FIRE VULNERABILITY ASSESSMENT OF ARCHITECTURAL DESIGN PARAMETERS WITH FUZZY LOGIC MODEL

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ABSTRACT

FIRE VULNERABILITY ASSESSMENT OF ARCHITECTURAL DESIGN PARAMETERS WITH FUZZY LOGIC MODEL

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There is a direct relationship between building characteristics and fire spread. Acceptability of fire safety design involves interoperability of fire safety objectives and building design input. In case of unacceptable fire safety design process, modifications are made in proposed building design parameters for which architects are decision makers. Therefore, in order to get an acceptable level of fire safety, vulnerability of building design parameters must be identified during the design process by architects. The vulnerability level provides performance evaluation of the building in terms of hazardous actions and critical building design parameters to get prevention measures during the design process. Conventional design of building parameters regarding fire safety direct architects to regulations. However, for most of the architects, deterministic approaches of regulations are perceived as restrictions for the creative basis of architecture. Regulation-based vulnerability evaluation systems use deterministic and single parameter approach, in which the parameter either follows the rules, or not. On the other hand, the rapid increase in complexity and amount of information on building systems requires quick-response evaluations based on the decision-maker's intuition, judgement, and experience. Moreover, increased building complexity reveals highly complex decision problems with multi-variables that are stochastic, unknown, and fuzzy. By providing complex interactions between variables, fuzzy logic enables qualitative descriptions of everyday reasoning. Therefore, in order to identify fire safety vulnerabilities of building variables based on expert opinion, this research uses fuzzy expert evaluation model. Fuzzy expert system helps the integration of uncountable, undefined, and uncertain information in the decision-making process. Previously studied fire safety fuzzy models do not cover all critical parameters of building characteristics, and focuses on comprehensive or active fire protection systems. In the proposed fuzzy fire safety vulnerability model, most critical building parameters regarding fire safety are determined through literature analysis. On the other hand, linguistic expert opinion is converted to membership functions through fuzzyTECH fuzzy logic toolbox, and rule-based interrelations of parameters are defined through human reasoning. Performing vulnerability evaluation with fuzzy expert model gives quick response and more accurate results based on human reasoning.

Keywords: Fire Safety Evaluation, Vulnerability Analysis, Fuzzy Logic, Fuzzy Expert System

ÖZ

BULANIK MANTIK MODELİ İLE MİMARİ TASARIM PARAMETRELERİNİN YANGIN KIRILGANLIKLARININ DEĞERLENDİRİLMESİ

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Yapı tasarım parametreleri ile yapıdaki yangın yayılımı arasında doğrudan bir ilişki bulunmaktadır. Bütüncül yangın güvenliği tasarımının uygunluğunun sağlanması için, yangın güvenliği hedefleri ve yapı tasarım girdilerinin birlikte çalışabilmesi gerekmektedir. Yangın güvenliği tasarım sürecinde uygunsuzluk olması durumunda, mimarın karar verici olduğu tasarım önerisinde değişiklikler yapılmaktadır. Bu nedenle, yapı elemanlarının yangın güvenliği açısından kırılganlık analizinin tasarım aşamasında yapılması, oluşabilecek uygunsuzlukların önceden tespiti açısından önemlidir. Kırılganlık analizi, yapının tehlikeli eylemler (yangın) ve kritik tasarım girdileri açısından performans değerlendirmesinin yapılması ve gerekli önlemlerin tasarım aşamasında alınmasını sağlamaktadır. Geleneksel değerlendirme sistemleri, yangın güvenliği tasarımı için mimarları yönetmeliklere yönlendirmektedir. Ancak, birçok mimar için yönetmelikler yaratıcı tasarım sürecine kısıtlamalar getiren uygulamalar olarak algılanmaktadır. Yönetmelik tabanlı kırılganlık taramaları determinist ve tek parametreli yöntemler uygulamaktadır. Diğer yandan, yapı sistemlerinin karmaşıklığının ve girdilerinin artması, karar vericinin sezgi, muhakeme deneyimlerini kullanarak hızlı yanıt verebilen değerlendirme yöntemlerini gerekli kılmaktadır. Yapı tasarımındaki karmaşıklığın artmasıyla, tahmini, bilinmeyen ve bulanık çoklu değişkenler ortaya çıkmaktadır. Bulanık mantık, değişkenler arasındaki ilişkileri ele alarak, kalitatif tanımlamalar ile basit muhakemeler yapmaya olanak sağlar. Bu nedenle, bu çalışmada yapı tasarım parametrelerinin yangın güvenliği açısından kırılganlık analizi için bulanık uzman sistem yöntemi kullanılmıştır. Bulanık uzman sistem, ölçülemeyen, tamamlanmamış ve belirlenemeyen bilginin karar verme sürecine entegre olmasını sağlar. Önceden çalışılmış yangın güvenliği bulanık mantık modelleri, bütüncül ya da aktif yangından korunma yöntemlerine dayanmakta, yapı tasarımındaki kritik parametrelerin hepsini kapsamamaktadır. Önerilen bulanık mantık kırılganlık modelinde, kritik tasarım parametrelini belirlemek için literatür taraması yapılmış, sözel değişkenlere bağlı uzman görüşleri fuzzyTECH bulanık mantık modülü ile üyelik fonksiyonlarına çevrilmiş, kural tabanlı model ile parametrelerin karşılıklı ilişkileri tanımlanmıştır. Yapının yangın güvenliği kırılganlık taramasının bulanık mantık yönetimiyle yapılması, insan mantığını temel aldığından, doğru aralıkta ve hızlı yanıt veren değerlendirme yapılmasını sağlar.

Anahtar kelimeler: Yangın Güvenliği Değerlendirmesi, Kırılganlık Analizi, Bulanık Mantık, Bulanık Uzman Sistem

To my beloved parents,

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LIST OF ABBREVIATIONS

AAC	: Autoclaved Aerated Concrete
AHP	: Analytic Hierarchy Process
ASTM	: American Society for Testing and Materials
BIM	: Building Information Modelling
BOCA	: Building Officials and Code Administrators International
CAD	: Computer Aided Design
FEMA	: Federal Emergency Management Agency
FSES	: Fire Safety Evaluation System
NFPA	: National Fire Protection Association
MCDM	: Multiple Criteria Decision Making
PASS	: Preliminary Assessment of the Egress System Safety
PBD	: Performance Based Design
RC	: Reinforced Concrete

CHAPTER 1

INTRODUCTION

In this chapter, background information, aim, objectives, and contribution of thesis are proposed regarding the argument. The disposition of the thesis is described in the last part of this chapter.

1.1.Background Information

People have been suffering from fire risk since the beginning of civilization. Although the probability of fire in an individual building is low, its high frequency amongst the whole building stock makes fire the most life and property-threatening hazard in any country. As the civilizations developed, protection from fire risk has evolved by forming safety codes and regulations. The tendency of forming regulations and evaluating building systems is due to providing life safety and protecting building property by controlling the fire and keeping the fire safety level of building within an acceptable risk range. Building regulations, in other words; prescriptive codes evolved over the last century, have been continuing to be the primary means to determine acceptable building fire safety level. However, most of the prescriptive design requirements are regarded as restrictive, which may be perceived as constraints by the architect. Although codes defined by authorities have been developing, they have become limited since the complexity of buildings, infrastructures, technical systems, and the needs of the society are grow at an increasing pace. Moreover, new construction methods, resulting from new and unfamiliar materials, new organizations of functions and occupancy classes, new equipment in the buildings, or different activities facilitated within building occupancy introduce new complex interactions. As the interactions get more complex, existing fire safety guidelines remain too generic to understand the relationships between building occupants and fire safety design measures; hence, they become less competent in evaluating fire safety performance of buildings. Moreover, missing important concerns owing to generic guidance may result with the danger of lacking detail solutions (Alvarez Rodriguez, 2012). Therefore, prescriptive approach directs fire safety designers to stretch the codes and standards according to specific projects (Alvarez Rodriguez *et al.*, 2014).

As an alternative method to prescriptive codes, while providing a flexible means of fire safety design, in 1970's fire safety engineers introduced performance based codes based on engineering calculation methods with scenarios. These codes were developed to promote innovation, implement cost-effective designs, and enhance international trade. Beck (1997) defined that the basic purpose of performance based design (PBD) approach as not developing solutions, but testing a design proposal whether it satisfies defined fire safety objectives. PBD system is composed of codes, guidelines, and evaluation tools. Codes are used to define goals and objectives with performance requirements such as acceptable access, egress, ventilation, fire protection, electrical services, sanitary services, *etc.* However, codes do not define the method of applying the requirements. Guidelines are utilized to define accepted methodologies used for system design. Evaluation and design tools are utilized to review and verify fire safety designs according to guidelines. Performance based evaluation tools are based on fire protection systems, in other words active means of fire safety design, which aim to alert building occupants and try to put out the fire by using fire alarms, sprinkler systems, and fire extinguisher systems. Being too fire focused and centered on the design of fire protection measures limits performance based methods by leading ignorance of important fire design aspects related to building components and occupants. Moreover, selection of precautions according to fire scenarios may result in evaluation of fire protection system performance rather than to test the overall building fire safety performance (Alvarez Rodriguez, 2012). In order to avoid evaluation of only active means fire protection measures, the evaluation process should include passive fire protection measures, which depend on designing a building in such a way that it is difficult for a fire to start and spread within, by means of fire protection walls and fire retardant materials. Designing of passive fire protection system starts with the building design. Therefore, important safety measures could may be involved in the preliminary design phase and architects could lead both the architectural and fire safety concerns at the same time. Examples of overall fire safety evaluation systems are based on checklists or grading systems designed to support implementation of regulation, and determination of the fire hazard level for specified building occupancy classification, providing involvement of expert opinion in grading phases.

As knowledge is being transformed into their digital representations in all fields, including legal domains, evaluation of buildings according to regulations are also imported into automated code compliance checking systems. These solutions control the accuracy of building systems in terms of fire regulation provisions. Computerized checklist systems have advantages over standard checklist procedures on detecting building vulnerabilities faster. However, these systems do not reflect the diversity of evaluation methods based on expert opinion and they are dependent to deterministic methods. Deterministic methods do not provide accurate modelling results in case of uncertainty (Ayçın & Özveri, 2015). Therefore, it is not possible to integrate code compliance checklists with human knowledge and building regulations at the same time.

Fire safety evaluation systems, on the other hand, even if experienced experts conduct them, are regarded as subjective and uncertain methods (Lo, 1999). This argument was developed from the nature of human reasoning, since it usually gives results in approximate ranges (Kecman, 2001). Rapid increase in the complexity and embedded information in building systems drastically limit the time available for making decisions. Therefore, human decision-making needs a quick-response analysis based on decision-maker’s intuition, judgement, and experience. The single-criterion and simple decision-making requirements of the past have today given way to highly complex decision problems involving multitudes of variables, which may be stochastic, fuzzy, or at worst unknown (Bushan & Rai, 2004). In their study of cognitive learning theories based on behavior of people on solving problems Kochen & Badre (1973) revealed that when people are asked to do subjective decision making on a subject in verbal categories rather than numerical categories, by which the consistency is improved and more accurate results are achieved. With the attempt to insert human knowledge in fire evaluation systems depending on linguistic variables, in this study, fuzzy logic system is preferred as a decision making and evaluation method for fire safety vulnerability analysis. Fuzzy logic helps to integrate uncountable, undefined, and uncertain information into decision-making process by converting hidden information into workable algorithms.

1.2. Aim and Objectives

The aim of this study is to check fire safety vulnerabilities of common architectural and fire safety design parameters by using a fuzzy expert system method to convert expert knowledge to decision-making tool. The objectives of the thesis are:

- to find out the common architectural and fire safety design parameters via literature review
- to determine linguistic variables and fuzzy membership functions of common parameters
- to consult expert opinion for fuzzy rule system evaluation
- to design a fuzzy expert system based on data and expert opinion on computer tool
- to test fuzzy logic based vulnerability evaluation system on İzmir Opera House building by identifying its weaknesses.

1.3. Contribution

Wide range applications of fire safety evaluations based on numerical expert grading have been conducted for comprehensive building analysis, which are summarized in the literature review part. However, expert evaluation as a nature of human knowledge tends to be vague or imprecise. After the first proposal of using fuzzy logic method in fire safety evaluation by Watts (1995), other researchers started to develop fire safety decision-making tools on active means of fire protection by using fuzzy logic. As a contribution to literature, this study designs vulnerability evaluation of fire safety parameters that have an effect on architectural design and evacuation process by adopting fuzzy expert system method. By doing so, this study provides fire safety vulnerability analysis tool for architects to be used as early as preliminary design phase.

1.4. Disposition

This dissertation is composed of five chapters. The first chapter covers background information, aim and objectives, contribution and disposition parts.

The second chapter comprises literature review about previous researches on vulnerability, fire safety evaluation methods, and fuzzy logic method, together with fire protection studies of these methodologies on building cases. At the end of this chapter, a critical review of literature is presented.

In the third chapter, material and method used in the dissertation is explained. Firstly, data related with fire safety parameters that have an effect on architectural design and evacuation process were derived from the literature and summarized. Secondly, membership functions of parameters were selected based on linguistic variables. Following that, interviews with the architects who deal with fire safety issues were conducted to define fuzzy rules to define the acceptable level of vulnerability. Since dealing with extensive amount of rule generation for the rule base might not be efficient in terms of applicability, interviewees were asked to select the most important three parameters for application. Membership functions and rules were then imported to the fuzzyTECH tool for ease of calculation. Finally, vulnerability assessment of İzmir Opera House is conducted through fuzzy rule based fire safety vulnerability system.

The fourth chapter is for results and discussion parts of this study, in which results on expert interview and vulnerability assessment is reported, outcomes of vulnerability assessment tool is discussed.

The last chapter of the dissertation is for conclusions. In this chapter, the methodologies conducted for the thesis are briefly summarized with their outcomes. Moreover, findings and advantages of fuzzy method to traditional methods are analyzed. Finally, ideas for future work are presented.

CHAPTER 2

LITERATURE REVIEW

This chapter is comprised of issues reviewed from the literature, which are presented in five sections. In the first part, the place and the importance of fire safety in architectural design process is explained through studies. In the second part, definition of vulnerability, vulnerability studies for hazard and antagonistic attacks, and vulnerability studies on fire safety and emergency evacuation are described. In the third part, fire safety evaluation methodologies, including fire safety evaluation system (FSES), Gretener method, Edinburgh model, and Analytic Hierarchy Process (AHP) are explained. Moreover, as a data gathering method from respondents about their domain of expertise, Delphi technique and application of fire safety evaluation methodologies on studies are assessed. In the fourth part, definition of fuzzy logic, structure of fuzzy model and fuzzy rule-based system together with fuzzy operation studies in fire safety are presented. Finally, in the critical review part, overall evaluation of literature is presented and the argument of the dissertation is put forward.

2.1.Architectural Design and Fire Safety

Since the earliest periods of architecture and building, architects' actions have been conditioned by rules, regulations, standards, and governance practices. A wide range of codes has an influence on the formal structure of detailed elements in relation to safety of building structures (Imrie & Street, 2011). The idea of implementing rules and regulations by architects is a contradictive issue since some architects see these rules as constraints under which creativity of architects cannot thrive. This approach claims that the rules govern every design aspect from physical dimensions to lighting levels, so that the building is already calibrated even before the designer starts to design (Wainwright, 2013). Therefore, architects perceive the codes contradicting the creative basis of their practice and express a deep ambivalence to them (Imrie & Street, 2011). Moreover, some predefined rules are not suitable for all building cases, which support the idea. For example, escape route distances used in contemporary regulations date back to British Fire Prevention Committee's report for Edinburgh's Empire Palace Theatre fire in 1911, in which audience could have evacuated safely in 2.5 minutes. The safe duration time identified by the national anthem play at the time of evacuation was translated into a linear escape distance by using variables, from room area to the size of exits to presumed shoulder for the width of the escapes (Wainwright, 2013). This example shows the a priori origins of some generic rules that designers unwittingly apply today. However, rules and regulation of building form and structure should not be perceived as external practices, but integral processes to form well-designed spaces. Architects' interface with rules and regulation is part of the dynamic of the architectural field, which gives a sense of the complexity of regulation to project (Imrie &Street, 2011). In integrated building design process, architects and engineers develop building specifications together from an early stage of the project. In this process, various key design objectives are taken into account to prioritize (Figure 2.1).

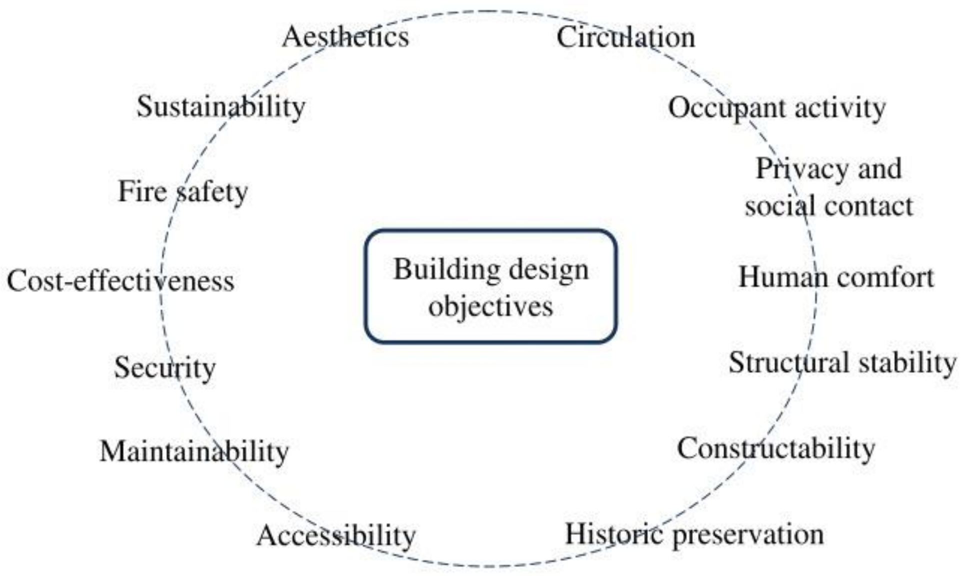


Figure 2.1 Design objectives of architects (Park *et al.*, 2014)

Fire safety, as a design concern, may not be given priority since it has low risk to occur. However, proper level of fire safety as a public good should be provided for all buildings regardless of design priorities of architectural design. Therefore, fire protection measures have been enforced in the form of building codes and standards, in which requirements are listed. At this point, gaps and overlaps, understandings and misunderstandings may occur between architects and fire-safety engineers. However, little research has been conducted on the extent to which architects' influence fire safety and how well fire protection engineers perceive the effects of building design on fire safety (Park *et al.*, 2014).

Kobes *et al.* (2010) developed fire response performance model, which divides type of fire response into three parts: (1) fire features, (2) building features, (3) human features (Figure 2.2). The first factor is the nature of the fire itself, including the process of ignition and combustion of materials, which generates heat and smoke. The second factor is building characteristics, including physically enclosed building environment in which activities are carried out. Finally, the human nature is included to analyze behavior, both in terms of individuals and group characteristics. As an example of interaction of components, an open door without an automatic closing device leads to the spread of fire throughout the building. Here, the characteristics of the building represent no automatic door closing, the characteristics of fire represent fire spread through the opening, and characteristics of people represent non-adaptive behavior that causes leaving the door open during evacuation (Park *et al.*, 2014).

