00	1.00	0.80	0.75	0.50
	No	**Exit signs** are visible, legible, conspicuous, and provide clear information.	0.60	0.70	0.50	0.50	0.30
		Exit signs are not visible, not legible, not conspicuous, or not provide clear information.	0.50	0.50	0.40	0.35	0.25

Table D.2. MAr analysis: people's movement capabilities.

		People's mobility		
		good	reduced	not possible
People's age	generic	generic GN	reduced R	assisted A
	less than 14 years	guided G	assisted A	assisted A
	from 14 to 65 years	standard S	reduced R	assisted A
	more than 65 years	guided G	assisted A	assisted A

Table D.3. MAr analysis: exposure factor EX.

	EX (refer to the worst condition identified within the table)				
	0.0	0.5	0.8	1.0	10.0
Hazard level	All cells with CHL = 0 AND no explosion risk		The maximum CHL identified in the cells is equal to 1	CHL > 1 in all the cells within the zone OR explosion risk	
Protection measures against fire	Compartment with fire barriers that ensure a protection rating greater than 15 min	Pressurization system that guarantees a pressure buildup of 25 Pa for at least 20 min		Compartment with fire barriers that ensure a protection rating less than 15 min	
Protection measures against explosion				Explosion risk AND barriers resistant against pressure buildup equal to 0.35 bar	Explosion risk AND barriers resistant against pressure buildup less than 0.35 bar

Table D.4. MAr analysis: hazards factor HZ_{MAr}.

HZ_{MAr} = ZHL × Smoke extraction system × Automatic suppression system × MAa test

ZHL		x	Smoke extraction system		x	Automatic suppression system		x	MAa test	
			Yes	No		Yes	No		Passed	Not passed
L	1.330		1.33	1.00		1.66	1.00		1.00	0.60
O	1.000		1.33	1.00		1.66	1.00		1.00	0.50
M	0.725		1.33	1.00		1.66	1.00		1.00	0.50
H	0.500		1.33	1.00		1.66	1.00		1.00	0.40
E	0.300		1.33	1.00		1.66	1.00		1.00	0.30

Table D.5. MAr analysis: people interaction factor PI.

Characteristics of people flow in the path	PI
Single flow	1.00
Main flow merges with flows from rooms	0.90
Main flow merges with flows from other paths	0.85

Table D.6. MAr analysis: safety factor SF_{MAr}.

Emergency plan	SF_{MAr}
Present	1.5
Not present	3.0

D.2 MAc analysis

The Move Away crossing gap analysis (MAc) checks whether the population can pass the transitions in both the warm and temporary-cold zones within a standard time. A transition is any section in the path where the characteristics or dimensions of the path change or where paths merge (points where a path become narrower or wider, points where a corridor enters a stairway, points where two or more paths merge).

MAc analysis assesses the egress capacity of the considered transition and it is passed if:

$$p^{MAc} \leq \frac{W_{eff} \cdot T_{std}^{1.37} \cdot HZ_{MAc} \cdot PF \cdot MP}{SF_{MAc} \cdot 350} \tag{D.2}$$

where:

p^{MAc}	=	number of persons present in the warm zone or in the temporary-cold zone;
W_{eff}	=	effective width (cm) of the transition (Figure D.1);
T_{std}	=	standard time (s) available to pass the transition checked. When the test is performed in the **warm zone** it is equal to T_{w-zone} (Section D.4). For the **temporary-cold zone** it is set equal to $T_{TC-ZONE}$= 300 s;
HZ_{MAc}	=	hazards factor (Table D.7);
PF	=	$pf_1 \cdot pf_2 \cdot pf_3 \cdot pf_4 \cdot pf_5$ (path flow factor, see Tables D.8, D.9, D.10, D.11, and D.12);
MP	=	merging path factor (Table D.13);
SF_{MAc}	=	safety factor (Table D.14).