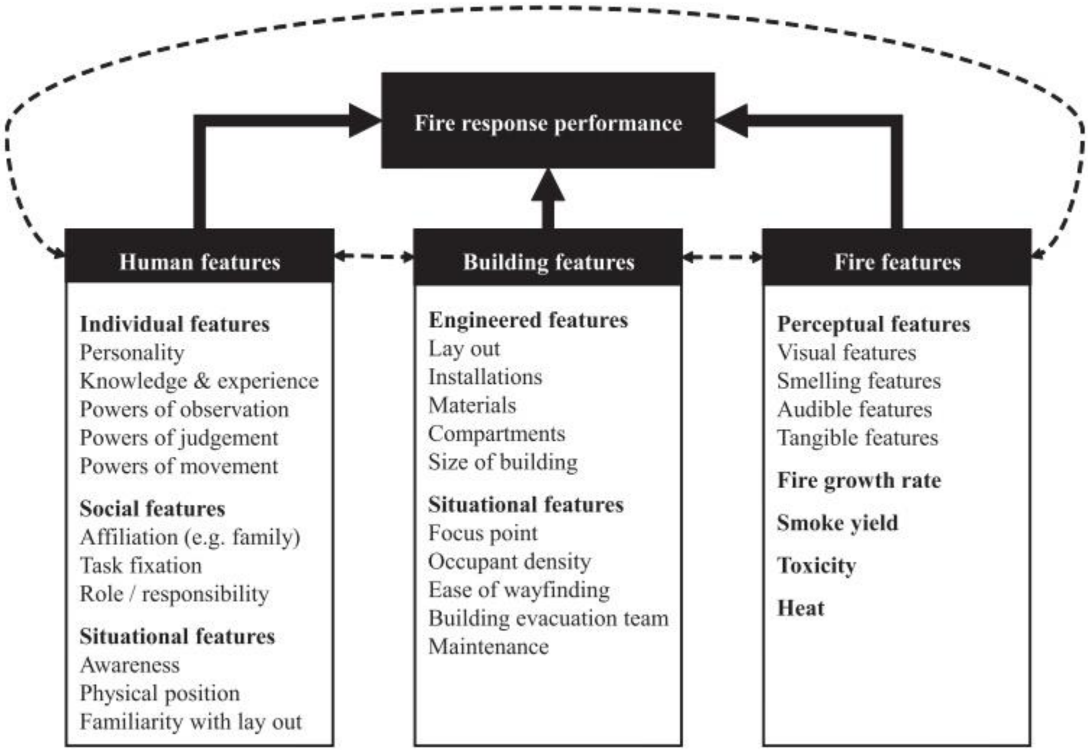


Figure 2.2 Fire response performance model (Kobes *et al.*, 2010)

Fire features can be regarded as active protection measures, where perceptual and visible sources of fire are active and heat and smoke exist. Human features are observable during and after evacuation time, for which the fire is active as well. On the other hand, in the fire safety design process, the priority must be given to precautions, aiming to prevent fire before it starts (Özkaya, 2015). There are precautions regarding fire and human features, which can be applied by informing and guiding occupants about evacuation process and controlling fire protection equipment regularly. On the other hand, most of the precautions regarding fire prevention measures including building layout, materials, and escape route design elements are part of building features and planned during in the building design process by the architect. Application of safety precautions direct architects to regulations. However, as mentioned in the beginning of chapter regulations can be perceived as constraints and interventions done by fire protection engineers. These complaints can be interpreted as disadvantages of the deterministic approach governed by rules and regulations, where the building either follows the rules, or not. For example, in terms of egress design, building either exactly fits travel distances determined by regulation or it is regarded as unsafe. However, for more accurate safety level results, rather than applying the deterministic approach, the fire safety level should be determined by defining vulnerability level of the building. Vulnerability level depends on performance evaluation of the building in terms of critical hazardous actions and design variables aiming to get prevention measures during the design process. In the following part of the literature analysis, definition of vulnerability and application of vulnerability analysis to buildings in terms of hazard and fire safety is reviewed.

2.2.Vulnerability

This study aims to develop a method using vulnerability analysis of buildings regarding fire safety. Therefore, definitions of vulnerability and application areas are reviewed in the literature.

Vulnerability may correspond to physical, economic, political, or social susceptibility; or a sense of community in case of natural or anthropogenic phenomenon. In general, vulnerability is defined as being susceptible to damage and as an internal risk factor, it occurs when the subject or system is exposed to a hazard and effected in terms of an inherent sensitivity (Cardona, 2013). The concept of vulnerability is used to define being susceptible to harm, powerlessness, and marginality of physical and social systems as a powerful analytical tool and to guide prescriptive analysis of actions to provide wellbeing and to reduce risk (Adger, 2006). Risk, as a complex and curious concept, represents an unreal, randomly changing possibility of something that still has not occurred. Therefore, if there is certainty there is no risk. Collective risk represents the possibility of future disaster, by announcing the possibility of dangerous phenomena will happen and subjects being susceptible will be affected. Reduction of risk in many cases is not possible by modifying hazard, so that the only way of it remains altering conditions of vulnerability, in other words decreasing the susceptibility, as a risk prevention and mitigation measure. Consequently, reducing hazard or vulnerability contributes to risk reduction, which means reducing the possibility of future disaster (Cardona, 2013).

Vulnerability analysis is used in natural sciences, applied sciences, and social sciences with different approaches. In social sciences, historians, psychologists, and sociologists consider risk as a ‘social construct’ and deal with individual and collective perceptions, representations, and interactions of social actors. However, engineers, geologists, and geographers generally follow a realist approach, based on quantified or objectively assessed methodologies based on hypothesis. For instance, the study of physical vulnerability deals with the degree of exposure and fragility of subjects to certain phenomena, which allows the elaboration of work in a multidisciplinary environment by the involvement of architects, engineers, economists, and planners. Thus, the consideration of hazard and vulnerability is found essential while forming the standards for building construction and infrastructure (Cardona, 2013).

In terms of constructing building design considerations, vulnerability assessment is needed to analyze building functions, systems, and site features to identify structural weaknesses and necessary redundancy for corrective actions and mitigations. Unlike threats, vulnerabilities can be controlled since the conditions or designs create the vulnerabilities themselves. Vulnerability analysis is conducted in four stages (Dusenberry, ed., 2010):

- organizing resources to prepare the vulnerability assessment

- evaluating the site and building
- preparing a vulnerability portfolio
- determining the vulnerability rating

In organizing resources to prepare the vulnerability assessment task, selection of assessment team is organized from senior individuals with experience in areas of civil, electrical, and mechanical engineering; architecture; site planning and security engineering. The level of the assessment is determined to designate detail levels, or tiers of assessment to decide "how detailed the evaluation must be." For this task, FEMA 452 guidelines for vulnerability assessment denote three detail levels. Level 1 involves quick analysis of site perimeter, building, general functions, infrastructure, and any related drawings and specifications by experienced assessment professionals. In level two, full site evaluation together with existing systems' analysis is conducted by assessment specialists. This level is mostly sufficient for high-risk buildings such as iconic commercial buildings, government facilities, cultural and educational institutions, hospitals, transportation infrastructure. Level 3, is detailed evaluation of facility and site by using blast and weapons-of-mass-destruction modeling to test building's response and recovery, for conceptual, schematic, and design development phases of new building facilities (FEMA 452 Guidelines, 2005).

In evaluating the site and building task, threat maps based on architectural concept drawings are produced to show the site from its outermost perimeter to its most sensitive internal areas. Preparing a vulnerability portfolio task involves collection of a large volume of data from previous tasks and organization of checklist. The checklist that is formed for the sake of FEMA 452 guidelines consists of 13 sections, each of which is assigned to an engineer, architect, or subject matter expert to be performed for the vulnerability assessment of related building systems and to document the results of the checklist. These sections are; site, architectural, structural systems, building envelope, utility systems, mechanical systems, plumbing and gas systems, electrical systems, fire alarm systems, communications and information technology, equipment operations and maintenance, security systems, and the security master plan. Determining the vulnerability-rating task reflects vulnerability ratings of weaknesses that design team identifies in previous tasks, which are commonly expressed in 1-10 numerical scale or a very-low-to-very-high linguistic scale shown in Table 2.1 (Dusenberry, 2010).

Table 2.1 FEMA 452 guidelines for vulnerability rating (Dusenberry, 2010)

Criteria		
Very High	**10**	One or more major weaknesses - asset extremely susceptible to an aggressor or hazard - lacks redundancies physical protection - entire building would be only functional again after a very long period of time after the attack
High	**8-9**	One or more major weaknesses - asset highly susceptible to an aggressor or hazard - poor redundancies physical protection - most critical functions would be only functional again after a long period of time after the attack
Medium High	**7**	An important weakness - asset fairly susceptible to an aggressor or hazard -inadequate redundancies physical protection - most critical functions operational after a long period of time after the attack
Medium	**5-6**	A weakness - fairly susceptible to an aggressor or hazard - insufficient redundancies physical protection - most part of the building would be only functional again after a considerable period of time after the attack
Medium Low	**4**	A weakness - Asset somewhat susceptible- fair level of redundancies physical protection – most critical function is only operational- after considerable time after the attack.
Low	**2--3**	A minor weakness – asset slightly increases- good level of redundancies physical protection – operational with short period of time after attack
Very Low	**1**	No weaknesses - excellent redundancies physical protection - operational immediately after an attack

Application of vulnerability analysis has a wide range of natural sciences to applied sciences, while the scope of this dissertation deals with studies related to building features in relation to fire safety. From this perspective, studies on hazard and antagonistic attacks, building egress systems are reviewed in the following vulnerability literature.

2.2.1. Vulnerability Literature for Hazard and Antagonistic Attacks

In hazard vulnerability analysis, identification of vulnerable groups and regions with the likelihood and consequence of the hazard is examined such as climate changes analysis, social-ecological systems analysis, sustainable livelihoods research and structural analysis as causes of natural hazards like flood and earthquake analysis. A general measure of vulnerability for both sustainable livelihoods and hazards traditions refers account dynamics of time and degree and severity of vulnerabilities (Adger, 2006). As a methodology of fire-introduced vulnerability evaluation, a screening tool was developed for the nuclear power industry. The tool uses two-phase evaluation of fire related reactor damage assessment. In the first phase, qualitative analysis for the areas that need significant safety are identified in order to safe shutdown of equipment, while in the second phase quantitative analysis are conducted, including fire frequency assessment, availability and dependability of the safe shutdown equipment, and fire protection performances. The second phase for those not screened out is rather quantitative. This includes an assessment of the fire frequency, availability and reliability of redundant safe shutdown equipment, and the performance of fire protection features (Hadjisophocleous & Fu, 2004). The events of September 11th 2001 forced people to enhance their knowledge about the world due to ineffective predictions of cascading impacts and root causes of attacks despite sophisticated models and monitoring systems. Thus, the need for integrated approaches to recognize and respond to hazards is emphasized by vulnerability science, which helps people to understand circumstances that reduce their response to threats when they are at risk. As a basis for risk and disaster reduction policies, vulnerability science builds on the integrated and multidisciplinary tradition of hazards research by using qualitative and quantitative approaches, employing historic to future perspectives and with problem-selection and problem-solving incorporations (Cutter, 2003). Federal Emergency Management Agency (FEMA, 2003) uses vulnerability analysis to mitigate the threat of terrorist attacks against high occupancy buildings. Vulnerability assessment is defined as the analysis of building functions, systems, and site features in a detailed manner to identify building weaknesses and to determine corrective actions that should be designed or performed to reduce these. On the belief that building design should comprise physical security, an engineering method for vulnerability analysis on terrorism and physical attacks is conducted by Nilsson, Frantzich, & Van Hees (2013) for multifunctional buildings, where overall complexity is increased. An aspect that needs to be considered in the method are listed such as a large number of stakeholders, domino effects (*e.g.*, fire following explosion), giving first priority to life safety, then the core function of the building, *etc*. Based on aspect attributes, selection and systematic evaluation of fire related scenarios in multifunctional buildings for antagonistic attacks are developed. In the scenario, vulnerability attribute delineates survival conditions of the system in internal and external stress exposition conditions such as isolation of the building of the actual event and separation of the building.

2.2.2. Vulnerability Literature for Egress Systems

There is little research about vulnerability literature for building systems in relation to fire safety, and these studies are exclusively compromised of egress system components of the building. According to National Fire Protection Association (NFPA) 101 Life Safety Code (2012) "means of egress" is defined as "a continuous and unobstructed way of travel from any point in a building or structure to a public way consisting of three separate and distinct parts: (1) the exit access, (2) the exit, and (3) the exit discharge". For the design and management of egress systems, safety is provided by prescriptive codes or performance based tools, mainly in the form of evacuation models. As an alternative to codes and evacuation models, some researchers use vulnerability analysis to test the egress system safety by developing new methods or combining multidisciplinary techniques. One of them is a preliminary assessment of the egress system safety (PASS) method, developed by Grimaz & Tosolini (2013). This approach analyzes the egress system vulnerability by using analytical equations on factors related with people–building–environment interrelations (Figure 2.3). The aim of the method is to provide a rapid check of egress system safety to identify weaknesses of egress system by checking the possibility that people have to reach or cross-gaps, and the presence of alternative gaps and paths.

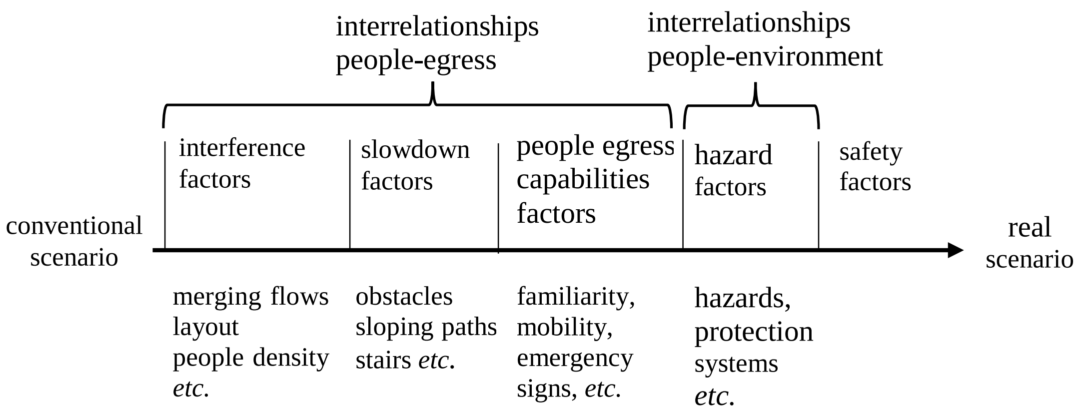


Figure 2.3. Factors effecting people–building–environment interrelationships (Grimaz & Tosolini, 2013)

Another egress system vulnerability analysis tool uses Space Syntax model, through which the selected building floor divided into visual space cells, and vulnerability analysis is conducted through crowds in the space, the competence of the occupants, spaciousness of the space, integration value of the space, visibility area of the occupants and distance between the egress point and space factors. While emphasizing the human factor and geometrical structure inputs, the method proved that although egress design standards are within the limits of existing codes and standards, the system may not be sufficient to cancel out vulnerabilities (Ünlü *et al.*, 2008). A wide range of fire safety attributes considered in the fire safety evaluation methods are summarized in following part of the literature review.

2.3.Fire Safety Evaluation and Decision Making Methods

Since absolute fire safety is unobtainable designing fire safety aims to achieve a level of fire safety regarded as 'safe enough', and the question of 'how safe is safe enough?' needs to be judged by 'risk evaluation' (Rasbash *et al.* 2004). Most fire safety evaluation systems use point-based systems named as risk ranking, index systems, and numerical grading systems, based on selected variables from personal judgment and experience, which are regarded as examples of semi-quantitative analysis (Hadjisophocleous & Fu 2004). As heuristic models, index systems are expressed by a single number of multi attribute variables of the entire building system (Šakėnaitė, 2010). Evaluation of the system requires a decision-making process, called multi-attribute decision-making (MADM), in which alternatives represent different choices available to the decision maker. In general, decision-making process consists activities of (Bushan & Rai 2004):

- studying the situation,
- organizing multiple criteria,
- assessing multiple criteria,
- evaluating alternatives based on the assessed criteria,
- ranking the alternatives,
- incorporating the judgements of multiple experts.

Alternatives need to be analyzed and prioritized with respect to multiple attributes. Attributes are referred to as goals; and different attributes represent different dimensions of evaluating the alternatives (Bushan & Rai, 2004). According to fire safety objectives, values are assigned to the selected attributes and evaluation is performed by comparing them with other assessments or standards. One way of evaluating fire safety is a multi-attribute evaluation system since fire safety design is comprised of more than one attribute to capture all relevant aspects. If the attributes for a decision problem are x1, x2, x3,…, xn, then evaluation function E (x1, x2, x3,…, xn) needs to be determined for performance assessment, then the overall outcome of the system is given by

$$E\,(x_1, x_2, x_3,\ldots, x_n) = \sum_{i=1}^{n} w_i\, R_i(x_i)$$

Where the w_i are weighting constants and R_i (x_i) are normalizing functions of attributes. In general, fire safety evaluation point systems are a simplistic way of evaluating fire safety, useful for screening, ranking, and setting priorities (Rasbash *et al.*, 2004).

Indexing systems, substituted for risk ratings, are defined as a link between fire science and fire safety, comprising many-sided factors that are difficult to evaluate and can be an expensive and time-consuming process when assessed with detailed and consistent methods. Risk ranking provides a utilized and validated evaluation for estimating relative fire risk, which enables a clear approach to arrive at decisions. Representing positive and negative features of fire safety, values are assigned according to expert knowledge and past experience. Examples of risk ranking approaches are index system, numerical grading, point schemes, and rating schedules. The most widely used methods for fire safety ranking systems are US Fire Safety Evaluation System, the Swiss Gretener method, and the Edinburgh method (Watts, 1993). In addition to Gretener's index and Fire safety evaluation system (FSES) index, other representative examples of indexing systems are FRAME index, and Dow's fire and explosion index method (Šakėnaitė, 2010). Dow's fire and explosion index method was developed by Dow Chemical company, providing an approach to assess risk exposure probability of process plant and suggesting fire protection and loss prevention plans. In terms of insurance rating schedules, one of the most commonly used one in the U.S is the ISO (Insurance Services Office), including estimated accounting and basic building grading depending on loss (Hadjisophocleous & Fu, 2004). During the application of evaluation methods, as an expert opinion gathering method, usually Delphi technique is applied. Delphi technique is a method for structuring a group communication process to deal with a complex problem. It is first used in 1953 by Dalkey and Helmers to apply experts' opinions in development of an atomic capability as a part of defense scheme. Delphi technique has been widely used for forecasting, since it gives more confidence to get group consensus. Essential features of Delphi process are (Shields *et al.,* 1990):

- Anonymity: Use of questionnaires or other formal communication channels to reduce effect of dominant individuals,
- Controlled Feedback: Conducting series of rounds by communicating o the members on previous result of round,
- Statistical group response: Ensure that every member of group is represented in the final response to reduce group pressure for conformity

Other methods for fire risk evaluation are narratives, checklist, and probabilistic methods. Narratives are used as list of recommendations for hazards and measures, which does not cover human activity. Checklists are used to identify risk factors as a qualitative way of identifying most hazardous events, without distinguishing among the important factors. Probabilistic methods use quantitative analysis of data assumptions and mathematical formulations to analyze risk distribution (Hadjisophocleous & Fu, 2004).

2.3.1. Fire Safety Evaluation System (FSES)

One of the point system approach is FSES (Fire Safety Evaluation System), based on NFPA 101 - Life Safety Code of the National Fire Protection Association, developed in the late 1970s at the Center for Fire Research, National Bureau of Standards to provide a uniform evaluation technique for fire safety (Rasbash *et al.,* 2004). FSES has been developed on the basis of fire risk ranking, NFPA101A, is three level method (Zhao *et al.,* 2004);

- The identification of fire safety attributes,
- The establishment of the relative weightings (importance) of each attribute,
- The process of evaluating the score for each attribute.

FSES has been continued to be adapted for the new editions of NFPA Life Safety Code, in which risk and safety parameters are treated individually (Watts, 1993). FSES is a hierarchical method, in which variables are represented with values, depending on quantities and physical characteristics with agreement, to answer question "How safe is safe enough?" For an alarm system case, among the values 0, 2, 3, 4, 5, value 0 represents absence of the alarm, while value 5 represents entire coverage of a building with alarm system (Šakėnaitė, 2010).

The FSES for Health Care Facilities is the first of FSES techniques among a variety of building occupancy evaluation systems. The aim of the system was to meet safety level defined by applicable code, and provide designer cost saving and functional alternatives. In the overall fire safety grading system, values assigned to each level are dimensionless and developed through consensus by three separate Delphi panels. In the scale system of panels, the most safeguard value is assigned to 10, and the parameters subtracted from safety are scored 0. By using this scale, parameters, which have a negative number, are evaluated as detrimental to life safety. In Table 2.2 safety parameter values used in FSES health care facilities are represented (Nelson & Shibe, 1980).

Table 2.2. FSES rating system for health care facilities (Nelson & Shibe, 1980)

PARAMETERS	PARAMETERS VALUES						
1 CONSTRUCTIONS	COMBUSTIBLE				NONCOMBUSTIBLE		
	WOOD FRAME		ORDINARY				
FLOOR OR ZONE	UNPROTECTED	PROTEC-TED	UNPROTECTED	PROTECTED	UNPRO-TECTED	PROTEC-TED	FIRE RESIST
FIRST	-2	0	-2	0	0	2	2
SECOND	-7	-2	-4	-2	-2	2	4
THIRD	-9	-7	-9	-7	-7	2	4
4TH &ABOVE	-13	-7	-13	-7	-9	-7	4
2 INTERIOR FINISH (Corr. & Exit)	CLASS C		CLASS B		CLASS A		
	-5		0		3		

Table 2.2. (Cont.)

<table>
<tr><td rowspan="2">3 INTERIOR FINISH (Rooms)</td><td colspan="2">CLASS C</td><td colspan="2">CLASS B</td><td colspan="2">CLASS A</td><td rowspan="2"></td></tr>
<tr><td colspan="2">-3</td><td colspan="2">1</td><td colspan="2">3</td></tr>
<tr><td rowspan="2">4 CORRIDOR PARTITIONS/ WALLS</td><td>NON OR INCOMPLETE</td><td><1/2 HR</td><td>≥1/2 TO 1 HR</td><td>≥ 1 HR</td><td colspan="3" rowspan="2"></td></tr>
<tr><td>-10(0)*</td><td>0</td><td>1(0)*</td><td>2(0)*</td></tr>
<tr><td rowspan="2">5 DOORS TO CORRIDORS</td><td>NO DOOR</td><td><20 MIN FR</td><td>≥20 MIN FR</td><td>≥20 MIN FR AND AUTO CLOSE.</td><td colspan="3" rowspan="2"></td></tr>
<tr><td>-10</td><td>0</td><td>$1(0)^{ttt}$</td><td>$2(0)^{ttt}$</td></tr>
<tr><td rowspan="2">6 ZONE DIMENSIONS</td><td colspan="2">DEAD END MORE THAN 100</td><td colspan="2">DEAD END 30 - 100</td><td colspan="3">NO DEAD ENDS >30 & LENGTH IS</td></tr>
<tr><td colspan="2">-6(0)**</td><td colspan="2">-4(0)**</td><td>>150</td><td>100 - 150</td><td><100</td></tr>
<tr><td rowspan="3">7 VERTICAL OPENNINGS</td><td colspan="2" rowspan="2">OPEN 4 OR MORE FLOORS</td><td colspan="2" rowspan="2">OPEN 2 OR 3 FLOORS</td><td colspan="3">ENCLOSED WITH INDICATED FIRE RESIST.</td></tr>
<tr><td><1 HR</td><td>≥1HR - 2 HR</td><td>>2 HR</td></tr>
<tr><td>-14</td><td></td><td>-10</td><td></td><td>0</td><td>$-2(0)^{t}$</td><td>$3(0)^{t}$</td></tr>
<tr><td rowspan="3">8 HAZARDOUS AREAS</td><td colspan="2">DOUBLE DEFICIENCY</td><td colspan="2">SINGLE DEFICIENCY</td><td colspan="2" rowspan="2"></td><td rowspan="3"></td></tr>
<tr><td>IN ZONE</td><td>OUTSIDE ZONE</td><td>IN ZONE</td><td>OUTSIDE ZONE</td></tr>
<tr><td>-11</td><td>-5</td><td>-6</td><td>-2</td><td colspan="2">0</td></tr>
<tr><td rowspan="3">9 SMOKE CONTROL</td><td rowspan="2">NO CONTROL</td><td colspan="2" rowspan="2">SMOKE PARTITIONS</td><td colspan="4">MECH. ASSISTED SYSTEM</td></tr>
<tr><td colspan="2">BY ZONE</td><td colspan="2">BY CORRIDOR</td></tr>
<tr><td>-5 (0)***</td><td colspan="2">0</td><td colspan="2">3</td><td colspan="2">4</td></tr>
<tr><td rowspan="3">10 EMERGENCY MOVEMENT ROUTES</td><td rowspan="2"><2 ROUTES</td><td colspan="6">MULTIPLE ROUTES</td></tr>
<tr><td>DEFICIENT CAPACITY</td><td colspan="2">W/O HORIZONTAL EXITS</td><td colspan="2">HORIZONTAL EXITS</td><td>DIRECT EXITS</td></tr>
<tr><td>-8</td><td>-2</td><td colspan="2">0</td><td colspan="2">3</td><td>5</td></tr>
<tr><td rowspan="3">11 MANUAL FIRE ALARM</td><td colspan="2" rowspan="2">NO MANUAL FIRE ALARM</td><td colspan="4">MANUAL FIRE ALARM</td><td rowspan="3"></td></tr>
<tr><td colspan="2">W/O F.D. CONN.</td><td colspan="2">W F.D. CONN.</td></tr>
<tr><td colspan="2">-4</td><td colspan="2">1</td><td colspan="2">2</td></tr>
<tr><td rowspan="2">12 SMOKE DETECTION & ALARM</td><td>NONE</td><td colspan="2">CORRIDOR ONLY</td><td>ROOMS ONLY</td><td colspan="2">CORRIDOR & HABIT. SPACE</td><td>TOTAL ZONE</td></tr>
<tr><td>0</td><td colspan="2">2</td><td>3</td><td colspan="2">4</td><td>5</td></tr>
<tr><td rowspan="2">13 AUTOMATIC SPRINKLERS</td><td>NONE</td><td>CORRIDOR</td><td colspan="2">CORRIDOR & HABIT. SPACE</td><td>TOTAL BLDG</td><td colspan="2" rowspan="2"></td></tr>
<tr><td>0</td><td>$2(0)^{tt}$</td><td colspan="2">8</td><td>10</td></tr>
</table>

NOTE
- * Use 0 when item 5 is -10
- ** Use 0 when item 10 is -8
- *** Use 0 zone with less than 31 patients in existing buildings

^{t} Use 0 when item 1 is based on first floor zone or an unprotected type of construction

^{tt} Use 0 when item 1 is based on an unprotected type of construction

^{ttt} Use 0 when item 4 is -10

FSES for business occupancies includes 12 parameters: (1) assessing construction, (2) segregation of hazards, (3) vertical openings, (4) sprinklers, (5) fire alarm, (6) smoke detection, (7) interior finish, (8) smoke control, (9) exit access, (10) exit system, (11) compartmentation (corridor-room separation), and (12) occupant emergency program.

- Construction parameter: to define construction types by code reference as noncombustible and combustible type of construction.
- Segregation of hazards: to identify hazardous areas, according to stored contents and activities, determination of hazard level (fully developed, structurally endangering, non-structurally endangering), determination of fire protection and determination of deficiency degree.
- Vertical openings: parameter to evaluate penetrations through doors, exit stairs, ramps, escalators, hoist-ways for elevators, conveyors, and shafts for pipes of building system ducts by assigning values,
- Sprinkler systems: to determine where it is needed, complying with code standards,
- Fire alarm parameter: to consider the presence and absence of an alarm system,
- Interior finish classification: to assign on flame spread ratings,
- Smoke control parameter: to assign values according to no presence of smoke barriers that restrict smoke movement, passive control of smoke systems through continuous smoke barriers with fire resistance rating, and active smoke control systems tested for blockage of smoke leakage between compartments,
- Exit access parameter: values to determine dead-end corridors, in which travel to an exit in one direction only,
- Exit systems: to detect whether with single routes or multiple routes (at least two separate means of egress routes) are available in travel paths, for which travel distances are limited through code,
- Compartmentation: values to decide the quality of separation between rooms and corridors, whether there exists no separation, incomplete separation, smoke resistive barriers, and fire resistive barrier separation,
- An occupant emergency program: to test fire drills every year and to ensure fire safety management.

2.3.2. Gretener Method

Another decision making tool is Gretener method, which is developed by Swiss Fire Prevention Service as an arithmetical evaluation of fire risk in buildings, arguing that statistical methods based on previous experience were not efficient to determine fire risk. In Gretener method, like in other risk ranking methods, values assigned for factors are not only based on statistics, but also experiential studies. Parameters used in Gretener method are ignition, fire spread, and fire protection, represented by empirically derived values, calculated with simple mathematical formulation (Watts, 1993):

R = A x B where;

R = fire risk, A= probability that a fire will start, and B= fire hazard or degree of danger

2.3.3. Edinburgh Model

Another type of multi-attribute evaluation model is Edinburgh model, based on the development of a hierarchical point system approach at the University of Edinburgh, sponsored by the UK Development of Health and Social Services. The objective of the Edinburgh model was to develop fire safety evaluation in UK hospitals as a systematic method, and adapted for the dwellings. Since fire safety is comprised of many factors, the Edinburgh model suggests a matrix of fire safety goals versus fire safety features to identify functions of two concepts. The hierarchy of fire safety decision-making levels representing fire safety is shown in Table 2.3. The series of matrices such as a matrix policy versus objectives, or a matrix objective versus strategies constructed to examine relationship of any two adjacent levels and relative importance of each parameter by weighting the parameters. Development of fire safety evaluation specific to building or space depends on parameter grading to determine the level of availability of each parameter in building or space. As a result, the sum of grades and weights is used to measure level of fire safety (Rasbash *et al.*, 2004). As a matrix method, Edinburgh method refers more than two categories of fire safety by suggesting a hierarchy of them, in other words decision-making levels. This hierarchy is presented as (1) Policy, (2) Objectives, (3) Strategies, and (4) Components.

Table 2.3. Hierarchy of fire safety decision-making levels (Rasbash *et al.*, 2004).

Level	Name	Description
1	Policy	Course or general plan of action adopted by an organization to achieve security against fire and its effects
2	Objectives	Specific fire safety goals to be achieved
3	Strategies	Independent fire safety alternatives, each of which contributes wholly or partly to the fulfillment of fire safety objectives
4	Attributes	Components of fire risk that are determinable by indirect measure or estimate
5	Survey items	Measurable features that serve as constituent parts of fire safety parameter

A matrix policy versus objectives define a fire safety policy by identifying most important objectives, while a matrix objective versus strategies identify relationships between determined factors. Therefore, a matrix can be constructed between any two levels of determining fire safety parameters (Watts, 1993).

2.3.4. Analytic Hierarchy Process (AHP)

Analytic Hierarchy Process (AHP) is a powerful multi-attribute evaluation technique by using pairwise comparisons. In AHP method pairwise comparison judgment matrices, factors that are not quantified, are considered, and in any systematic process can be effectively analyzed by using AHP (Shields *et al.*, 1990). AHP was developed by Saaty in 1980, as an easily understood and implemented methodology for taking complex decisions. The simplicity of the method enables the widespread use of AHP in multiple fields of research. The methodology of AHP includes the following steps (Bushan & Rai 2004):

- Step 1: The problem consists hierarchy of goal criteria and alternatives,
- Step 2: Data collected from experts. Pairwise comparisons are done according to quantitative scale described in Table 2.4,
- Step 3. Pairwise comparisons are generated,
- Step 4. Relative importance is compared,
- Step 5. Consistency of matrix is evaluated.

- Step 6: The rating of each alternative is multiplied by the weights of the sub-criteria to get local ratings with respect to each criterion. Then local ratings are then multiplied by the weights of the criteria and get global ratings are achieved.

Table 2.4. Scale for quantitative comparison of alternatives (Bushan & Rai 2004)

Options	Numerical value(s)
Equal	1
Marginally strong	3
Strong	5
Very strong	7
Extremely strong	9
Intermediate values to reflect fuzzy inputs	2,4,6,8
Reflecting dominance of second alternative compared with the first	Reciprocals

In the problem of how various variables of the fire safety dynamic system incorporate multiple objectives, the hierarchical structure is developed as a framework itself composed of dynamics unique to the system, and functional interactions of its components together with the impacts of them to entire systems. The hierarchical structure is represented in Figure 2.4 descending from the overall objectives to sub-subjects, tactics components, and elements.

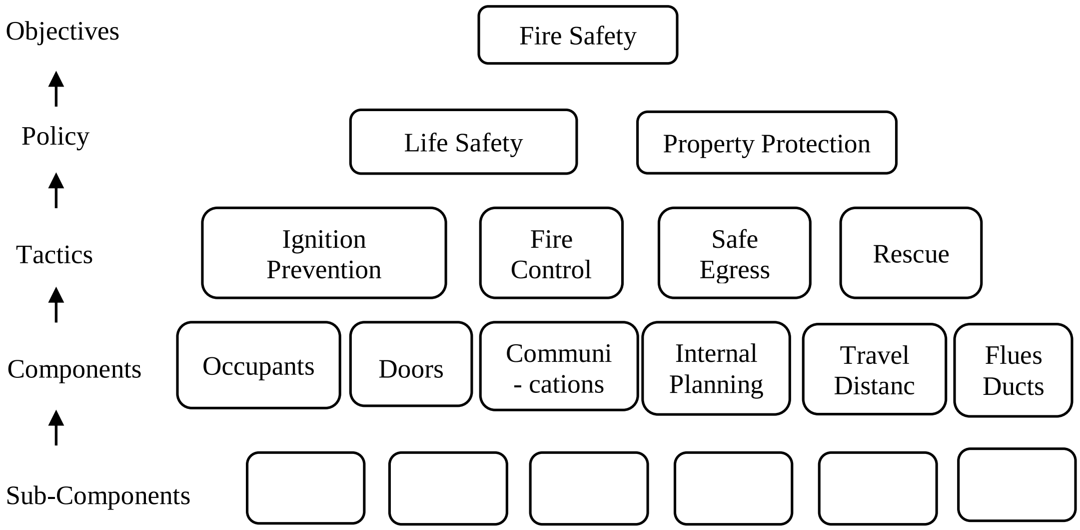


Figure 2.4. The structure and logic of the fire safety evaluation points scheme (Shields *et al.*, 1990)

Delphi technique and AHP are applied together as tools to develop fire safety evaluation schemes for public assembly buildings using expert opinion. The Delphi group agreed with hierarchical structure and principal objectives, tactics and components of fire safety for public assembly buildings assigns values to components according to their relative importance (Shields *et al.*, 1990).

2.3.5. Parameters of Fire Safety Evaluation and Decision Making Methods

Most of the fire safety evaluation and decision making methods deal with holistic fire safety factors, including building, human, and fire aspects. Among wide range applications of ranking evaluation methods that are reviewed in this research, building parameters in relation to fire safety are used in the methodology. The review table, which presents all fire safety related parameters of researches by using evaluation methodologies, is represented in Appendix A, Table A1.

Shields *et al.*, (1990) suggests nine parameters for fire safety evaluation scheme in public assembly buildings, which are (1) users, (2) means of egress, (3) management, (4) fire suppression equipment, (5) detection and communication systems, (6) furnishings, (7) interior finishes, (8) building services and equipment, and (9) fire and smoke control. Parameters related to building aspects are means of egress as construction has a primary role in egress such as doors and exit corridors, furnishings used in public entertainment such as curtains, carpets and seating, and interior finishes including wall and ceiling surface materials.

Donegan, Taylor, & Meehan, (1991) computerized fire safety evaluation of dwellings using an expert system. Proposed system uses a weighted ranking emerge from a consensus of expert opinion through Delphi technique. Components are clustered into three parts as human measures, building specific or passive measures, and supportive or active measures. Among the eleven components of system, building specific measures related to this study is internal design, survey volume, and means of escape, hazard protection, and external envelope.

Watts (1992) designed the basic assumption for the indexing method, which proposes that a relatively small number of factors account for the most of the problems of fire protection. Systematically combining pertinent fire protection factors requires that the factors are measurable. On the basis of standard risk levels of occupancy classes, Watts (1992) emphasizes the assessment system defined by the American Society for Testing and Materials (ASTM) Standard Practice for Assessment of Fire Risk Occupancy Classification (E 931). Fire risk assessment system designs a logical foundation based on calculations to determine the level of fire performance. There are 12 parameters related to fire risk, to which weights are assigned. Total value is determined through risk rating values and availability of fire detection and suppression systems. Parameters are sleeping, evacuation, density, confined/restrained, impairment, occupant control and training for death and injury analysis. Parameters related to property loss are fuel load, response time, involvement, fire control, while parameters related to ignition potential are determined through purposeful and accidental fire ignition. Hirschler (1994) developed the proposed indexing system as an empirical tool to be used for fire standards, to determine threat levels of generic occupancy classes, and to compare occupancy unknown hazards with known hazards. For instance, in the live-in occupancies everyone sleeping at the same time takes normal grading, while occupancies with no person awake and alert takes high grading.

Lo's (1999) method is developed for assessment of fire safety for existing housing buildings in Hong Kong. Upgrading existing buildings to current prescriptive standard takes huge cost, so that a holistic fire risk assessment is suggested to assure the building's safety level and to prioritize the factors by using a risk ranking method. The system categorizes fire safety attributes in five as (1) a means of escape and warning system, (2) ignition prevention and fire resistant construction, (3) means of access for firefighting and emergency vehicle access, (4) fire services installations, and (5) building characteristics and management. Among the categories, building parameters in relation to fire safety design are width, number and configuration of exit routes, travel distance, population distribution pattern, emergency lighting, ignition prevention and fire resistant construction, compartmentation size, fire rated doors, walls, floors, barriers, *etc*. and flame spread prevention. Zhao *et al.* (2004) developed the method as a simulation approach for ranking of fire safety attributes of existing buildings based on AHP method. Data for ranking each attribute are collected by conducting face-to-face interviews with the officers in the fire safety department. At the end, five objectives, which are same with Lo (1999) are ranked in hierarchical models under the aim of providing life safety.

Karlsson & Larsson (2000) developed risk index method for assessing fire safety in multi-story apartment buildings. The data used in the structure of risk index method is derived from a Delphi panel of experts. Then, weights are assigned to index method parameters. The index method has hierarchical levels of fire safety, including “policy” at the top as the fire safety performance of a wood frame building, then the primary “objectives” as to provide life safety and to provide property protection, *etc.* Then the “strategies” as established safe egress and control fire growth, *etc.*, and “parameters” with “sub-parameters” determined by direct or indirect measure or estimation. There are 17 parameters of methods, including building factors of internal linings, compartmentation, structure separating, doors, windows, façade, attic, escape routes, and structure-load-bearing.

Watts & Kaplan, (2001) compared and combined two most widely used risk-indexing systems, FSES and Building Officials and Code Administrators International (BOCA), by using multi-attribute evaluation method for historic buildings called Historic Fire Risk Index (HFRI). HFRI system uses a single numerical value in fire safety decision making to analyze safety features, hazards, and other risk parameters. Combined parameters of HFRI system have 20 parameters, in which vertical opening weighted factor has calculated the most. Other parameters related to building construction and egress are building height, building area, the maximum travel distance, corridor walls/corridor/room separation, means of egress/exit system, segregation of hazards, compartmentation, dead ends/exit access, interior finish, unit separations, elevator control and egress emergency lighting.

Chow, (2002) proposed a study of multi-attribute ranking system called EB-FSRS for assessing the fire safety provisions in existing high-rise nonresidential buildings in Hong Kong. From the reviewing results, three groups of attributes were proposed in the EB-FSRS. These are the passive building construction, fire services installation, and key risk parameters, all following the local fire safety requirements. The concept is similar to those equivalent concepts on fire safety parameters of the NFPA FSES. In the method passive building construction, fire services installation, and software management for fire risk are given same relative importance values. Passive building construction parameters reviewed in this research include building height, evacuation route, width of the staircase, smoke doors and fire resistive construction.