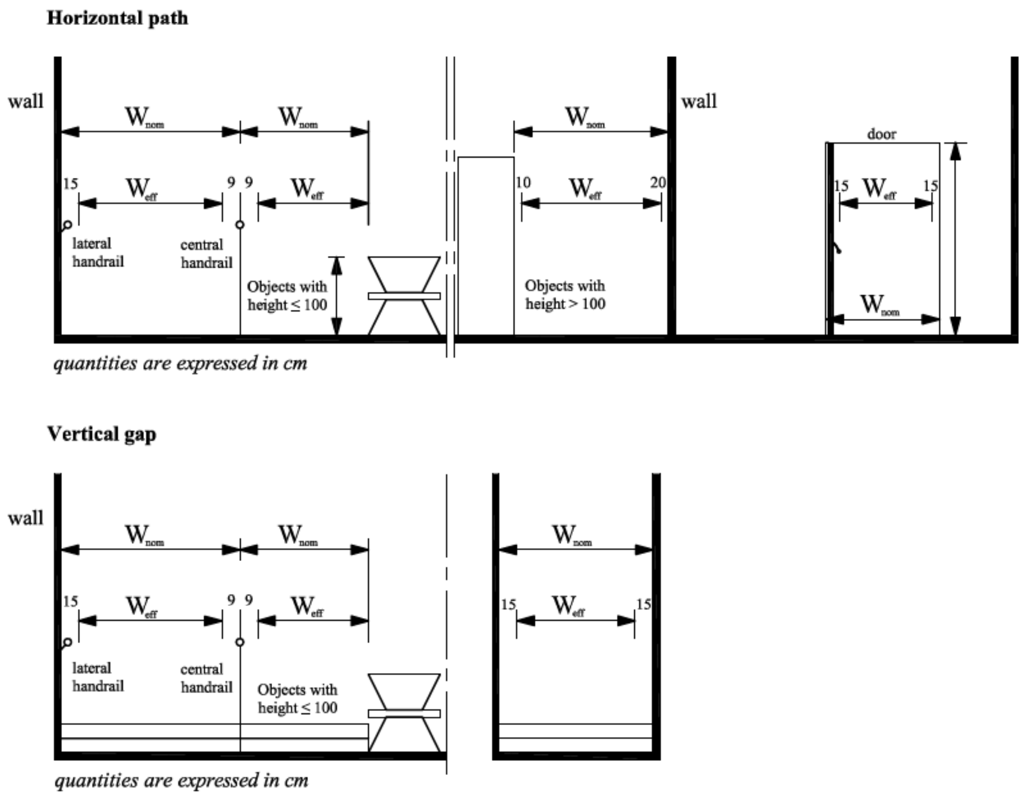


Figure D.1. Effective width W_{eff} (in cm) of transition points.

Table D.7. MAc analysis: hazards factor HZ_{MAc}.

	ZHL				
	L	O	M	H	E
HZ_{MAc}	1.2	1.0	0.8	0.5	0.1

Table D.8. MAc analysis: path flow factor pf_1. W_{body} is the person's width (generic people: 55 cm; people on wheelchair: 75 cm; people carrying bags: 90 cm; people in bed: 110 cm.

		Path width (cm)		
		$W_{nom} \leq W_{body}$	$W_{nom} > W_{body}$ $W_{eff} \leq W_{body} + 20$ cm	$W_{eff} > W_{body} + 20$ cm
Path height H (cm)	$H \geq 200$	0.00	0.87	1.00
	$170 \leq H < 200$	0.00	0.33	0.50
	$H < 170$	0.00	0.00	0.00

Table D.9. MAc analysis: path flow factor pf_2.

Path slope		
Horizontal	Up	Down
1.00	0.75	0.75

Table D.10. MAc analysis: path flow factor pf_3.

Door swing direction	
Inward	Outward
0.50	1.00

Table D.11. MAc analysis: path flow factor pf_4.

Path characteristics				
Horizontal, uniform and no stairs	With widenings or narrowings	Uniform ramp	Stairway with more than 15 or less than 3 stairs	Not straight or not uniform
1.00	0.95	0.90	0.80	0.80

Table D.12. MAc analysis: path flow factor pf_5.

Stair configuration					
no stair	raiser = 16.5 cm tread = 33.0 cm	raiser = 16.5 cm tread = 30.0 cm	raiser = 17.8 cm tread = 27.9 cm	raiser = 19.0 cm tread = 25.4 cm	raiser > 22.0 cm tread < 24.0 cm
1.00	0.90	0.85	0.80	0.75	0.00

Table D.13. MAc analysis: merging path factor MP.

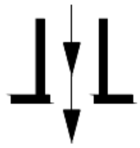
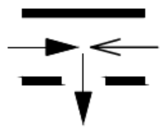
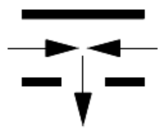
Characteristics of flows at the checked transition		Scenario	MP
Flow Main Secondary	Single (main or secondary)		1.00
	Multiple and not merged (main or secondary)		1.00
	Main flows merge with secondary flows (n. flows ≥ 2)		0.90
	Main flows merge (n. flows ≥ 2)		0.85
	Main and secondary flows converge from opposite directions (n. flows ≥ 2)		0.80
	Main flows converge from opposite directions (n. flows ≥ 2)		0.75

Table D.14. MAc analysis: safety factor SF_{MAc}.

Emergency plan	SF_{MAc}
Present	1.6
Not present	3.0

D.3 MAa analysis

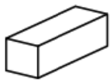
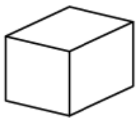
The Move Away alternative path analysis (MAa) checks the presence of alternative and practicable paths in both the warm and temporary-cold zones.

In the **warm zone** MAa analysis is passed if it is possible to reach a temporary-cold, refuge or safe zone when reversing.
In the **temporary-cold zone** MAa analysis is passed if it is possible to reach a refuge or safe zone when reversing without crossing a warm zone.

D.4 Standard time T_{w-zone} for the warm zone

The standard time T_{w-zone} for the warm zone is estimated as summarised in Table D.15.

Table D.15. Modality of T_{w-zone} estimation as a function of the warm zone geometrical configuration.

Geometrical typology of the warm zone	T_{w-zone}
Corridor 	Figure D.2
Room 	Figure D.3
Shaft 	Table D.16

Referring to Figures D.2 and D.3, V_{fill} is the volume (m^3) of the warm zone that has to be filled with the fire combustion products before the conditions become untenable:

$$V_{fill} = (V_{w-zone} - V_{h-zone}) - (A_{w-zone} - A_{h-zone}) \cdot LLH$$

where:

V_{w-zone}	=	volume of the warm zone (m^3);
V_{h-zone}	=	volume of the hot zone (m^3);
A_{w-zone}	=	floor area of the warm zone (m^2);
A_{h-zone}	=	floor area of the hot zone (m^2);
LLH	=	height (m) of the smoke-free layer in the warm zone (generally set equal to 2 m).

The Equivalent Smoke Generator class ESG to adopt is obtained from Table D.19 once the volume of the hot zone V_{h-zone}, the characteristics of the combustible materials in the hot zone (Table D.17), and the number of openings (doors) between the hot zone and the remaining part of the warm zone are given (Tables D.18 and D.19). If two or more cells of fire origin (hot zones) are present within the warm zone, the Equivalent Smoke Generator class ESG to adopt is the worst class identified.

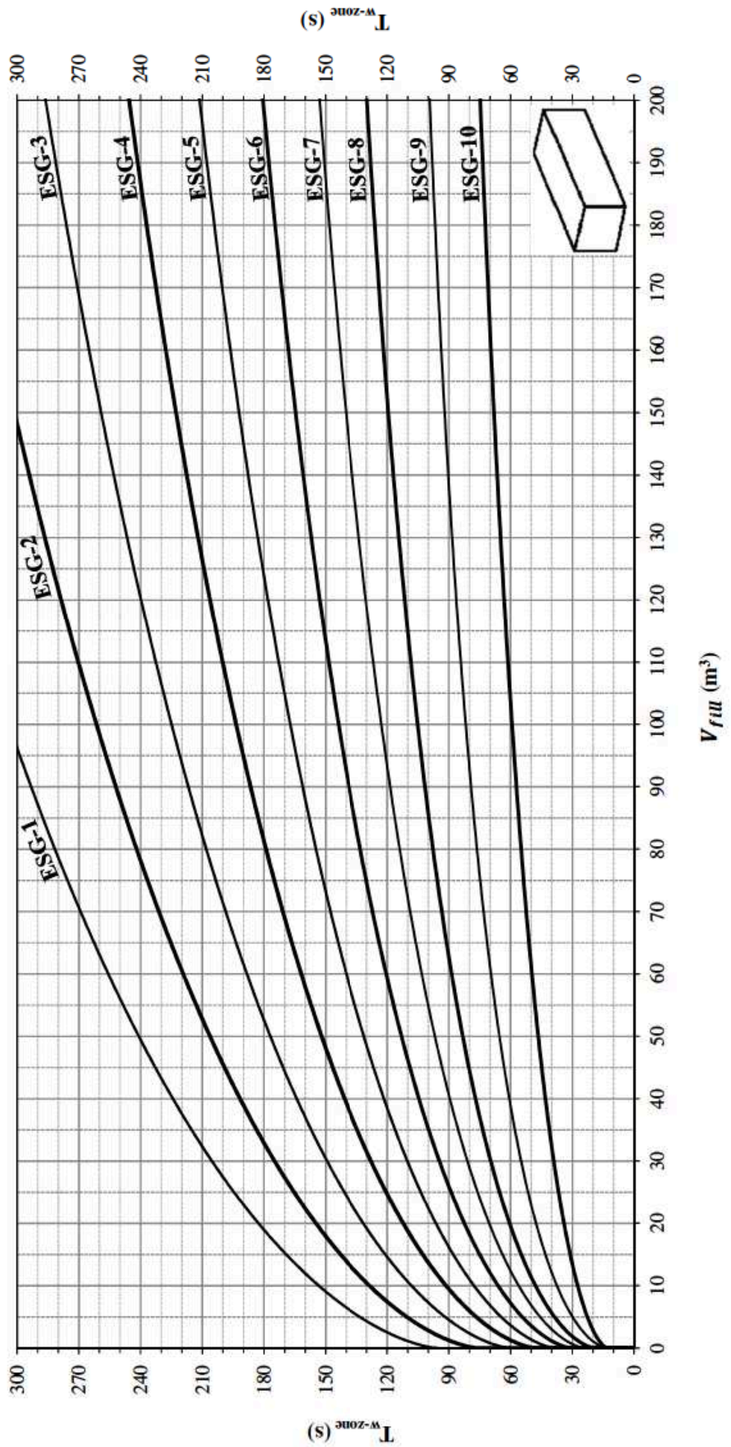


Figure D.2. T_{w-zone} (s) for corridors as a function of ESG class.