Chen *et al.*, (2012) reported evaluation factors for hotel building fire safety based on nine investigation reports between 1980 and 2006 in Taiwan. According to disaster-cause ratio method, the number of death, the number of injured, fire and smoke spread, evacuation safety, fire location and causing factors are developed. The importance ratios of fire prevention, evacuation, mitigation, fire control and resistance strategies were determined accordingly. The first dimension of disaster-cause is fire and smoke spread in buildings. Factors of the first dimension corresponds absence of firefighting equipment on emergency openings, absence of proper distances between stations, lack of fire compartment for guest rooms, lack of fire sprinklers, and incomplete fire compartments. Second dimension is evacuation safety. Disaster cause reasons of evacuation safety are alarm system absence, flammable materials in escape routes, locked doors and stairways, lack of emergency power supply, unfamiliarity of staff with exits, stack effect caused by not closing the doors on escape routes, improper evacuation signs, and insufficient design of fire and smoke compartments. Third dimension among the disaster reasons are listed by location, including fires occurred in guest rooms, in unused spaces, at special interfaces and in electrical control and converter rooms. Fourth and the last dimension of disaster causes are fire causes. Fire spread due to inappropriate use of fire, wire and electrical fires, arson in unused spaces like lifts and safety stairs and incompetent construction methods are reasons of disaster listed in the selected hotel fire cases. After the literature review of four dimensions, Delphi method is applied to 50 experts to determine evaluation factors, after which the weighting of factors determined by AHP method.

2.4.Fuzzy Logic

The concept of fuzzy sets is developed by Lotfi Zadeh (1965), Professor and Head of the Electrical Engineering Department at the University of California at Berkeley. Fuzzy logic is based on the idea that all things admit of degrees: temperature, height, speed, distance, beauty – all come on a sliding scale. For example; “The motor is running really hot," "Tom is a very tall guy"; "Electric cars are not very fast" (Negnevitsky, 2011).

Zadeh (1965) defined fuzzy sets as a set of mathematical principles for knowledge representation based on degrees of membership rather than on crisp membership of classical binary logic. As a result, fuzzy logic has an important role in human thinking, communication, information, and abstraction. Fuzzy system approach for modeling human judgment and decision-making has critical features. On the contrary, to crisp sets, applications of fuzzy systems use the concept of a fuzzy set, the members of which belong to it to some degree between interval [0, 1]. The degree is defined as the membership degree and specified as a real number in the interval [0, 1] (Özyurt, 2010). Unlike two-valued Boolean logic, fuzzy logic is multi-valued. It deals with degrees of membership and degrees of truth. Fuzzy logic uses the logical values between 0 (completely false) and 1 (completely true) (Negnevitsky, 2011).

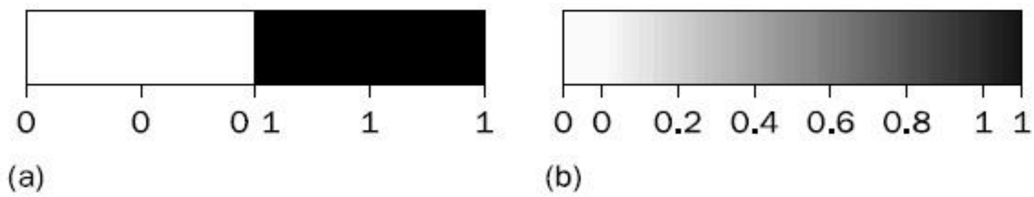


Figure 2.5 Range of logical values in Boolean and fuzzy logic

(a) Boolean Logic; (b) Multivalued

Iliadis (2005) defines crisp set and fuzzy set functions as follows;

In crisp sets, $\mu(X) = 1$ if $X \in S$,

0 if $X \notin S$

In fuzzy sets, all X members between 0 and 1 has different membership degree

$\mu(X)$ - [0, 1]

Watts (1995), who first suggests the use of fuzzy theory in fire safety, defines fuzzy logic as "information conveyed by words." Most words are inherently vague and depend on some arbitrary qualification for crisp application. Fuzzy control requires less information since it works in linguistic terms, and it can absorb human knowledge without having to translate it into a complex mathematical model. The membership function defines the shape of the fuzzy set. Several input parameters with corresponding subdivisions are combined with expert opinion to give an output value. Although input parameters could be explained numerically, the output parameter can only be defined linguistically meaning the use of fuzzy sets (Özyurt, 2010).

2.4.1. Fuzzy Expert System

Experts usually rely on common sense when they solve problems, including vague and ambiguous terms. Since the root of fuzzy theory is based on linguistic variables, the idea of representing expert knowledge in a computer directs researchers to fuzzy logic. The knowledge based decision-making model using fuzzy theory is defined as a fuzzy expert system. Negnevitsky (2011) defines a fuzzy expert system have five main steps:

Step 1. Specify the problem and define linguistic variables,

Step 2. Determine fuzzy sets,

Step 3. Construct fuzzy rules,

Step 4. Encode the fuzzy sets and fuzzy rules to perform fuzzy inference,

Step 5. Evaluate and tune the system.

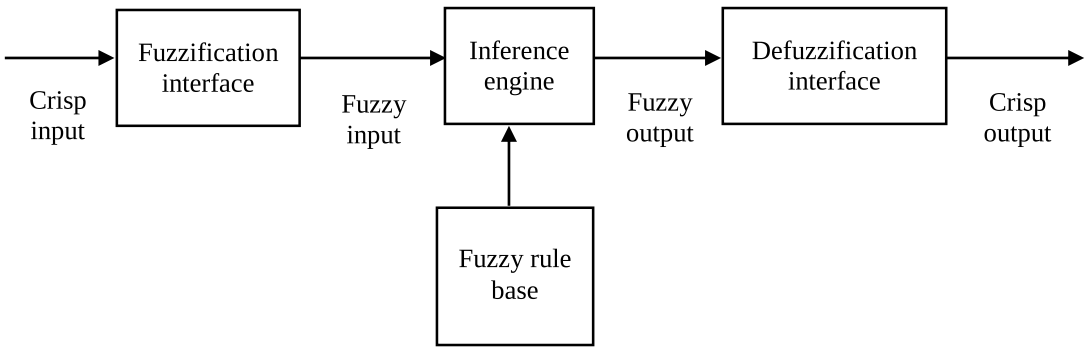


Figure 2.6 Fuzzy expert system model (Nilashi *et al.*, 2011)

The relationships between each step form the structure of fuzzy expert system shown in Figure 2.6. The main components are a fuzzification interface, a fuzzy rule base (knowledge base), an inference engine (decision-making logic), and a defuzzification interface. The first process is fuzzification, where the input variables are fuzzified through membership functions. In fuzzification phase, the degree of belonging of input variables is determined. In rule base component, fuzzy rules are set in the form of if-then rules by using linguistic variables. A fuzzy rule can be defined in the form: “IF x is A THEN y is B” where x and y are linguistic variables; and A and B are linguistic values determined by fuzzy sets. Fuzzy if-then rules and fuzzy reasoning are the basis of fuzzy expert systems, which are the most important modeling tools based on fuzzy set theory. Inference engine computes the consequence of each rule (Nilashi *et al.*, 2011). The most commonly used fuzzy inference technique is the Mamdani method (Negnevitsky, 2011). In Mamdani method represented in Figure 2.7, in order to provide rule strength, the minimum operator is used to compute fuzzy for combining multiple fuzzified inputs. In the output membership function, maximum operator is used to compute fuzzy (Cook, 2007).

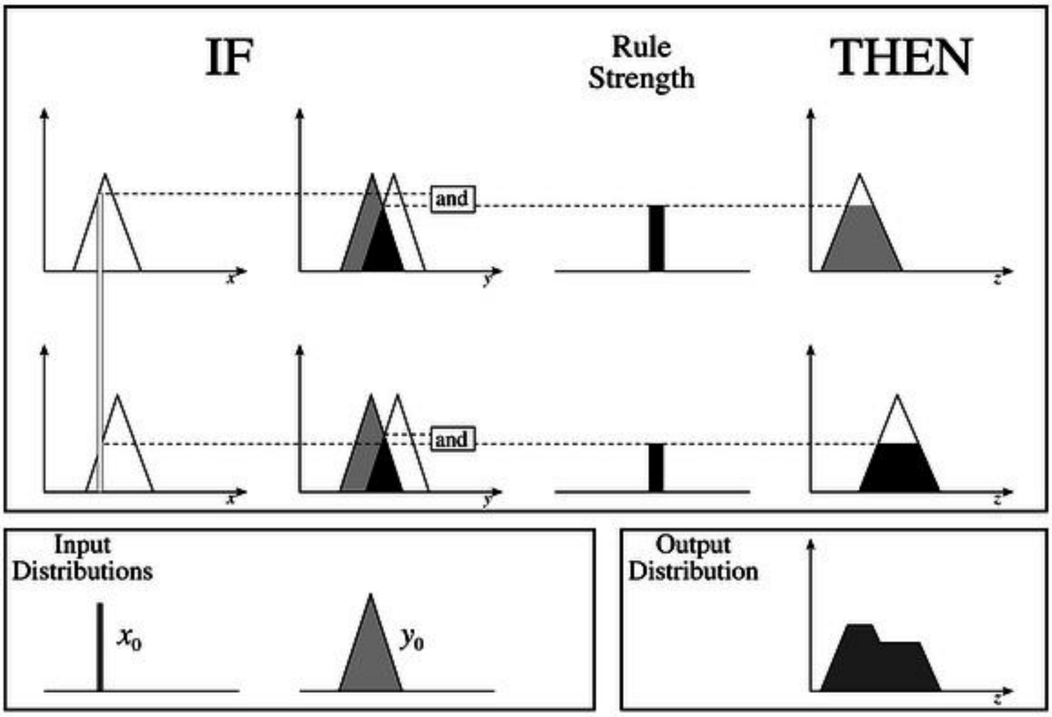


Figure 2.7 A two input, two-rule Mamdani fuzzy inference system (Cook, 2007)

Finally, in defuzzification phase, fuzzy output is converted to crisp output. Among the several defuzzification methods, most preferred one is centroid technique, based on finding one crisp number corresponding to the center of mass of fuzzy output (Figure 2.8).

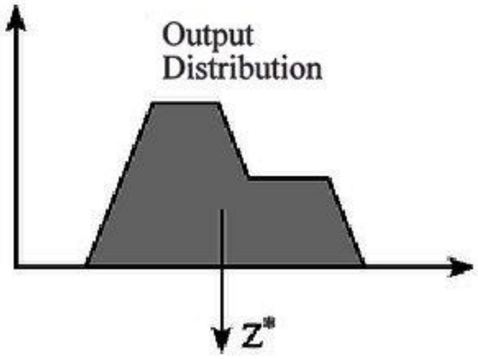


Figure 2.8 Defuzzification using center of mass

2.4.2. Application of Fuzzy Logic in Fire Safety Field

Fuzzy logic was first suggested by Watts (1995) to be used in fire safety evaluation and applied by some researchers in different fields of fire safety subjects. According to Watts (1995), most fire safety problems are not clear-cut and not have simple answers. On the contrary, they are complex and vague, requiring diffused answers, rather than commonly proposed closed-end answers so that fuzzy logic is useful for fire safety solutions.

Lo (1999) suggested a system for fire safety evaluation of existing buildings combining fuzzy logic and AHP methods in holistic multi-attribute evaluation system. The method is expanded by Liu *et al.,* (2009) and tested on fuzzy analysis for means of escape and warning system parameter with sub-parameters of an average width of exit routes, total number of exit routes, the maximum travel distance, average population distribution pattern, configuration/indication of exit routes and average emergency lighting level based on requirements of Hong Kong's Means of Escape Code.

Paralikas and Lygeros (2005) focused on uncertainties in the assessment of industrial hazards, and developed rapid assessment and relative ranking method for chemical substances hazards. The approach uses AHP for incorporation of hazard properties and fuzzy logic to deal with linguistic variables. Hazard properties for the proposed method are grouped as fire hazard properties, special hazard properties, physical properties and burning properties.

There are also some recent works on fuzzy fire safety evaluation. One of them is conducted by Guang-Wang and Hua-Li (2011) as a fire risk assessment model for high-rise buildings, which calculates index weights by AHP and suggests a fuzzy pattern recognition model with reference to the high-rise building fire safety design specifications. Another fuzzy model is suggested by Issa, Azmani, and Amami (2013) as a vulnerability analysis model of fire spreading in a building using fuzzy logic with input variables of "oxygen volume," "combustion speed," and output variable of "fire duration." Fuzzy membership functions are determined through questionnaires proposed to some experts in fire safety domain. Khanna (2013) proposed a fire detection model for forest fires with input variables of temperature, humidity, CO density, light intensity, and output variables of fire probability and fire direction. Xie, Liang, and Wang (2014) prepared a fuzzy evaluation model for cooking fire-extinguishing system based on reliability of sprinkler, pipe network, fire detection device, alarm device, and water mist variables. Kong *et al.* (2014) generated fire scenarios of fire protection system failure by combining fuzzy sets and event tree model, with input variables of fire growth rate and pre-evacuation time, and output variable of fire risk for life safety.

2.5.Critical Review of Literature

Fire safety precautions direct architects to regulations, however regulations can be perceived as constraints and interventions in the design process. This is because rules and regulations apply a deterministic approach rather than flexible and performance based evaluation tools. Most of the performance based evaluation tools are based on fire protection systems, which aim to alert building occupants and try to put out the fire by using fire alarms, sprinkler systems, and fire extinguisher systems. Being too fire focused on the design of fire protection measures limits performance based methods by leading ignorance of important fire design aspects related to building components and occupants. Moreover, selection of precautions according to fire scenarios may result in evaluation of fire protection system performance rather than to test the overall building fire safety performance. Therefore, in order to apply comprehensive fire safety measures including building components and occupants, multi-criteria decision-making methods are proposed for fire safety. However, most of the decision-making tools follow the deterministic approach as well by taking direct values from regulations. On the other hand, the predictable and deterministic world of the past has been replaced by the uncertain, random, and disorderly world of today. Different attributes represent different dimensions of alternatives, and may be in conflict with each other, may not be easily represented on a quantitative scale, may not be directly measurable, and may be stochastic or fuzzy.

The single-criterion and simple decision-making requirements of the past have today given way to highly complex decision problems involving multitudes of variables, which may be stochastic, fuzzy, or at worst unknown. Moreover, human decision-making needs a quick-response analysis based on the decision-maker's intuition, judgement, and experience. As a result, in order to insert uncertainty and human knowledge to fire safety evaluation systems, fuzzy logic method is used for vulnerability evaluation of building characteristics in terms of fire safety. Vulnerabilities of a building need to be determined to ensure an acceptable fire safety level starting from the preliminary design phase. Previous researches on fire safety fuzzy evaluation are reviewed in the literature. They focus on fire safety evaluation of existing buildings (Lo, 1999 and Liu *et al.,* 2009), uncertainties in the assessment of industrial hazards (Paralikas & Lygeros 2005), fire risk assessment for high-rise buildings (Guang-Wang, & Hua-Li, 2011), fire spreading in a building (Issa *et al.* 2013), and fire detection model (Khanna, 2013). Comprehensive fire safety fuzzy methods do not cover all critical parameters of building characteristics.

This research aims to prove the direct relationship between building characteristics and fire spread, and identification of building vulnerabilities in the design process. For this purpose, critical building components in terms of fire safety are identified through literature review. Most of the fire safety evaluation methods that use ranking systems has proven their arguments by giving the highest priority to building parameters. Among nine fire safety evaluation researches conducted between 1991 to 2012, seven of them weighs the highest ratio to building parameters. Donegan, Taylor,and Meehan (1991) weigh fire safety parameters over 500 by giving 205 to passive fire safety parameters including internal design, survey volume, means of escape, hazard protection, and external envelope. The highest priority ranking is given to means of escape and warning system parameters with ratios of 34% and 51% by Lo (1999) and

Zhao *et al.* (2004). The most important parameters in the system are a number of exit routes, travel distance and emergency lighting. Karlsson and Larsson's research prepared in 2000 has doors with 6.8% weight and highest priority among 17 fire safety variables. Similarly, among 20 parameters in Watts and Kaplan (2001) research, vertical opening and building construction have highest weighing values with 18% and 12% weights. In the fire safety evaluation system prepared by Chow (2002) highest-ranking factor is passive building construction parameters with 63.3% ratio. Passive building construction components include building height, evacuation route, width of the staircase, smoke doors, and fire resistive construction. Recently, Chen *et al.* (2012) conducted an evaluation system which gives highest ratio at 45% to fire control and resistance factors. Most critical variables are listed as fire door accessibility and fire and smoke-proof function, safety area and fire resistance of the compartment, fire barriers with vertical openings (ducts, elevated areas, stairs, elevators, openings of exterior walls) and control of fire and smoke spread of evacuation routes.

When most critical three building parameters are listed among 9 evaluation systems, 8 different parameters are achieved which; means of escape, structure-separating/building height, doors, compartmentation/hazard protection, vertical openings, furnishing, interior finishes, and external envelope/façade. By using all critical parameters, fuzzy vulnerability analysis model in terms of building characteristics is proposed in this research.

CHAPTER 3

METHOD AND MATERIAL

In this study, since suitable for the uncertain nature of fire safety evaluation, fuzzy expert system method is selected to find out vulnerability level of building characteristics in terms of fire safety and possible measures to decrease it. Expert systems aim to bring experts' skills to solve specific problems and provide a structure to deal with uncertainties. Using expert system based on fuzzy logic has advantages since it directly maps into natural language by capturing complex interactions between variables in linguistic terms, enabling everyday reasoning (Özyurt, 2010). There are two types of fuzzy expert systems: fuzzy control systems and fuzzy reasoning. Fuzzy control systems first achieved by Mamdani in 1976 and widely accepted first in Japan, then throughout the world. The system is characterized by a simple process. Firstly, numbers are accepted as inputs, then in fuzzification phase input numbers are translated into linguistic terms such as slow, medium, and fast. Rules are defined to map input linguistic variables onto output linguistic variables. Finally, output linguistic variables are translated into output numbers, which is defuzzification process. The drawback of the fuzzy control system is that, the input and the output parameters are restricted to numbers. On the other hand, in fuzzy reasoning systems, although fuzzification, inference module, and defuzzification phases are structured in the same order, it both deals with numeric and linguistic data input and output (Siler & Buckley, 2005). This study deals with both numeric and linguistic data, therefore the method is based on fuzzy expert reasoning system. In this chapter, fire safety vulnerability assessment parameters, evaluation model structure and İzmir Opera House as a case study is explained.

3.1 Parameters of Fuzzy Vulnerability Assessment Model

This research aims to reinforce the direct relationship between building characteristics and fire spread, by referring to effects of building design inputs on the acceptability of fire safety design. Type of fuzzy expert system used in this study is selected as fuzzy reasoning since building design input has several components both numeric and linguistic data. Therefore, the fuzzy reasoning expert system is structured to detect the vulnerabilities of building characteristics in terms of fire safety. Figure 3.1 shows the framework of fire safety design process adapted from NFPA 101 (2012), by combining fire safety objectives and building design input. According to the framework, if the intersection of the building design input and fire safety design input results in unacceptable design, the system directs designers to modification of a proposed building design. Consequently, acceptability of proper fire safety design directly depends on the suitability of building design input with general fire safety objectives.