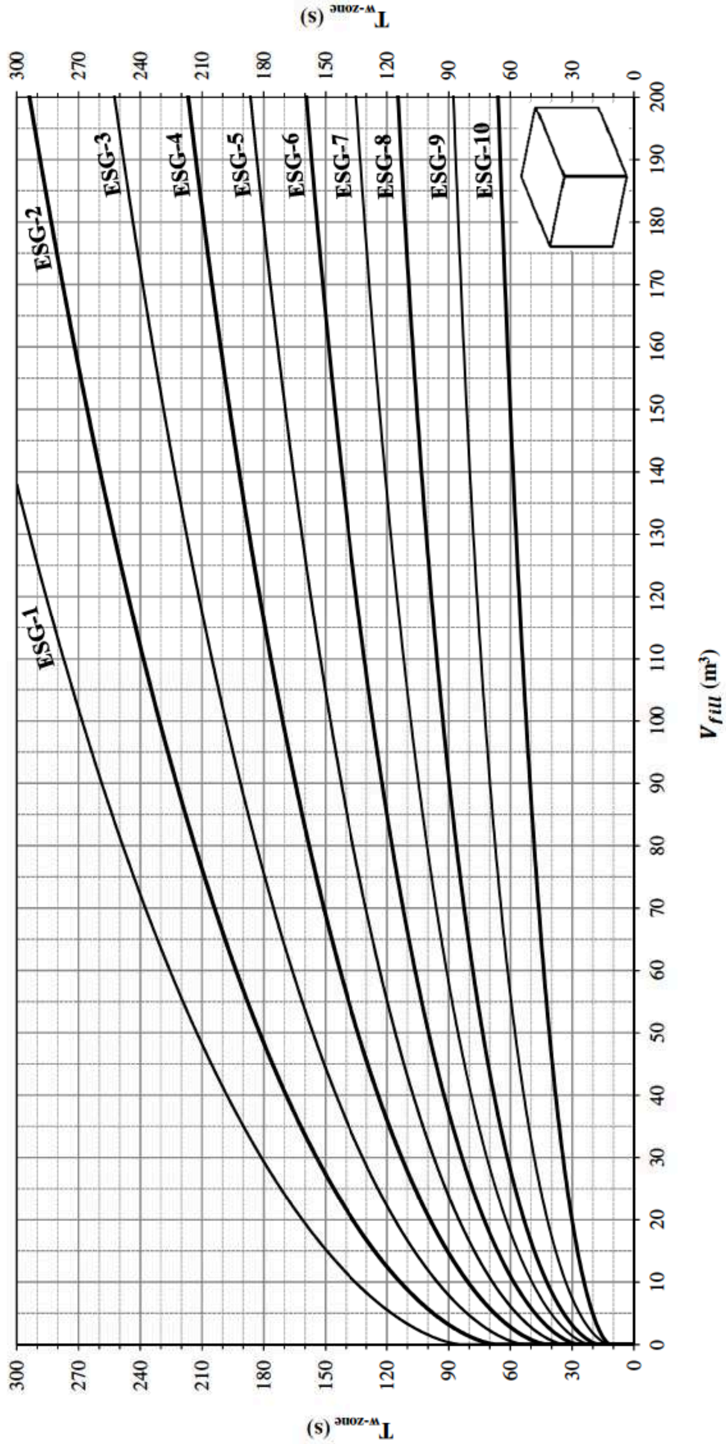


Figure D.3. T_{w-zone} (s) for rooms as a function of ESG class.

Table D.16. T_{w-zone} (s) for shafts as a function of ESG class.

	Equivalent Smoke Generator class (ESG)									
	ESG-1	ESG-2	ESG-3	ESG-4	ESG-5	ESG-6	ESG-7	ESG-8	ESG-9	ESG-10
$T_{w\text{-}zone}$ (s)	150	120	105	90	80	70	60	50	40	30

Table D.17. Smoke Velocity classes (SV) as a function of the characteristics of the combustible materials in the hot zone.

Combustible materials in the hot zone	Type	Examples	Smoke Velocity class (SV)
Solids	Three-dimensional	wood furniture, wood, books, pillows, bedding elements, etc.	S
	Plastic furniture	bin, clothes hunger, displays, stands, etc.	F / S[a]
	Thin solids	paper, cardboard, fabrics, packing material, etc.	UF / S[a,b]
	Electronic devices	computer, printer, power panels, etc.	S
	Linear furnishings	carpets, curtains, generic coverings, etc.	F / S[a]
	Upholstered furniture	seat sofas, mattresses, etc.	M / S[a]
	Thermoplastics, High-toxic-emission-yield	non-fire resistant or melting plastics, foams, synthetic resins, etc.	UF / S[a]
	Pallets		F / S[a]
	Highly flammable	matches, cellulosic material, phosphorus, etc.	UF / S[b]
	Dusty materials		UF / S[b]
	Reactive compounds		UF / S[b]
Liquids			UF / S[b]
Gases			UF / S[b]

[a] if fire-retardand or occupied surface $< 5\ \%\ A_{h\text{-}zone}$
[b] if confined, sealed, closed in safety cabinets, in pipes, etc.

Table D.18. equivalent smoke classes (es) as a function of the volume of the hot zone $V_{hot\ zone}$ and Smoke Velocity class SV.

Hot zone volume $V_{h\text{-}zone}$	Smoke Velocity class (SV)			
	S	M	F	UF
$V_{h\text{-}zone} > 250\ m^3$	es-1	es-3	es-5	es-7
$100 < V_{h\text{-}zone} \leq 250\ m^3$	es-2	es-4	es-6	es-8
$50 < V_{h\text{-}zone} \leq 100\ m^3$	es-3	es-5	es-7	es-9
$V_{h\text{-}zone} \leq 50\ m^3$	es-4	es-6	es-8	es-9

Table D.19. Equivalent Smoke Generator classes (ESG) as a function of the volume of equivalent smoke class es and number of doors between the hot and warm zones.

		Number of doors between hot and warm zones			
		1 door	2 doors	3 doors	4 doors
equivalent smoke class (es)	es-1	ESG-1	ESG-2	ESG-3	ESG-4
	es-2	ESG-2	ESG-3	ESG-4	ESG-5
	es-3	ESG-3	ESG-4	ESG-5	ESG-6
	es-4	ESG-4	ESG-5	ESG-6	ESG-7
	es-5	ESG-5	ESG-6	ESG-7	ESG-8
	es-6	ESG-6	ESG-7	ESG-8	ESG-9
	es-7	ESG-7	ESG-8	ESG-9	ESG-9
	es-8	ESG-8	ESG-9	ESG-9	ESG-10
	es-9	ESG-9	ESG-9	ESG-10	ESG-10

E
PE Analysis

E.1 PEr analysis

The Primary Escape reaching gap analysis (PEr) is made in the hot zone and checks whether the population can reach the gaps between the hot zone and its adjacent zones within the standard time T_{h-zone}.

PEr analysis assesses the length of the longest path within the hot zone that the occupants have to travel in order to reach their nearest gap. The distance is measured considering the obstacles present. PEr is passed if:

$$PL_{max} \leq \frac{v_{max} \cdot T_{h-zone} \cdot EC \cdot HZ_{PEr}}{OP \cdot SF_{PEr}} \tag{E.1}$$

where:

PL_{max}	=	length of the longest path (m) towards the nearest gap that has to be reached to move away from the hot zone. It is measured considering the obstacles present;
v_{max}	=	standard travel speed (set equal to 0.7 m s^{-1});
T_{h-zone}	=	standard time (s) available to move away from the hot zone, as defined in Section E.4;
EC	=	egress capabilities factor (Tables E.1 and E.2);
HZ_{PEr}	=	hazards factor (Table E.3);
OP	=	obstructed path factor (Table E.4);
SF_{PE_r}	=	safety factor (Table E.5).

Table E.1. PEr analysis: egress capabilities factor EC. The people's movement capabilities are defined as a function of people's mobility and age (see Table E.2).

			People's movement capabilities				
			GN	S	G	R	A
Familiarity with the building	Yes		1.00	1.00	0.80	0.75	0.50
	No	**Exit signs** are visible, legible, conspicuous, and provide clear information.	0.60	0.70	0.50	0.50	0.30
		Exit signs are not visible, not legible, not conspicuous, or not provide clear information.	0.50	0.50	0.40	0.35	0.25

Table E.2. PEr analysis: people's movement capabilities.

		People's mobility		
		good	reduced	not possible
People's age	generic	generic GN	reduced R	assisted A
	less than 14 years	guided G	assisted A	assisted A
	from 14 to 65 years	standard S	reduced R	assisted A
	more than 65 years	guided G	assisted A	assisted A

Table E.3. PEr analysis: hazards factor HZ_{PEr}.

		CHL				
		0	I	II	III	IV
Zone protection system	None	1.33	1.00	0.75	0.50	0.30
	Automatic suppression	1.85	1.66	0.90	0.83	0.50
	Smoke extraction	1.75	1.40	0.70	0.67	0.40
	Automatic suppression and smoke extraction	2.00	1.90	1.05	1.00	0.60

Table E.4. PEr analysis: obstructed path factor OP.

		Obstacle characteristics		
		Movable	Joined with other obstacles	Fixed
People density d (p m^{-2})	low ($d \leq 0.4$ p m^{-2})	0.67	0.67	0.67
	medium ($0.4 < d \leq 1.0$ p m^{-2})	0.80	0.67	0.80
	high ($d > 1.0$ p m^{-2})	1.00	0.80	0.90

Table E.5. PEr analysis: safety factor SF_{PEr}.

Characteristics of the paths	**SF_{PEr}**
Only one path to reach the gap is present	2.0
Multiple but asymmetrical paths to reach the gap are present	1.8
Multiple and symmetrical paths to reach the gap are present	1.7
Multiple and symmetrical paths to reach gaps adjacent to a refuge or safe zones are present	1.4

E.2 PEc analysis

The Primary Escape crossing gap analysis (PEc) is carried out at the gaps of the hot zone. It checks whether the maximum number of people present in the hot zone can pass through the gaps that connect the hot zone with its adjacent zones within a standard time.

PEc is passed if:

$$p^{PEc} \leq \frac{\sum_{i=1}^{n.gaps} (\phi \cdot nL_i \cdot GF_i \cdot LI_i) \cdot T_{h-zone} \cdot HZ_{PEc}}{SF_{PEc}} \qquad \text{(E.2)}$$

where:

p^{PEc}	=	number of people that can occupy the hot zone;
ϕ	=	standard flow at the gap (set equal to 1.4 p s^{-1});
nL_i	=	number of lines at the gap $nL_i = \text{int}\left(\frac{W_{nom}}{W_{body}}\right)$;
GF_i	=	$gf_1 \cdot gf_2$ (gap flow factor at the gap i, see Tables E.7 and E.8);
LI_i	=	line interaction factor at the gap i (Table E.9);
T_{h-zone}	=	standard time (s) available to move away from the hot zone, as defined in Section E.4;
HZ_{PEc}	=	hazards factor (Table E.10);
SF_{PE_c}	=	safety factor (Table E.11).