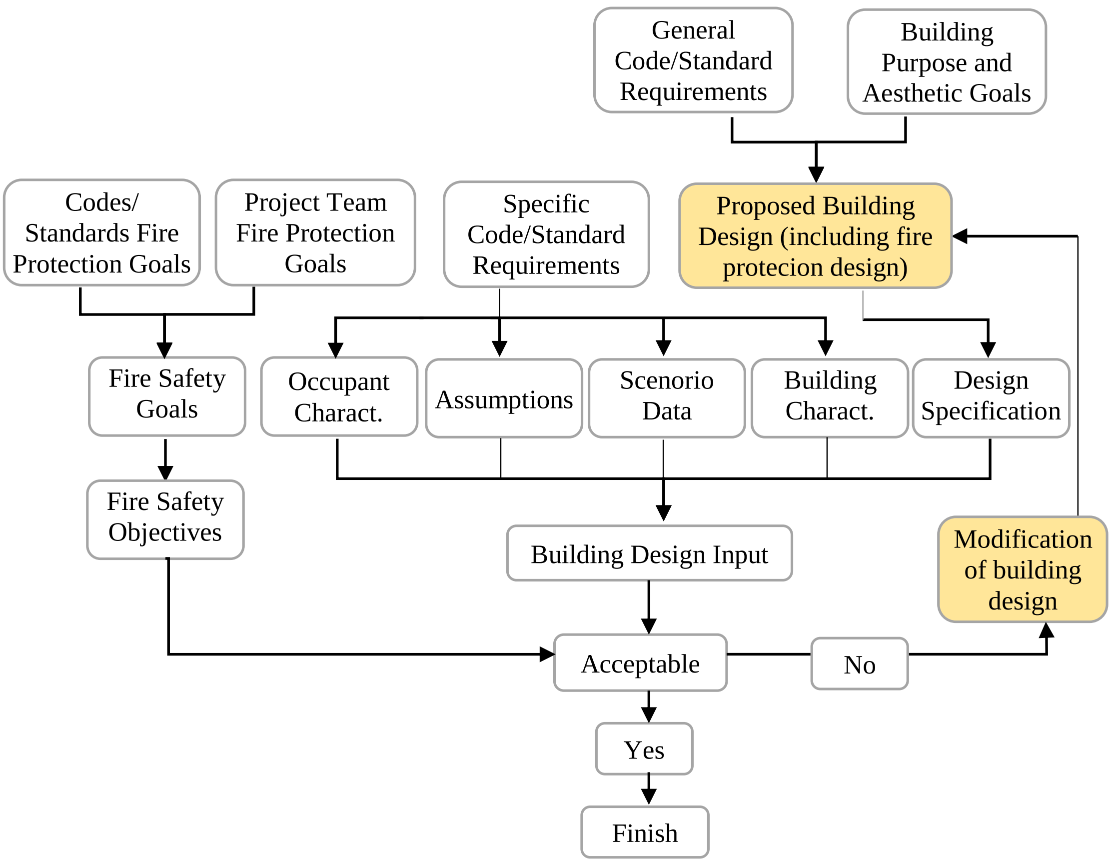


Figure 3.1 Fire safety design process (NFPA 101, 2012)

The building design process has several inputs including fire protection design. Critical building components in terms of fire safety are identified and used as input parameters of fuzzy expert system. In order to identify the most critical parameters, among nine fire safety evaluation researches conducted between 1991 to 2012, the most high-ranking and the most critical three building parameters are selected. As a result, eight critical parameters are identified and listed from most mentioned at least as: (1) escape route, (2) structure-separating/building height, (3) doors, (4) compartmentation/hazard protection, (5) vertical openings, (6) furnishing, (7) interior finishes, and (8) external envelope/façade. In Figure 3.2 framework of the most critical parameters of fire safety in the building design process are represented.

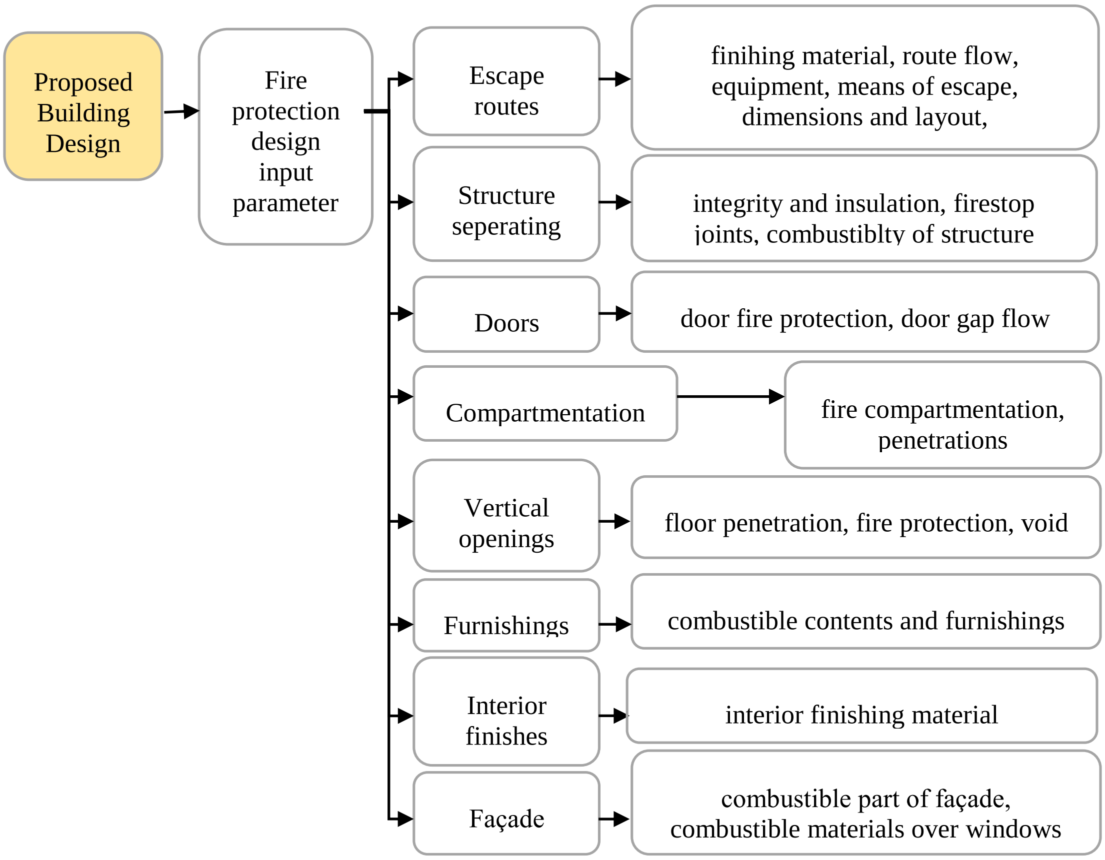


Figure 3.2 Critical building characteristics input parameters in fire safety design

In the scope of this thesis, only the most critical building characteristics in terms of fire safety are tested through the fuzzy expert system, so that a comprehensive evaluation of eight building criteria is proposed. In order to develop a comprehensive fire safety vulnerability assessment of critical building characteristic parameters, input variables for escape route, door, structural separation, compartmentation, vertical openings, combustible contents and furnishings, interior finishes, and façade are determined in this section. Evaluation tables for each building characteristic parameter with sub parameters are generated for expert opinion by using literature analysis. For the critical vulnerability analysis, among all parameters of comprehensive fire safety evaluation researches, escape route parameter is listed first among other critical and high-ranking variables. However, for this research, as a threshold matter, only escape route vulnerability is assessed to test the applicability of the method.

3.1.1 Escape Route Vulnerability Input Variables

An escape route is a safe route, provided for people to travel from any point in the building to a safe place beyond the building (UCL, 2000). While designing escape routes, the main strategy is to provide safe and simultaneous evacuation to all occupants, as soon as a fire has been confirmed. Additional factors of escape route design are; establish a required width of exits to adjust evacuation, provide the minimum number of separated exits, comply the limitation of travel distances, and correspond to fire protection requirements in stair enclosures and exit corridors. In this research, for the first application phase of comprehensive building characteristics vulnerability assessment, escape route input parameters are evaluated. Escape route fuzzy vulnerability assessment sub-parameters are fire reaction classifications of interior finishing materials, escape route flow, escape route equipment, means of escape and route dimensions and layout. The vulnerability assessment framework of sub-parameters and their input parameters are represented in Figure 3.3.

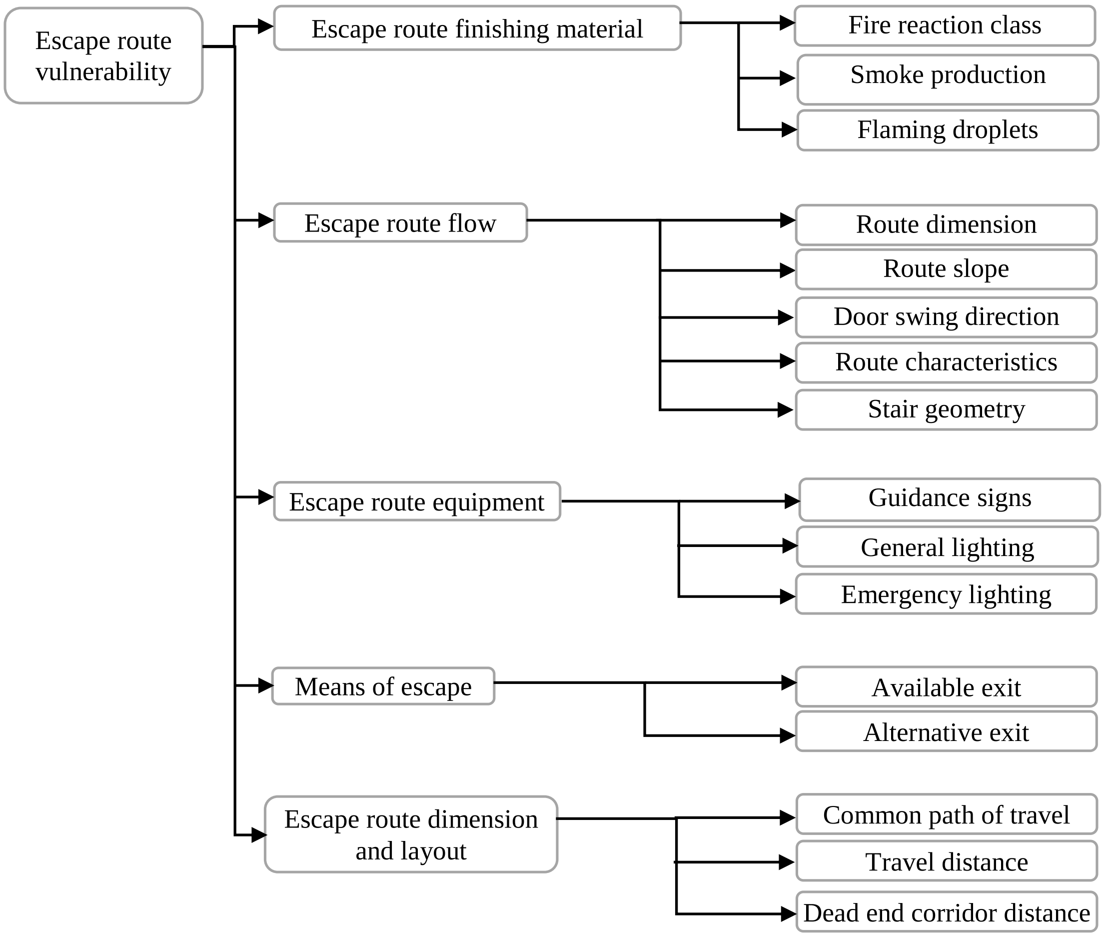


Figure 3.3 Escape route vulnerability level input parameters

Escape route evaluation of input parameters is derived from fire safety standards and expert opinion. Escape route finishing reaction to fire classification input parameter module evaluates fire performance level of escape route wall, floor, and ceiling materials according to 13501-1 materials classification of reaction to fire standard. Sub-parameters of finishing material are fire class, smoke development class and falling parts and droplets class; by which module generates rules based on standard. In the second module, geometrical information of escape route is evaluated through route dimension (width/ height), route slope, door swing direction (outward/ inward), route characteristic (with stairs/ with transitions), and stair geometry (step rise/ tread width). The evaluation grading of second module on the 0 and 1 range is adopted from the literature. In the third module, features of the equipment on the escape route are evaluated. Sub-parameters of equipment are guidance sign conditions, general lighting conditions and emergency lighting conditions. In the fourth module, available and alternative means of escape components are evaluated. The components of means of escape are; exit doors, stairs, and exit ways through balconies and windows. Finally, in the fifth module, evaluation of travel distances, common path distances, dead end distances, and layout are evaluated through limits of fire safety standards.

a. Escape Route Finishing Reaction to Fire Classifications

In terms of fire safety field, interior finishing materials are defined as materials that are attached or applied to walls, ceilings, or wall-ceiling surfaces. Various studies for interior building materials conducted in terms of surface burning characteristics, such as flame spread and smoke developed performance criteria, by using fire test methods to investigate their limit of contribution to fire growth when exposed to fire conditions. (Online Certifications Directory, 2015). The main purpose of studies and tests is to determine combustibility (noncombustible/ combustible) and fire resistance of interior building finishes. Noncombustible materials are defined as materials that are not capable of igniting and burning. Determining noncombustibility is assessed with standard test ASTM E-136. On the contrary, combustible materials will ignite, burn, support combustion, or release flammable vapors (NCDOI OSFM Evaluation Services, 2011). Combustible materials are defined as materials that readily ignite and burn such as wood-plastic composite and plastic products commonly used for decking and siding. The relative combustibility of different materials is determined by a flame spread index and heat release rate parameters (Quarles, 2013). Flame spread, used to assess surface burning characteristics of building materials, is one of the most tested fire performance properties. The most widely accepted flame spread classification system defined in the National Fire Protection Association Life Safety Code, NFPA 101, as a test for developing flame spread rating by American Society for Testing and Materials (ASTM) Test Method E 84, commonly known as the tunnel test, since the test is conducted by placing material horizontal tunnel (Steiner Tunnel) in 10-minute exposure (Department of Public Safety and Corrections, 2015) Flame spread Classification of interior wall and ceiling finish materials is done according to this flame spread test (ASTM E 84), which determines relative burning behavior by visually observing the flame spread of tested material.

Another accepted fire classification system is Euro-class system, which is adopted by many members of European Union and Turkey, to decide on the classification of reaction to fire. In Euro-class system, classification of building materials' reaction to fire in terms of three properties of building material is done: (1) fire spread, (2) smoke intensity, and (3) burning droplets. There are seven classes in terms of reaction to fire; A1, A2, B, C, D, E, F. These categorization building construction materials is published in standard EN 13501-1 "Fire classification of construction products and building elements – Part 1: Classification using test data from reaction to fire tests".

Existing national methods use different sizes of fire sources and fire tests to evaluate fire safety of building materials. However, the minimum parameters to be considered are, flame spread, damaged length and falling parts and droplets (Enhos, 2014). NPFA 101 flame spread index gives the performance criteria of combustibility and smoke development indexes available for most of common materials separated into three classes. On the other hand, the EN standard classification is based on reaction to fire classification based on the performance criteria test together with additional classification data of smoke production and falling parts and droplets in the more comprehensive notification. Moreover, Turkish standards are adopted from EN standards, the fire performance data available for construction materials in Turkey case are mostly available in EN 13501-1 standard.

In this study, the method used to determine vulnerability levels based on materials classification of reaction to fire (EN13501-1) since it enables a more comprehensive evaluation, and has an availability of fire classification for a wide range of materials, therefore flexibility in material selection. Linguistic variables of fire performance of materials based on fire reaction classes, smoke development classes and falling part and droplet classes are listed in Table 3.1. Reactions to fire of some common materials are determined through European standards without testing. For the materials evaluated in this study, classifications are adopted from the research conducted by Demirel & Altındaş (2006), and listed in Table 3.2.

Table 3.1 Classification of material‘s reaction to fire (Turkeys regulation on fire safety, TS EN 13501-1 Table-2/Ç)

Material Reaction to Fire	European Classes
Noncombustible	A1
Very Limited Combustible	A2-s1, d0
Limited Combustible	B, C-s1, d0 A2-s2, d0 A2, B, C-s3, d0 A2, B, C-s1, d1 A2, B, C-s1, d2
(minimum)	A2, B, C-s3, d2
Flammable	D- s1, d0 D- s2, d0 D- s3, d0 E D- s1, d2 D- s2, d2 D- s3, d2
(minimum)	E- d2
Easily Flammable	F

Table 3.2 Fire reaction classes for selected materials (adapted from Demirel & Altındaş, 2006)

Material Definition	Classification	Material Reaction to Fire
Concrete	A1	Noncombustible
Steel, Stainless steel, Aluminum	A1	Noncombustible
Autoclaved aerated concrete	A1	Noncombustible
Gypsum and gypsum based plasters	A1	Noncombustible
Gypsum boards	A2-s1, d0 B-s1, d0	Very Limited Combustible Limited Combustible
Plywood	D- s2, d0	Flammable
Solid wood sheeting	D- s2, d0	Flammable

b. Escape Route Flow

The increase in population and complexity of buildings brings forward building safety in case of fire. In order to accomplish safety task of buildings, besides designing and implementing proper fire protection system, effective egress system needs to be designed. Egress system has many components; in brief, it is defined as a path of travel that occupants reach to a safe place without affecting from fire (Grimaz. & Tosolini, 2013). Additionally, egress system should provide safe evacuation of occupants with quick response time.

Vulnerability analysis permits identification of factors that affect the response of egress system when exposed to fire conditions. Indeed, vulnerability analysis aims to determine critical factors impetuously and without simulating evacuation process. Identification of escape route critical points could be helpful in both design and management of building safety (Grimaz & Tosolini, 2013). Once the critical points of the design are diagnosed, measures can be taken rapidly, providing important timesaving. Improper design of escape route flow with irregular and congested corridor routes and unsafe stairways may cause time delay during evacuation. The time delay in case of emergency is such a critical factor that, before the last person in the building to reach the protected area can be measured in minutes. Design of escape route flow is crucial, especially on the floors directly above and below the fire floor. Therefore, in case of fire, the impact of an accident is greater, if the staircase is not designed or restricted properly (Leur & Scholten, 2013). In order to evaluate and improve escape route flow, for the second sub-parameter of escape route vulnerability assessment, detail analysis of escape route flow is planned by using research conducted by Grimaz & Tosolini (2013) on vulnerability analysis of escape routes. Input parameters of escape route flow are represented in Table 3.3. According to the table, route flow is affected by route dimensions, route slope, route characteristics, door swing direction on the route, and stair geometry.

Table 3.3 Escape route flow evaluation (Grimaz & Tosolini, 2013)

<table>
<tr><td rowspan="5">f_1</td><td rowspan="5">Route dimensions</td><td rowspan="2">Route height (cm)</td><td colspan="3">Route width (cm)</td></tr>
<tr><td>W ≤ 55</td><td>W≤ G+20</td><td>W> G+20</td></tr>
<tr><td>h > 200</td><td>0.00</td><td>0.87</td><td>1.00</td></tr>
<tr><td>170< h <200</td><td>0.00</td><td>0.33</td><td>0.50</td></tr>
<tr><td>h < 170</td><td>0.00</td><td>0.00</td><td>0.00</td></tr>
<tr><td colspan="6">W: person width (0.55 m for generic people type, 0.75 m for people on wheelchair, 0.90 m for people carrying shopping bags, 1.10 m for people in bed).</td></tr>
<tr><td rowspan="2">f_2</td><td rowspan="2">Route slope</td><td colspan="3">Horizontal plane</td><td>1.00</td></tr>
<tr><td colspan="3">Sloping rate</td><td>0.75</td></tr>
<tr><td rowspan="2">f_3</td><td rowspan="2">Door swing directions</td><td colspan="3">Outward</td><td>1.00</td></tr>
<tr><td colspan="3">Inward</td><td>0.50</td></tr>
<tr><td rowspan="5">f_4</td><td rowspan="5">Route characteristics</td><td colspan="3">Horizontal, without stairs</td><td>1.00</td></tr>
<tr><td colspan="3">With transitions</td><td>0.95</td></tr>
<tr><td colspan="3">Slope</td><td>0.90</td></tr>
<tr><td colspan="3">Stairway with 3-15 steps</td><td>0.80</td></tr>
<tr><td colspan="3">Not straight or regular route</td><td>0.80</td></tr>
<tr><td rowspan="7">f_5</td><td rowspan="7">Stair geometry</td><td colspan="4">If stair present</td></tr>
<tr><td colspan="2">Riser (cm)</td><td colspan="2">Tread (cm)</td></tr>
<tr><td colspan="2">16,5</td><td>33</td><td>0,90</td></tr>
<tr><td colspan="2">16,5</td><td>33-30</td><td>0,85</td></tr>
<tr><td colspan="2">16,5 -17,8</td><td>30 -28</td><td>0,80</td></tr>
<tr><td colspan="2">17,8 – 19</td><td>28 -25,5</td><td>0,75</td></tr>
<tr><td colspan="2">> 22</td><td>< 24,0</td><td>0.00</td></tr>
</table>

c. Escape Route Equipment

Evaluation of emergency route equipment parameter comprises assessment of guidance sign, general lighting, and emergency lighting conditions for each escape route. Planning a safe guidance for pedestrians is important since they are vulnerable to emergency events (Chu & Yeh, 2012). Guidance signs, also known as emergency evacuation signs, have an important role in guiding evacuees to exit ways (Liu *et al*, 2011). With proper design of exit signage design, signs are required to be placed in immediately visible parts of escape routes such as corridors and passageways with clear indication of travel direction. Previous studies reveal that guidance signs may not be perceived during evacuation due to smoke development during a fire event. In this case, illuminated exit signs classified as electrically powered, self-luminous, and photoluminescent exit signs are required to provide safe evacuation (Budzinski, 2016).