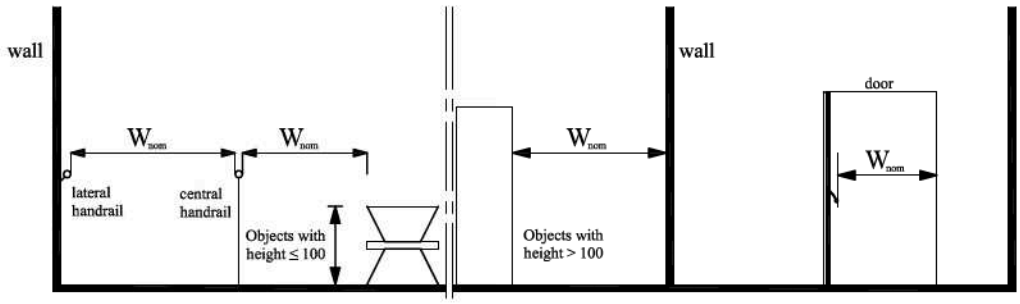


Figure E.1. Nominal width of gaps (W_{nom}).

Table E.6. PEc analysis: body width W_{body}.

People's characteristics	W_{body} (cm)
Generic	55
On wheelchair	75
With shopping trolley or carrying bags	90
In bed	110

Table E.7. PEc analysis: gap flow factor gf_1.

Gap		
Horizontal	Sloping up	Sloping down
1.00	0.75	0.75

Table E.8. PEc analysis: gap flow factor gf_2.

Door swing direction			
Inward or sliding			Outward
people density $d \leq 0.4$ p m^{-2}	people density $0.4 < d \leq 1.0$ p m^{-2}	people density $d > 1.0$ p m^{-2}	
0.90	0.75	0.67	1.00

Table E.9. PEc analysis: line interaction factor LI. See also Figure E.1 and Table E.6 for the definitions of W_{nom} and W_{body} respectively.

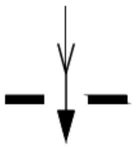
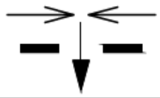
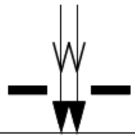
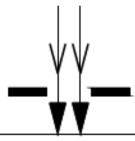
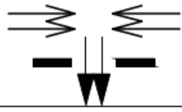
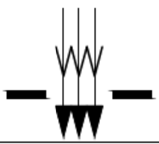
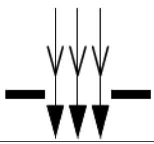
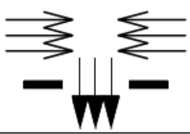
Number of lines converging at the gap (nL_i)		Characteristic of lines converging at the gap	Net width W_{net} (cm) $W_{net} = W_{nom} - \sum_{i=1}^{nL} W_{body}$	LI_i
1	Single line		$0 < W_{net} < 20$ cm	0.67
			$20 \leq W_{net} < 40$ cm	0.90
			$40 \leq W_{net} < 55$ cm	1.00
	Converging from opposite direction		Any	0.67
2	Side by side		$0 < W_{net} < 20$ cm	0.80
			$20 \leq W_{net} < 55$ cm	1.00
	Converging from opposite directions		Any	0.67
3	Side by side		$0 < W_{net} < 30$ cm	0.80
			$30 \leq W_{net} < 55$ cm	1.00
	Converging from opposite directions		Any	0.67
> 3			$0 < W_{net} < 40$ cm	0.75

Table E.10. PEc analysis: hazards factor HZ_{PEc}.

	CHL				
	0	I	II	III	IV
HZ_{PEc}	1.2	1.0	0.8	0.5	0.1

Table E.11. PEc analysis: safety factor SF_{PEc}.

Number and characteristics of gaps	**SF_{PEc}**
Single gap	3.0
Asymmetrical paths towards multiple gaps	2.5
Symmetrical paths towards multiple gaps	2.0
Symmetrical paths towards multiple gaps adjacent to refuge or safe zones	1.6

E.3 PEa analysis

The Primary Escape alternative gap analysis (PEa) is carried out in the hot zone in order to check the presence of alternative and practicable gaps. PEa is passed if at least one gap that can be reached without crossing a no-passable area is present in the hot zone.

The **no-passable area** is the area close to a gap that cannot be crossed due to the presence of a fire at the gap. It is defined by the physical boundaries of the hot zone (e.g. walls) and by a circle with origin in the midpoint of the gap which radius length R_i is as defined in Table E.12.

PEa analysis should be performed at all gaps within the hot zone. When the maximum dimensions (length or width) of the hot zone are less than 15 m PEa analysis is not carried out.

Figure E.2 shows an example of PEa test.

Table E.12. Radius R_i (m) for the no-passable area.

	CHL				
	0	I	II	III	IV
R_i (m)	3.0	4.0	5.0	7.5	10.0

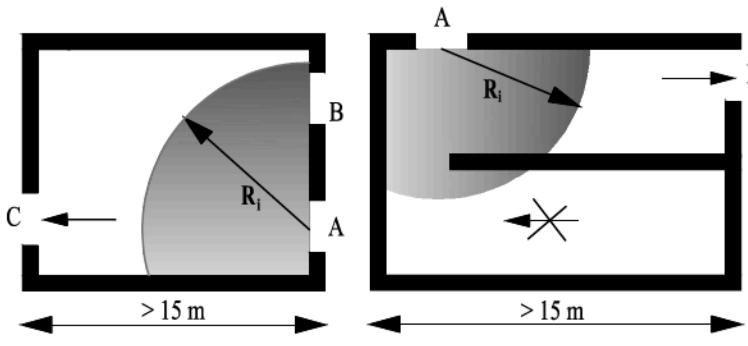


Figure E.2. (a) B: no practicable gap; C: alternative and practicable gap. PEa is passed thanks to the presence of one alternative and practicable gap. (b) PEa is not passed due to the impossibility to reach gap B without crossing the no-passable zone.