Illumination during the exit discharge process is not only important for exit signs, but also required for emergency illumination of evacuation paths. In non-emergency case, general lighting system serves for illuminating the building. General lighting, also referred to as ambient lighting, is designated for overall illumination of an area. Besides, general lighting enables the occupant to see and walk safely by providing a comfortable level of brightness without glare (American Lighting Association, 2016). In case of escape route design, either general lighting can be manually turned on or it can be always on by providing additional power supply. Emergency illumination, on the other hand, is required to supply when the general lighting fails. Emergency lighting is required for aisles, corridors, exit passageways, stair enclosures, and for any other means of egress component in the building (Budzinski, 2016). According to NFPA Standards, emergency egress illumination time for exit signs and emergency lighting is 90 minutes. The illumination must be operated with or without utility supply power so that, either a generator that supplies power at the same voltage and frequency as the utility, or central rechargeable battery, or individual rechargeable battery for each exit sign and luminaire must be used (Bleeker & Gregory, 2005).

In initial equipment design phase, regardless of being on emergency escape route or an anti-panic area, luminaries are placed in specific hazardous locations to provide illumination for safe travel along the escape route, and for highlighting safety equipment and signs. Specific locations where a luminaire must be provided are; (a) at each exit door, (b) all safety exit signs, (c) outside and near each final exit, (d) near stairs so that each tread receives direct light, (e) at each change of direction, (f) near each first aid post, (g) near any other change of floor level, (h) at each intersection of corridors, and (i) near each piece of firefighting equipment and call point (Figure 3.4).

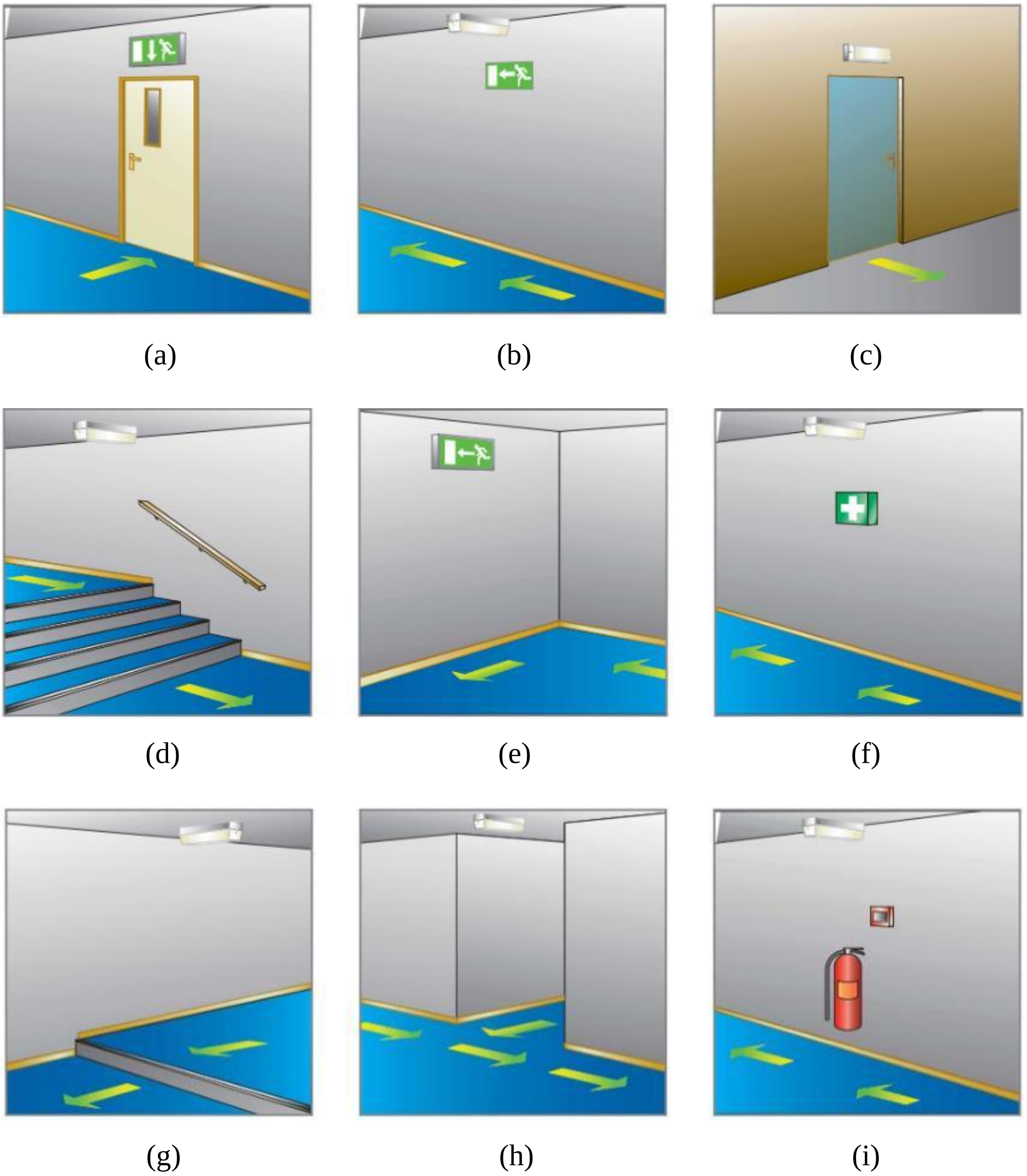


Figure 3.4. Specific locations of escape route luminaries (Technical Code, 2000: Emergency lighting design guide)

Input parameters of escape route equipment determined as guidance sign, general lighting and emergency lighting, through the research conducted by Karlsson & Larsson (2000) on risk analysis of multistory apartment buildings (Table 3.4). In this research, evaluation of equipment conditions is designed on the bases of initial building design with categorical functions, since exact data on minimum illuminance levels (Lux) may not be available in the initial design phase. When the points of specific locations have been covered, additional luminaires with proper illuminance levels required to be used in escape routes. For the designers want to use numerical illuminance level data for evaluation, BS5266 / EN1838 standards for emergency lighting design can be used.

Table 3.4 Escape route equipment vulnerability evaluation (Karlsson & Larsson, 2000)

Guidance Signs	**General Lighting**	**Emergency Lighting**	**Vulnerability Level**
Illuminating Light	Always on	Provided	
Illuminating Light	Always on	Not Provided	
Illuminating Light	Manual	Not Provided	
Illuminating Light	Manual	Provided	
Normal	Always on	Not Provided	
Normal	Always on	Provided	
Normal	Manual	Not Provided	
Normal	Manual	Provided	
None	Always on	Provided	
None	Always on	Not Provided	
None	Manual	Provided	
None	Manual	Not Provided	

Means of Egress

Egress route is the travel path from a room to final exit. Final exit is the place where escape route from a building terminates by giving direct access to a 'Place of Safety' such as a street, passageway, walkway, or open space, and sited to ensure that persons can disperse safely from the vicinity of the building and the effects of fire. In case of emergency, occupants from each room of the building may have either a single alternative or multiple alternatives to evacuate from the building. Single means of egress route exits if there is no direct exit or multiple means of egress, while multiple exits consist at least two separate means of egress routes from room to outside of building. Multiple means of egress might be directly open to the public way through door, enclosed exit stairway or exit passageway, which is defined as "direct escape." On the other hand, there may be intermediate path in between means of egress door and outside, in this case, multiple routes are defined as leading to escape route (Chow & Lui, 2002). Single exit may be permit if the travel distance is short and the occupant load is low. However, providing alternative escape routes through multiple means of egress enables a safe route in case of one escape route is affected by fire and smoke (Zhao *et al.*, 2003). Schematic diagram of multiple means of egress components with direct escape is represented in Figure 3.5.

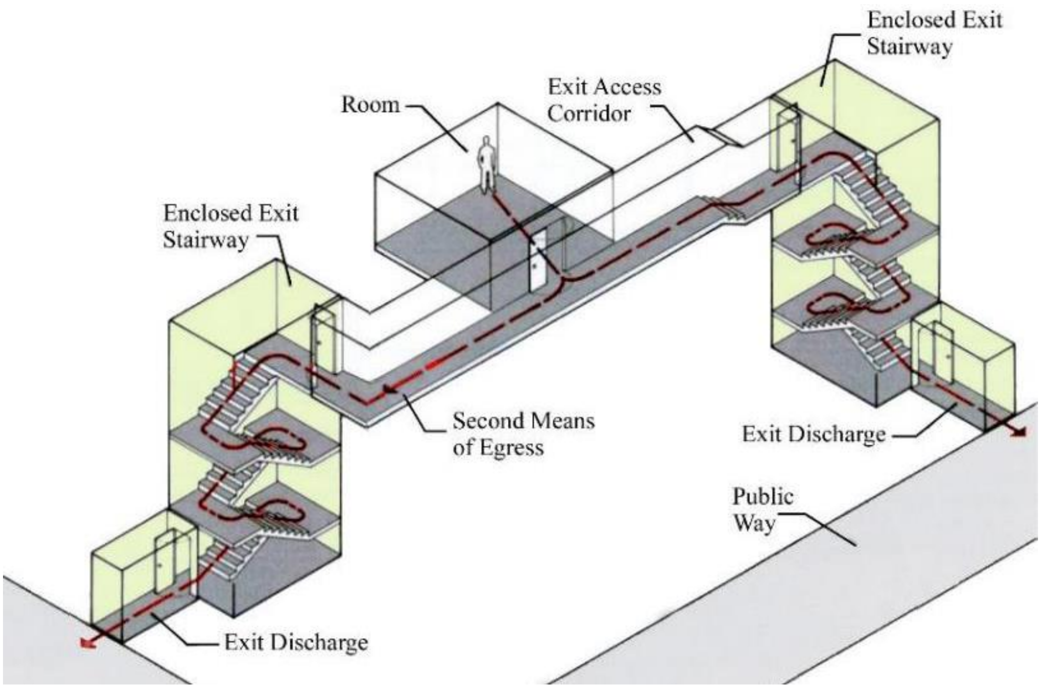


Figure 3.5 Multiple means of egress path

Although alternative means of egress such as windows, balcony or elevators are not acceptable through fire safety codes, in this research the effect of planning such alternative means through building design is evaluated. Whether the occupant should use emergency elevators during evacuation is always a question, since they are practical for occupants with disabilities and elderly people (Semple, 1993). However, there is a danger of smoke inhalation if there is a smoke in elevator shafts and deliver of occupants to the floor that contains the fire. Therefore, precautions of fire and smoke invasion to elevator shafts need to be taken before occupants are directed to the elevators. Using windows for alternative means of egress can be planned for levels lower than or equal to ground floor, and balconies can be egress alternatives if they are separated from building interior and minimize accumulation of smoke or toxic gases is provided.

In this study, means of egress evaluation parameters are identified through egress system spatial configuration model by Grimaz and Tosolini (2013) and type of escape route model by Karlsson and Larsson (2000). Therefore, means of egress evaluation model indicated in Table 3.5 is assessed by fire safety experts.

Table 3.5 Means of egress vulnerability evaluation

Exit available (staircase/ exit door)	**Alternative Exit (emergency elevator/ window/ balcony *etc.*)**	**Vulnerability Level**
Single	Not present	
Single	One alternative	
Single	At least two	
Multiple Leading	One alternative	
Multiple Leading	At least two	
Multiple Direct	Not present	
Multiple Direct	Present	

d. Escape Route Distances and Layout

From the fire safety point of view, placing the means of egress components (exit doors, enclosed exit stairways, exit passageways) in proper distances and layout in architectural plan is as important as providing an acceptable number of them. Escape route path distances from each room to each means of egress component is defined as travel distances. Travel route is required to be safe and accessible. The route path to an exit may not pass through kitchens, storage rooms, bedrooms, hazardous areas, workrooms, restrooms, or any other locked room (Luxenburg, 2009). The travel distance is measured along the route that is actually travelled, and not the straight-line distance (UCL, 2000). Common path of travel and dead-end corridor are measured using the same principles used to measure travel distances. Common path of travel limits the merge of multiple travel distances by measuring the path until the multiple travel routes are separated while dead end corridor exists if there is no path to travel and occupant may enter to a corridor thinking that there is an exit (NFPA 101, 2012). The measurement of travel distances, common path and dead end corridor distances are adapted from NFPA 101 (2012) and expressed in Figure 3.6, Figure 3.7, and Figure 3.8.

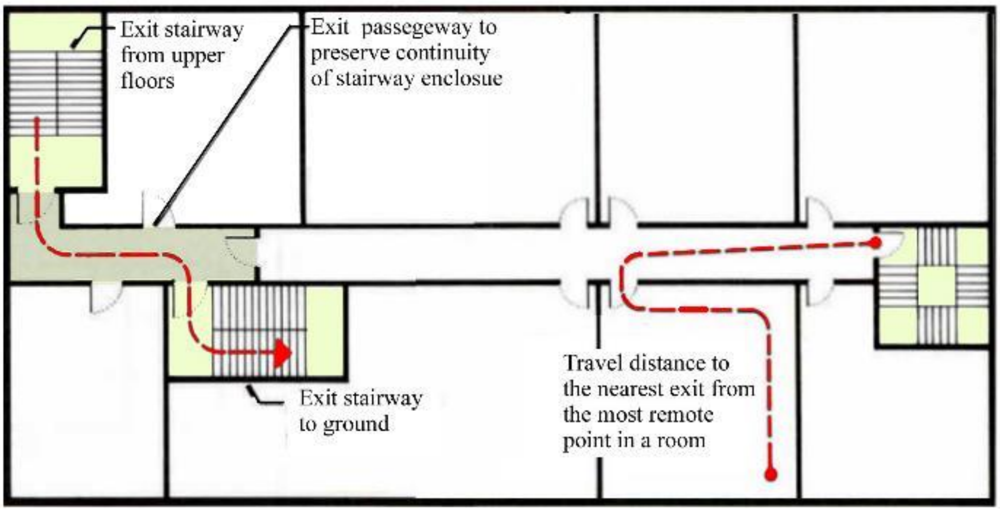


Figure 3.6 Travel distances through stairways and exit passageways

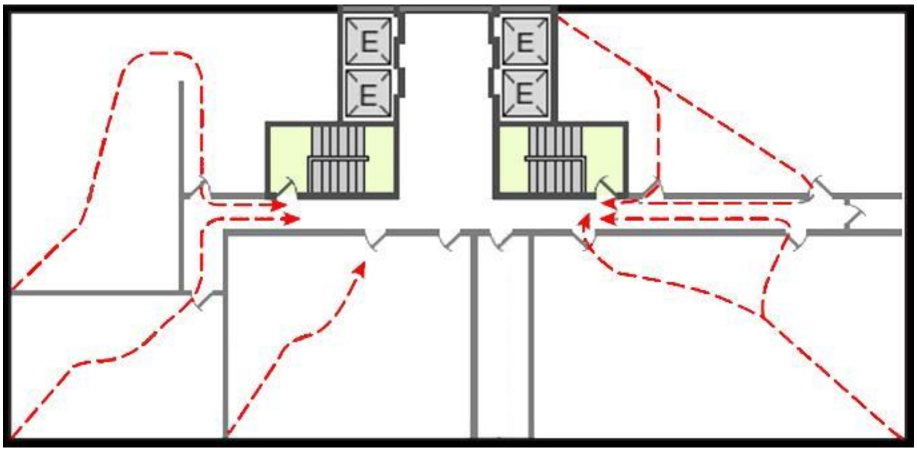


Figure 3.7 Common path of travel

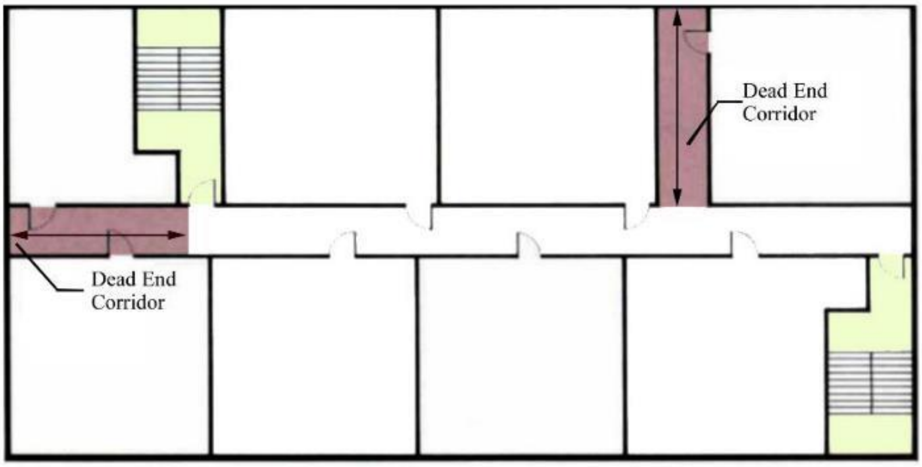


Figure 3.8 Dead end corridor

Table 3.6 Escape route distances and layout vulnerability evaluation

Common Path Of Travel	**Travel Distance**	**Dead End Corridor Distance**	**Vulnerability Level**
Within limits	Within limits	Within limits	
Within limits	Exceed the limits	Within limits	
Within limits	Within limits	Exceed the limits	
Within limits	Exceed the limits	Exceed the limits	
Exceed the limits	Within limits	Within limits	
Exceed the limits	Within limits	Exceed the limits	
Exceed the limits	Exceed the limits	Within limits	
Exceed the limits	Exceed the limits	Exceed the limits	

The maximum distances for common path of travel, travel distances, and dead end corridor distances are specified in the fire safety regulations depending on occupancy classifications. Table 3.6 is planned to show expert intuition to define relationships between escape route distances and layout, in order to provide an acceptable safety level. The length restrictions are determined through current Turkish Fire Safety Regulation (2015 - Table 5/B), based on assembly occupancies. According to regulation, for assembly occupancies with sprinkler protection common path of travel is limited to 25m, Travel Distances is limited to 60m, and dead end corridor is limited to 20m.

3.1.2 Door Vulnerability Input Variables

One of the critical building parameters is door, which is primarily used for access entrance or exit (NFPA 101, 2012). In terms of fire safety, fire doors have important role in not only access control but also protecting occupants and property from hazards, as well as compartmentalize (separate) the building into specific fire areas. Fire doors are used in exits, in enclosed exit stairs, exit passageways, and horizontal exits (Wroblaski, 2010). Door evaluation analyses depend on fire protection and door gap flow factors.

Fire protection factors are determined through fire risk analysis of multistory apartment buildings by Karlsson & Larsson (2000), while gap flow factors are determined through vulnerability analysis of escape routes by Grimaz and Tosolini (2013). Consequently, door input variables are planned to be evaluated in terms of fire protection (integrity and insulation -EI), closing type (manual or automatic), gap position (horizontal or sloping), swing direction (outward and inward) and density of people using the door. Integrity (E) is the ability of door to prevent flame and hot gasses passage when exposed to fire from one side, while insulation (I) is the ability of door to limit the temperature rise for the unexposed face. For fire doors, integrity and insulation are measured in minutes, and the minutes represent the time door loses its integrity, permits smoke, and fire to pass through it. Integrity and insulation may not be needed for each door component of building, while door gap flow is critical for each door. Evaluation table for door vulnerability analysis is represented in Table 3.7.