E.4 Standard time T_{h-zone} for the hot zone

The standard time T_{h-zone} (s) for the hot zone zone is calculated as:

$$T_{h-zone} = (1 - \gamma_{surf})t_{LLH}$$

where t_{LLH} is estimated from Figure E.3 and γ_{surf} is a factor adopted to consider the surface A_{liq} of the flammable liquids (if present) exposed to air (Table E.14).

Referring to Figure E.3, H_{h-zone} it the height of the hot zone (m). CSF classes are defined in Table E.13 as a function of the floor area of the hot zone A_{h-zone} and of the Smoke Velocity classes SV. (Table E.14).

Table E.13. Cell Smoke Filling classes (CSF) as a function of hot zone surface (A_{h-zone}) and Smoke Velocity classes SV.

Hot zone floor area A_{h-zone}	Smoke Velocity class (SV)			
	S	M	F	UF
$A_{h-zone} > 150$ m^2	CSF-1	CSF-4	CSF-7	CSF-9
$120 < A_{h-zone} \leq 150$ m^2	CSF-2	CSF-5	CSF-7	CSF-9
$100 < A_{h-zone} \leq 120$ m^2	CSF-3	CSF-6	CSF-8	CSF-10
$85 < A_{h-zone} \leq 100$ m^2	CSF-4	CSF-7	CSF-9	CSF-10
$70 < A_{h-zone} \leq 85$ m^2	CSF-5	CSF-7	CSF-9	CSF-11
$60 < A_{h-zone} \leq 70$ m^2	CSF-6	CSF-9	CSF-10	CSF-11
$50 < A_{h-zone} \leq 60$ m^2	CSF-7	CSF-9	CSF-10	CSF-12
$40 < A_{h-zone} \leq 50$ m^2	CSF-8	CSF-10	CSF-11	CSF-12
$30 < A_{h-zone} \leq 40$ m^2	CSF-8	CSF-10	CSF-11	CSF-12
$A_{h-zone} \leq 30$ m^2	CSF-8	CSF-10	CSF-12	CSF-12

Table E.14. Smoke Velocity classes (SV) and γ_{surf} as a function of the characteristics of the combustible materials in the hot zone.

Combustible materials in the hot zone	Type	Examples	Smoke Velocity class (SV)	γ_{surf}
Solids	Three-dimensional	wood furniture, wood, books, pillows, bedding elements, etc.	S	0
	Plastic furniture	bin, clothes hunger, displays, stands, etc.	F / S [a]	0
	Thin solids	paper, cardboard, fabrics, packing material, etc.	UF / S [a,b]	0
	Electronic devices	computer, printer, power panels, etc.	S	0
	Linear furnishings	carpets, curtains, generic coverings, etc.	F / S [a]	0
	Upholstered furniture	seat sofas, mattresses, etc.	M / S [a]	0
	Thermoplastics, High-toxic-emission-yield	non-fire resistant or melting plastics, foams, synthetic resins, etc.	UF / S [a]	0
	Pallets		F / S [a]	0
	Highly flammable	matches, cellulosic material, phosphorus, etc.	UF / S [b]	0
	Dusty materials		UF / S [b]	0
	Reactive compounds		UF / S [b]	0
Liquids			UF / S [b]	$\frac{A_{liq}}{A_{hot\ zone}}$
Gases			UF / S [b]	1 / 0 [b]

[a] if fire-retardand or occupied surface < 5 % $A_{h\text{-}zone}$
[b] if confined, sealed, closed in safety cabinets, in pipes, etc.

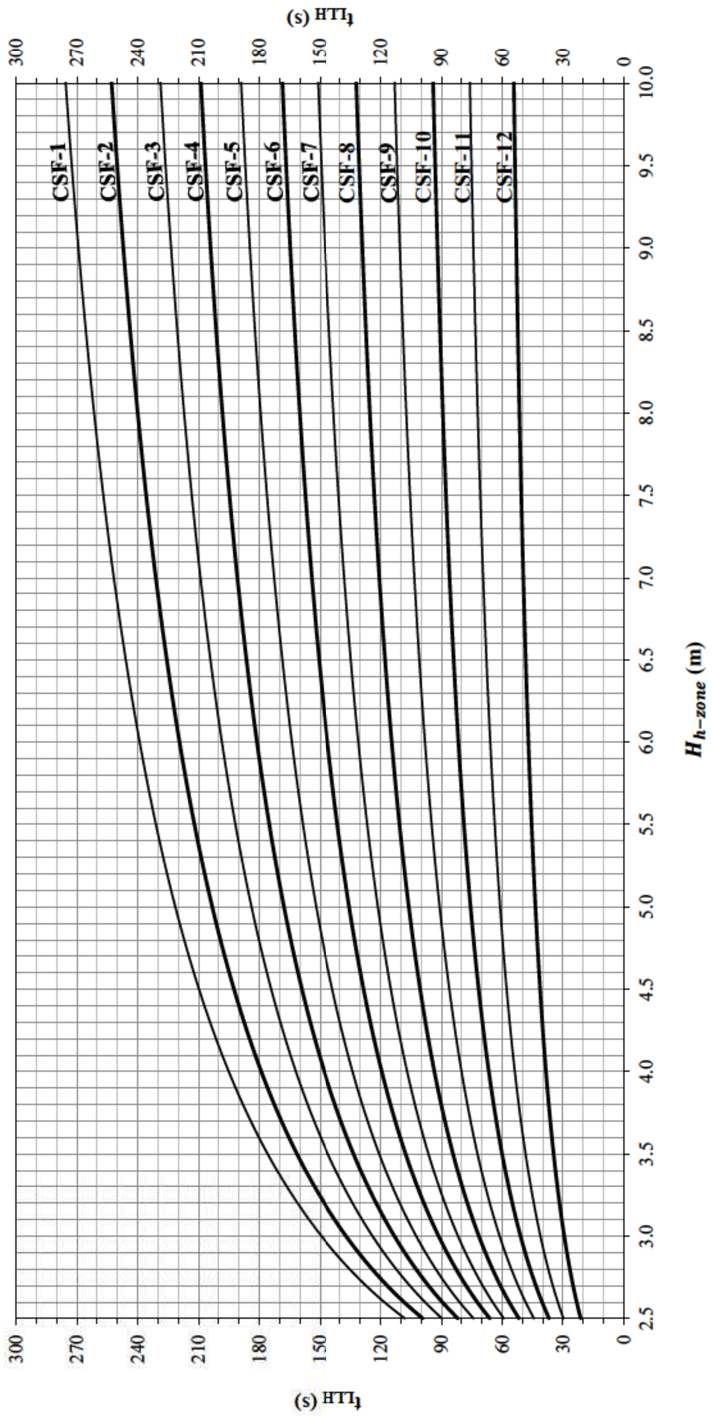


Figure E.3. t_{LLH} (s) for the hot zone as a function of CSF class.

Publications list

Peer-Reviewed Journals

S. Grimaz, E. Tosolini. Application of Rapid Method for Checking Egress System Vulnerability. *Fire Safety Journal*, 58:92-102, 2013.

Specialised Journals

S. Grimaz, E. Tosolini. Vie d'esodo, ecco il test che considera i fattori umani. *Antincendio*, 01:36-45, 2011. (*Means of egress. This is the test that includes human factors. In Italian*).

Conference Proceedings

E. Tosolini, S. Grimaz, E. Salzano (in press). A Sensitivity Analysis of Available Safe Egress Time Correlation. *Paper accepted for publication in the Chemical Engineering Transactions.*

E. Tosolini, L.C. Pecile, S. Grimaz. LabCUBE$_{egress}$: a laboratory for a selective study of peoples movement and human behaviour during egress situations. In *Proceedings of the 5th Human Behaviour in Fires International Symposium*, pages 148-158, Cambridge, UK, 2012. ISBN 978-0-9556548-8-6.

E. Tosolini, S. Grimaz, L.C. Pecile, E. Salzano. People Evacuation: Simplified Evaluation of Available Safe Egress Time (ASET) in Enclosures. *Chemical Engineering Transactions*, 26:501-506, 2012. In V. Cozzani and E. De Rademaeker, editors, *Proc. CISAP5 5th International Conference on Safety & Environment in Process Industry*, ISBN 978-88-95608-17-4; DOI:10.3303/CET1226084.

E. Tosolini, L.C. Pecile, A. Garcia-Agreda, E. Salzano, S. Grimaz. Analisi di sensitività del tempo disponibile per l'esodo (ASET) in caso di incendio in spazi confinati. In *Atti del Convegno sulla Valutazione e Gestione del Rischio negli Insediamenti Civili ed Industriali*, VGR 2012, Pisa, 3-5 Ottobre 2012. ISBN 978-88-902391-1-3. (*Sensitivity analysis of available safe egress time (ASET) in compartment fires. In Italian*).

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S. Grimaz, E. Tosolini, G. Dolcetti. A quick method for emergency evacuation design in work places. *Chemical Engineering Transactions*, 19:433-438, 2010. In S. Pierucci and J. Klemes, editors, *Proc. CISAP4 4th International Conference on Safety & Environment in Process Industry*, ISBN 978-88-95608-11-2.

E. Tosolini, G. Capellari, L. Pecile, S. Grimaz S. L'evacuazione in spazi confinati: un problema a forte connotazione ergonomica. In *Atti del IX Convegno Nazionale SIE*, Roma, 27-29 Ottobre 2010, pages 622-623, 2010. (*Evacuation in confined spaces: an ergonomic issue. In Italian*).

L. Pecile, E. Tosolini, G. Capellari, S. Grimaz. Analisi di casi d'incendio in luoghi affollati in una prospettiva di progettazione ergonomica. In *Atti del IX Convegno Nazionale SIE*, Roma, 27-29 Ottobre 2010, pages 624-625, 2010. (*Analysis of fires in crowded spaces and ergonomic design. In Italian*).

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