Table 3.7 Door fire protection vulnerability evaluation (Karlsson & Larsson, 2000; Grimaz. & Tosolini, 2013)

Parameter	Input Variables	Vulnerability Level		
Doors fire protection	Integrity and Insulation	Type of closing		
		Manually		Self-Closing
	EI < EI 30			
	EI 30 ≤ EI < EI 60			
	EI 60 ≤ EI < EI 90			
	EI 90 ≤ EI			
Doors gap flow	Gap position	Horizontal plane		
		Sloping plane		
	Door swing direction	People density d (person/m2)		
		d ≤ 0.4	0.4 < d ≤1.0	d >1.0
	Outward			
	Inward			

3.1.3 Structural Separation Vulnerability Input Variables

Structural separation parameter evaluates fire resistance capability of structural materials and whether the construction provides enough time for people to evacuate before it collapses (Quarles, 2013). Therefore, evaluation of structural fire resistance is important to determine how long structural elements of building resist fire by keeping their inherent design properties. The resistance of structural elements, as in the case of fire doors, is measured in minutes, in terms of integrity and insulation (Enhos, 2014). Structural separation vulnerability evaluation analysis depends on construction material fire resistance, design of firestop joints, intersections, and concealed spaces, and combustibility of structural design elements. Factors are determined through fire risk analysis of buildings research conducted by Karlsson and Larsson (2000). Vulnerability level evaluation criteria is listed in Table 3.8.

Table 3.8 Structural separation vulnerability evaluation (Karlsson & Larsson, 2000)

Parameter	**Input Variables**	**Criteria**	**Vulnerability Level**
Structural Separation	Fire resistance	R< R 30	
		R30 ≤ R < R60	
		R60 ≤ R < R 90	
		R 90 ≤ R < R 120	
		R120 ≤ R	
	Firestop joints, intersections and concealed spaces	Reinforced concrete frame structure with voids and no firestops	
		Ordinary design of joints, intersections and concealed spaces without special consideration for fire safety	
		Joints, intersections and concealed spaces have been tested and show endurance in accordance with the EI of other parts of construction	
		Joints, intersections and concealed spaces specially designed for fire spread prevention	
		Homogeneous construction with no voids	
	Combustible part of the load bearing structure	Both load bearing structure and insulation are combustible	
		Only the load bearing structure is combustible	
		Only the insulation is combustible	
		Both load bearing structure and insulation are non-combustible	

3.1.4 Compartmentation Vulnerability Input Variables

Compartmentation corresponds to physical barriers for preventing fire and smoke spread. Compartmentation is one of the most critical building characteristics to limit development and spread of a fire and smoke. Fatal fire examples show that there is a high probability of fire and smoke spread in staircase compartment areas (Kobes *et al*, 2010). Vulnerability level evaluation factors are determined through fire risk analysis of buildings research conducted by Karlsson and Larsson (2000) in Table 3.9. Fire resistance of compartmentation spaces has been required to be evaluated since providing temporary, but enough fire protection through fire resistance compartmentation enables survival of the occupants while remaining in the structure. Compartment space within a building describes the part enclosed by fire barriers on all sides, including the top and bottom. (NFPA 101, 2012). Moreover, the penetration in between any compartment areas (floors, walls, etc.) with or without qualified equipment required to be evaluated. This is because leaky fire compartmentation may lead to smoke spread, resulting in large damages (Nilsson, 2013).

Table 3.9 Compartmentation vulnerability evaluation (Karlsson & Larsson, 2000)

Parameter	**Input Variables**	**Criteria**	**Vulnerability Level**
Fire Compartmentation	Resistance, integrity and insulation	REI < REI 30	
		REI 30 ≤ REI < REI 60	
		REI 60 ≤ REI < REI 90	
		REI 90 ≤ REI < REI 120	
		REI 120 ≤ REI	
	Penetrations	Penetrations with no seals	
		No qualified penetrations	
		Qualified penetrations	
		Special installation shafts or ducts with qualified penetrations	
		No penetrations	

3.1.5 Vertical Openings Vulnerability Input Variables

Vertical openings are defined as an opening through a floor or roof, including components such as stairways; elevators shafts, dumbwaiters, expansion joints and seismic joints; shafts, or spaces used for light, ventilation, or building services. It is important to control fire and smoke spread through openings whether through suitably enclosed or protected measure to ensure reasonable safe means of egress. Vertical opening vulnerability assessment criteria are determined through fire risk index research conducted by Watts and Kaplan, (2001). Input variables listed in Table 3.10 are based on determining whether the vertical opening open to contiguous floors or not, fire protection of vertical opening enclosure walls, and availability of fire stopping through vertical opening connection. Enclosure depends on whether they are open (or with incomplete enclosure), or enclosed. For more detailed analysis of enclosed vertical openings that are, the fire resistance in terms of minutes and hours of rating of the enclosure may be used to determine the vulnerability evaluation input parameter (Chow, & Lui, 2002).

Table 3.10 Vertical opening evaluation table (Watts & Kaplan, 2001)

Parameter	**Input Variables**		**Vulnerability Level**
Vertical Openings	Vertical opening open to contiguous floors	Provided	
		Not provided	
	Enclosed with fire protected walls	Provided	
		Not provided	
	Availability of fire stopping	Provided	
		Not provided	

3.1.6 Combustible Content and Furnishing Vulnerability Input Variables

The presence of combustible materials may have a strong influence to minimize the necessary time to achieve the indefensible conditions in the building (ASET) in case of evacuation, especially if materials have a high fire reaction. In general, hazard contents are classified in three levels: low hazard contents, ordinary hazard contents and high hazard contents. Low hazard contents are with low combustibility, no self-generating fire, so the only possible danger to use emergency exits may result from panic, smoke, or external fire source. Ordinary hazard contents are prone to burning, and give considerable volume of smoke, but poisonous fumes and explosions are not observed. On the other hand, high hazard contents are likely to burn with poisonous fumes or explosions. In this study, combustible content and furnishing vulnerability level input variables are adopted from research of Grimaz & Tosolini (2013), since the parameters listed in Table 3.11 are common for most of the building occupancy types.

Table 3.11 Combustible contents and furnishings vulnerability evaluation (Grimaz & Tosolini, 2013)

Parameter	**Vulnerability Level**			
Input Variables	**If present**	**If ignite but not give flame give off slight smoke**	**If stored in safety cabinets**	**If present in pipes or spray**
No combustible content and furnishing				
Plastics or combustible carpets				
Pillows or bedding elements				
Upholstered furniture or mattresses				
Electronic devices				
Highly flammable solids or dusty materials				
Flammable liquids				
Flammable gases				
Reactive compounds				
Radioactive materials				
Explosives				

3.1.7 Interior Finishes Vulnerability Input Variables

Evaluation of interior finishes is performed during the escape route vulnerability analysis. Therefore, in this section only detailed explanations of material test methods will be explained briefly. First of all, determining non combustibility is assessed with standard test ASTM E-136 (Standard Test Method for Behavior of Materials in a Vertical Tube Furnace at 750°C), in which, three of four samples of tested material should meet the determined criteria. If the weight loss of the specimen during the test is 50% or less, the recorded temperature is less than 30°C, and no flaming from specimen after 30 second, then it is determined as non-combustible. This criterion is useful for construction materials. The second criterion is; if the weight loss of the specimen during the test exceeds 50%, then the temperature cannot be greater than temperature measured at that specific location, and no flaming at any time during the test. This criterion is for materials that contain large quantities of water and not permitted to apply exterior use of construction materials (Quarles, 2013). Examples of non-combustible materials are; Portland cement concrete, gypsum concrete used in drywall or poured gypsum floor toppings, brick masonry, concrete block masonry, ceramic tiles, metals except aluminum (aluminum is classified as limited-combustible), magnesium and magnesium alloys, sheet glass, block glass, and uncoated glass fibers, mineral wool, rock wool. If the material has a structural base of non-combustible material, the combustible surfacing is not more than 0.125” (0.3cm) thick, and the surfacing has a flame spread less than 50 when tested in accordance with ASTM E 84, materials can be classified as non-combustible (NCDOI OSFM Evaluation Services, 2011). On the other hand, combustible materials will ignite, burn, support combustion, or release flammable vapors. NCDOI OSFM Evaluation Services, 2011. Combustible materials are defined as materials that readily ignite and burn such as wood-plastic composite and plastic products commonly used for decking and siding. The relative combustibility of different materials is determined by a flame spread index and heat release rate parameters (Quarles, 2013)

Flame spread classification of interior wall and ceiling finish materials is done according to this flame spread test (ASTM E 84), which determines relative burning behavior by visually observing the flame spread of the tested material. Materials are rated Class A, Class B, or Class C according to their performance in this test; Class A

(0-25), Class B (26-75) and Class C (76-200) and all three classes common acceptable smoke development index is 0-450. The relative indication accepts flame spread and smoke developed index of reinforced concrete board zero, while grading red oak wood flooring flame spread and smoke-developed index of 100 (International Building Code, 2009). In specification of materials for interior finish of buildings and other structures, the flame spread behavior of the material may be as important as strength, ease of application, appearance, durability and other qualities (Gross, 1958).

Finally, in the Euro-class system; system, fire performance of construction products except floorings is based on four fire test methods: non-combustibility test, the gross calorific potential test, the single burning item (SBI) and ignitability test. The same methods, excluding SBI test are used for floorings with the addition of the radiant panel test. In non-combustibility test, specimen is inserted into a vertical furnace with about 750 °C temperature, then the temperature change (ΔT) is monitored, flaming time (tf) is visually observed and the mass loss of the specimen is determined (Δm). Gross calorific potential (PCS) test determines the maximum heat release of completely burned product. A powdery specimen is inserted into closed cylinder surrounded by a water jacket, and the temperature rise during burning is measured. On the bases of temperature rise and specimen mass PCS is measured in MJ/kg or MJ/m2. Single burning item test, the performance of specimen is evaluated for an exposure period of 20 minutes, and heat release rate (HRR) is measured by oxygen consumption calorimetry, smoke production rate (SPR) is measured in the exhaust duct, falling of flaming droplets or particles is visually observed during first 600 seconds of heat exposure, and lateral flame spread is observed. The classification is based on fire growth rate index (FIGRA), lateral flame spread (LFS), and total heat release (THR600s). For ignitability test, the specimen is exposed to direct flame. Two different flame application times and test durations are used. The flame application time is 15 seconds and the test is ended after 20 seconds after removal of flame for class E while for classes B, C and D flame application time is 30 seconds and the maximum duration is 60 seconds after removal of the flame (Hakkarainen *et al.,* 2015). At the end, Euro-class System, classifies building materials' reaction to fire into in terms of three properties of building material, fire spread, smoke intensity and burning droplets. There are 7 classes in terms of reaction to fire are; A1, A2, B, C, D, E, F

These categorization building construction materials are published in standard EN 13501-1 "Fire classification of construction products and building elements – Part 1: Classification using test data from reaction to fire tests". According to EN 13501-1, A1 classified products, have well-known reaction to fire such as concrete, mineral fibers, foam glass, fibrocement, lime, metals (iron, steel, copper, zinc, aluminum, lead), gypsum, mortars with inorganic binders (*e.g.* Cement, lime, masonry mortar or gypsum), clay (bricks, slabs, chimney claddings), calcium-silicate materials, natural stone and slate materials, glass, ceramics, none of which contain more than 1 % per weight or volume homogeneously dispersed organic content (Lehner, 2005). Since the minimum parameters of flame spread, damaged length and falling parts and droplets are covered by Euro-class system, and the fire performance data available for construction materials in Turkey case are mostly available in EN 13501-1 standard, Euro-class system is used in this research

3.1.8 Façade Vulnerability Input Variables

The new building façade and curtain wall applications may overcome fire safety concerns. The first critical factor effecting façade fire safety vulnerability is combustibility of façade assembly. The combustibility of the façade assembly components has a direct impact on the fire spread. Despite the fire impact, combustible materials may be used in façade wall assemblies to improve energy performance, to minimize water and air infiltration, and to fulfill aesthetic design concerns. The examples of combustible assemblies include exterior insulation finish systems, metal composite claddings, and weather-resistive barriers (White & Delichatsios, 2014).

Secondly, ignition of materials on the unexposed side of windows has key importance. The principle of the fire spread occurs through the radiation transmitted through a glass layer to combustible materials or through fire burning, which breaks down the window and permit the hot gas flow through top part of the opening. As a result, flame projecting out and upward from the window through the façade occurs since exterior building part provides enough air for hot gases that are unable to burn inside due to limited air. From the fire dynamics perspective, it is known that flames emitting from an exterior window can extend higher than 5m above the top of the window (O’Connor, 2008).

Finally, one of the main fire safety goals for a building design is to restrict the vertical fire spread through façade so that the smoke and flames are not expanded from the fire origin floor (Lamberto and Cancelliere, 2013). Therefore, the presence of voids in between façade and floor areas is one of the important concerns in façade vulnerability assessment. In terms of curtain wall design, either curtain wall panel may be supported to structural floor slab edge and required continuous or extended slab over the building envelope, or curtain wall may be positioned outside edge of the floor system with void space and requires sealing with an approved material or system to obstruct the fire spread. On the basis of this information, vulnerability input parameters are determined as combustible part of façade, combustible materials above windows and void through fire risk analysis, research conducted by Karlsson and Larsson (2000), and represented in Table 3.12.

Table 3.12 Façade vulnerability evaluation (Karlsson and Larsson, 2000)

Parameter	Input Variables	Criteria	Vulnerability Level
Façade	Combustible part of façade	> 40 % of façade area is combustible	
		20-40 % of façade area is combustible	
		< 20 % of façade area is combustible	
		0% of façade area is combustible	
	Combustible materials above windows	Yes	
		No	
	Void	Continuous void in combustible façade	
		Void with special design solution for preventing fire spread (e.g., fire stop barriers)	
		No void	

3.2 Fire Safety Fuzzy Vulnerability Assessment Model Structure

The fire safety evaluation model designed for this study comprises fuzzy vulnerability assessment of eight critical parameters based on linguistic data from the literature and expert opinion. The structure of fuzzy expert model is based on five steps of Negnevitsky (2011), which are:

Step 1. Problem definition and linguistic variables,

Step 2. Database and membership functions,

Step 3. Construction of fuzzy rules,

Step 4. Encoding the fuzzy sets and fuzzy rules to perform fuzzy inference,

Step 5. Evaluation of the system.

In problem definition and linguistic variable definition steps, the purpose of the vulnerability assessment model and verbal evaluation scale for the assessment is explained. In the second step, database of input variables used in the evaluation are expressed by the degree of belonging, in other words the membership functions over 100%. This step compromises fuzzification process. In the third step, fuzzy rules are set in the set in the form of if-then rules by using linguistic variables. The rules generated for expert opinion by conducting structured interview are listed in this phase. In the fourth step, by using the inference system fuzzy membership sets and fuzzy rules are coded on the software interface. Finally, in the fifth step, the membership functions are converted to crisp vulnerability level as an output value, which is called defuzzification process. For this step, centroid technique is used to find one crisp number corresponding to the center of mass of fuzzy output membership function. In the following parts of this section, detailed explanations of vulnerability assessment model steps are proposed.

3.2.1 Problem Definition and Linguistic Variables

a. Definition of Problem

The fire safety vulnerability model structure is tested for escape route evaluation. Escape route vulnerability level assessment tables listed in section 3.1.1 are evaluated by experts based on linguistic variables.

b. Linguistic Variables:

Vulnerability is defined as a function of impact, sensitivity, and susceptibility, however, vulnerability is not a directly measurable parameter so that it depends on linguistic information (Siler & Buckley, 2005). Linguistic variables are expressions used every day to verbalize importance and context. For example; ‘This room is hot” is specific expression and it represents an opinion independent from temperature measuring system, besides it can be understood by most of the listeners. The condition of linguistic variables connected to a crisp variable. A crisp variable is an absolute value used in computer programs. On the other hand, a linguistic variable has a proportional nature, represented by fractional values in the range of 0 to 1 (Banks, 2008). Accordingly, linguistic variables reflect human knowledge without having to translate it into a complex mathematical code. In this research, linguistic variables of each parameter related to architectural design phase that affects fire safety performance are determined according to safety levels as: unqualified, qualified, medium, safe and very safe (Figure 3.9).

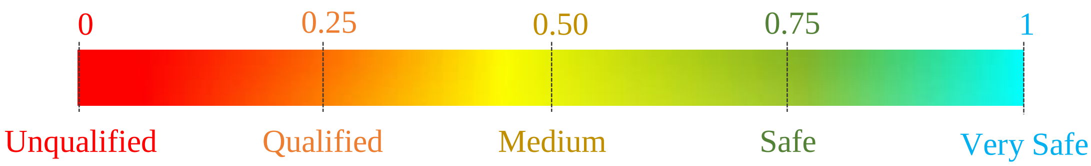


Figure 3.9 Vulnerability linguistic levels in color scale

3.2.2 Database and Membership Functions

Data used in the fire safety fuzzy vulnerability system is derived from fire safety standards and from expert opinion by structured interview. The input variables of the system are generated in two different functional types; categorical functions and fuzzy membership functions. By using numeric and linguistic data available for escape route input parameters, categorical functions are generated in crisp numbers, while fuzzy membership functions are generated in the form of triangular membership functions. Triangular fuzzy numbers are preferred since they have simple use of equations and understandable graphic representation. In order to find a membership degree for any (x) vulnerability level in the triangular membership function the equation 1 is used. In the equation 1, defined by a lower limit a, an upper limit b, and a value m, where a <

m < b; membership degree equation µ (x) and functional diagram are shown in Figure 3.10. Membership functions are used to as input variables to perform the first phase of fuzzy expert model (fuzzification) and as output variables to calculate vulnerability level results.

$$\mu(x) = \begin{cases} 0, & x \leq a \\ \dfrac{x-a}{m-a} & a < x \leq m \\ \dfrac{b-x}{b-m} & m > x > b \\ 0, & x \geq b \end{cases} \qquad \text{(Equation 1)}$$

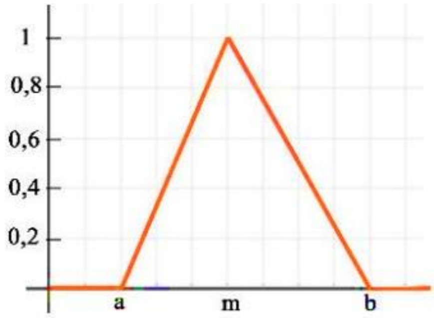


Figure 3.10 Triangular membership degree equation and functional diagram

a. Membership Functions of Escape Route Input Variables

Triangular membership function used in escape route vulnerability level assessment is generated in fuzzyTECH software and displayed in Figure 3.11. Although the rule-based system is based on linguistic variables, the results are extracted in the form of triangular membership functions corresponding vulnerability levels from unqualified to very safe. Therefore, in order to perform the fuzzification, linguistic variables are converted to triangular membership functions. Triangular fuzzy membership function conversion of linguistic variables used in fuzzification and defuzzification phase is represented Table 3.13.

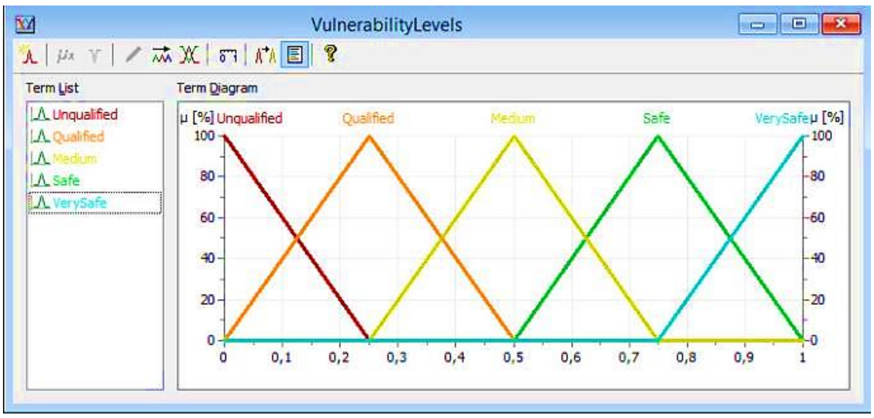


Figure 3.11 Vulnerability level linguistic variables and color scale (fuzzyTECH)

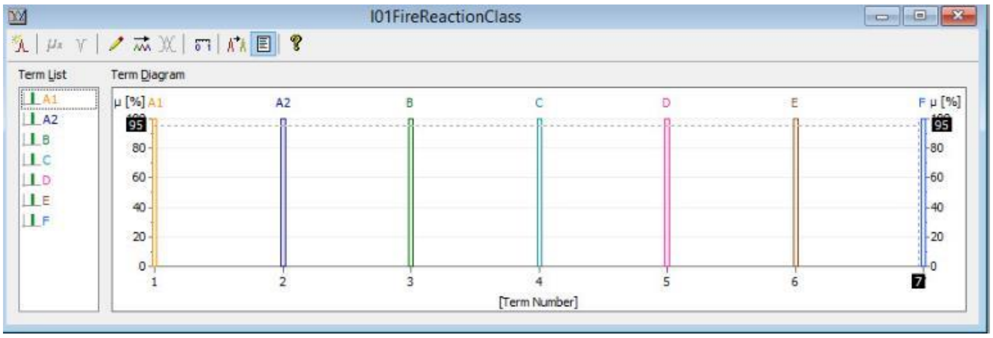
Table 3.13 Linguistic variables correspond to membership functions

Linguistic Variables	Triangular Fuzzy Number
Unqualified	(0, 0, 0.25)
Qualified	(0, 0.25, 0.50)
Medium	(0.25, 0.50, 0.75)
Safe	(0.50, 0.75, 1)
Very Safe	(0.75, 1, 1)

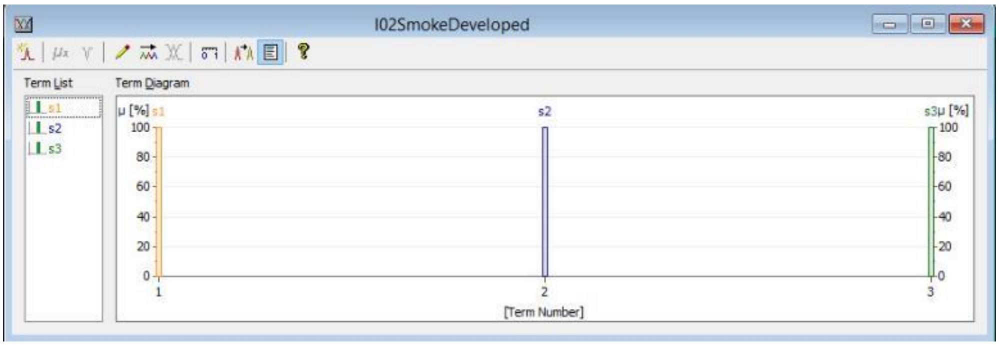
b. Escape Route Finishing Material Vulnerability Membership Functions

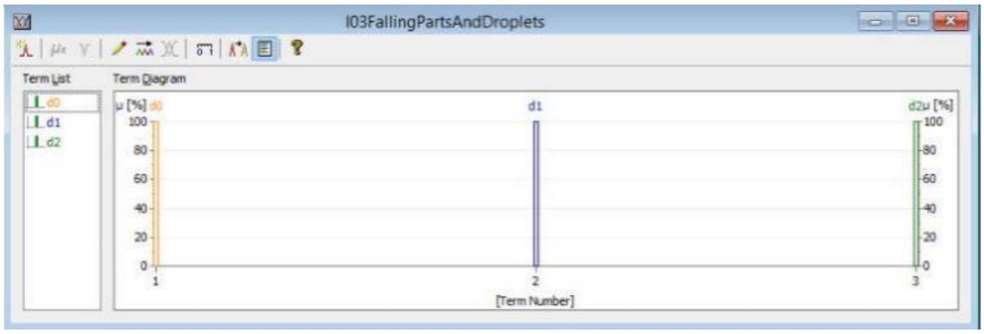
Fire safety performance of escape route interior finishing materials has three input variables expressed in linguistic terms in the form of categorical diagrams. The first input variable has seven classes in terms of reaction to fire; A1, A2, B, C, D, E, F. Smoke development classes have three categories: s1, s2, s3, and falling part and droplet classes has three categories: d0, d1, d2. Categories are listed from highest safety to lowest safety and diagrams are generated through fuzzyTECH software, which represented in Figure 3.12.

(a)



(b)





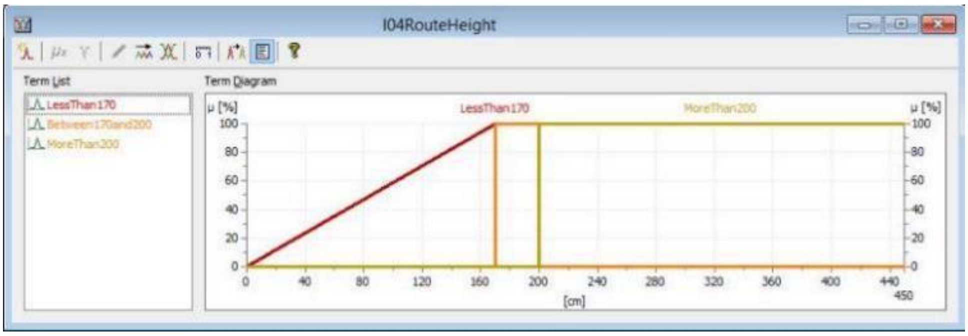
(c)

Figure 3.12 Materials' fire reaction input parameters' categorical diagrams (fuzzyTECH)

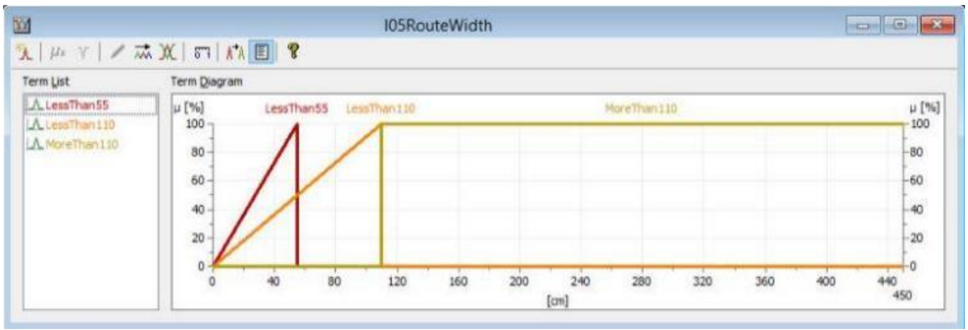
a) Fire Reaction Classes b) Smoke Development Categories c) Droplet Categories

c. Escape Route Flow Vulnerability Membership Functions

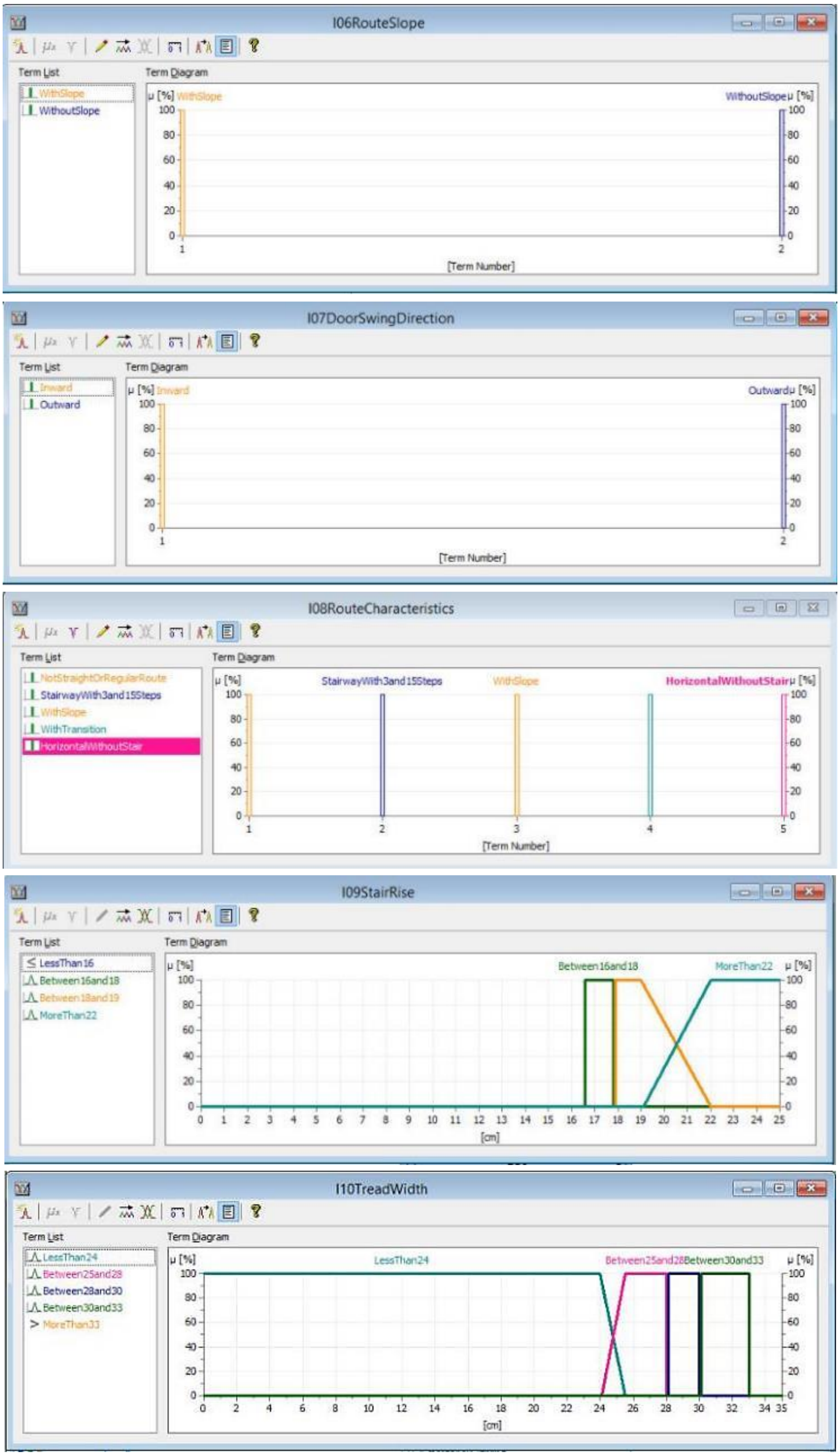
Escape route flow parameter has seven input variables: route height, route width, route slope, door swing direction, route characteristics, stair riser and stair tread dimensions. Route height and route width are determined through categorical interval diagrams based on dimensions. On the other hand, route slope, door swing direction and route characteristics have categorical diagrams with choices. Finally, stair riser and tread dimensions are designed as fuzzy membership functions based on acceptable intervals. Escape route flow input parameter diagrams are generated through fuzzyTECH software and represented in Figure 3.13.



(a)



(b)



(c)

(d)

(e)

(f)

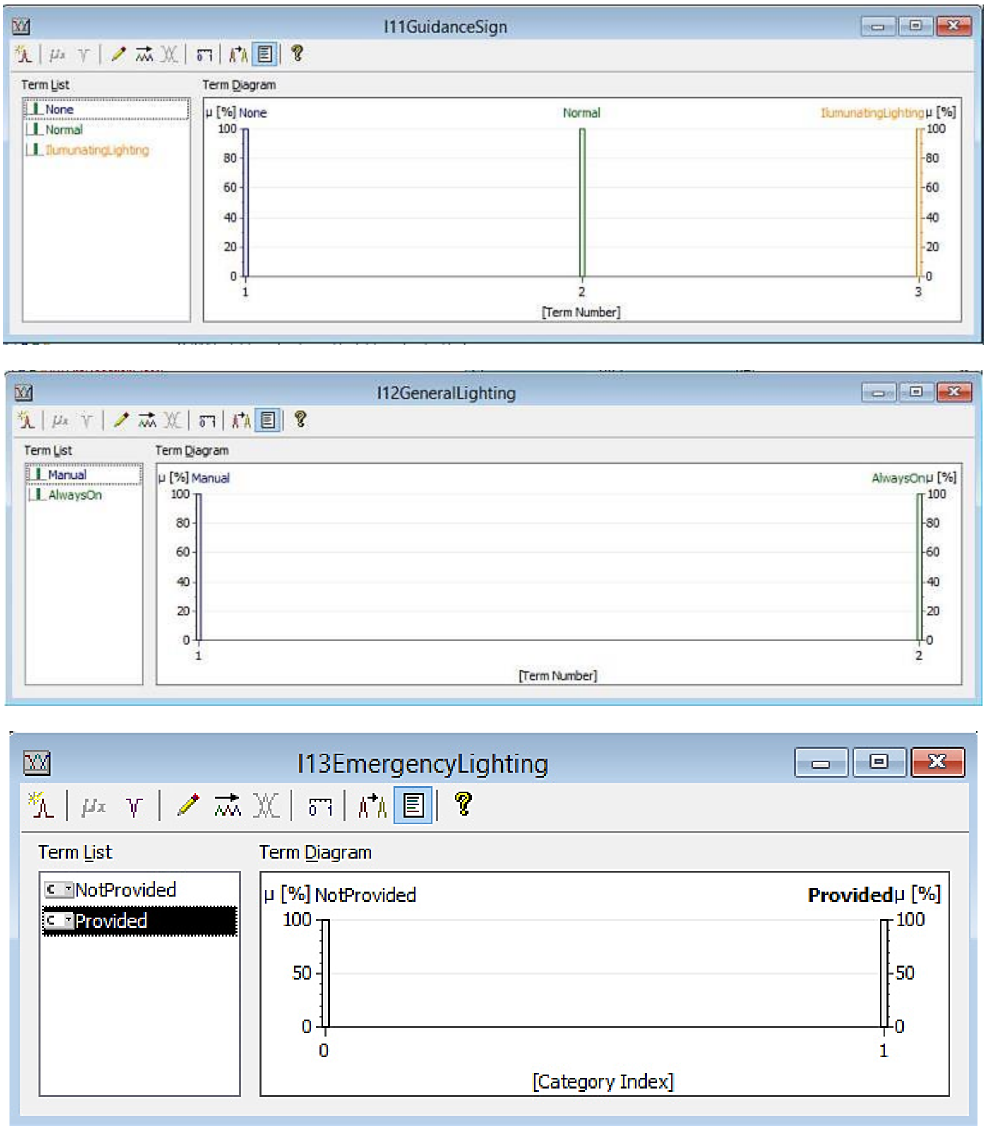
(g)

Figure 3.13 Escape route flow input parameters (fuzzyTECH)

a) Route Height b) Routh Width c) Routh Slope d) d) Door Swing Direction e) Route Characteristics f) Stair Rise g) Tread Width

d. Escape Route Equipment Vulnerability Membership Functions

Input parameters of escape route equipment vulnerability assessment are guidance sign, general lighting, and emergency lighting. Escape route equipment input variables are determined as linguistic parameters, so that categorical membership functions are used. Evaluation parameters are not provided, normal lighting or illuminating light for guidance sign, manual or always on for general lighting, and provided or not provided for emergency lighting. Categorical diagrams are generated through fuzzyTECH software and represented in Figure 3.14.



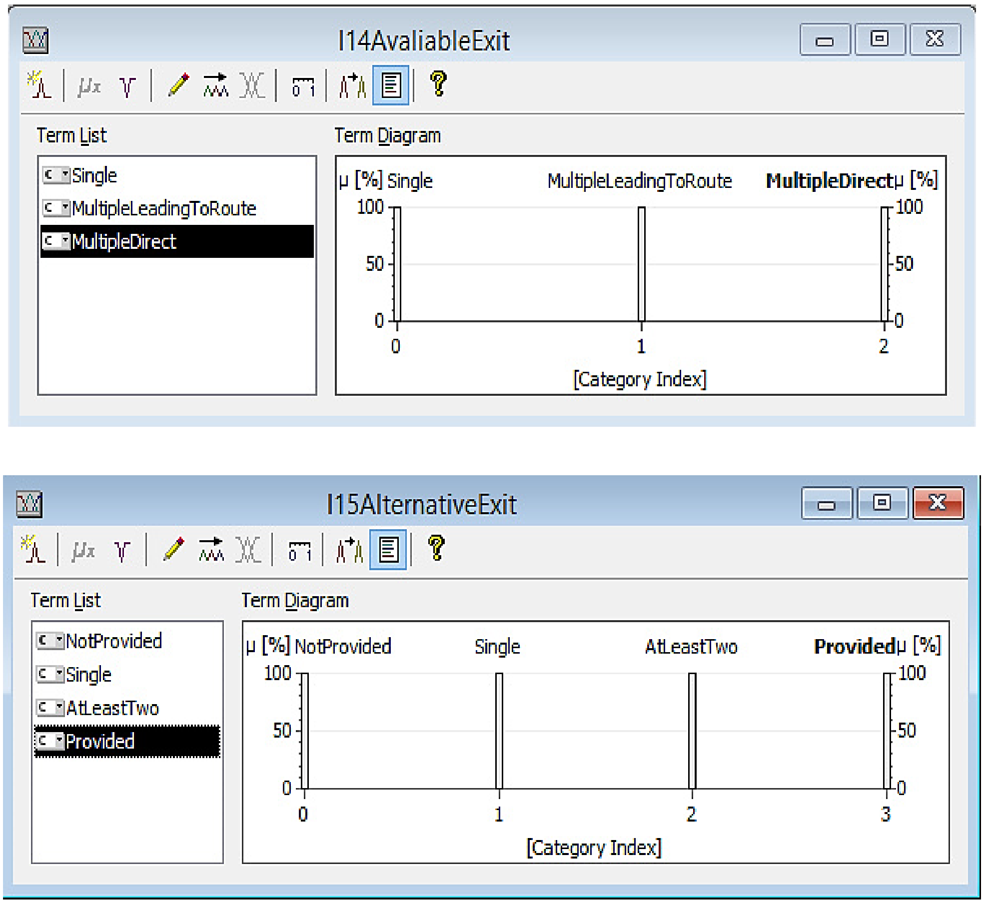
a) b) c)

Figure 3.14 Escape route equipment input parameters (fuzzyTECH)

a) Guidance Sign b) General Lighting c) Emergency Lighting

e. Means of Escape Vulnerability Membership Functions

Available exit and alternative exit are input parameters of means of egress vulnerability assessment. Evaluation factors are single, multiple leading and multiple direct for available exit, not provided, single, multiple and provided for alternative exit. Means of escape categorical evaluation diagrams generated through fuzzyTECH software are shown in Figure 3.15.



a)

b)

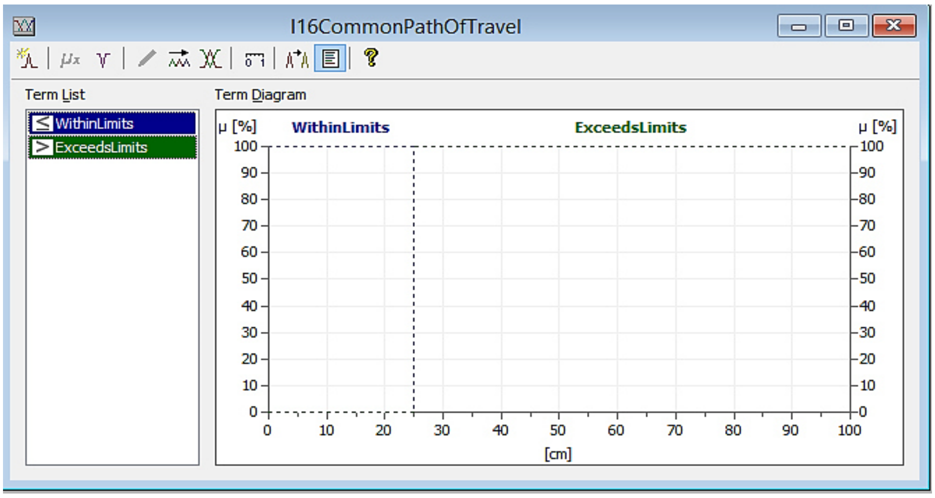
Figure 3.15 Means of egress input parameters (fuzzyTECH)

a) Available Exit b) Alternative Exit

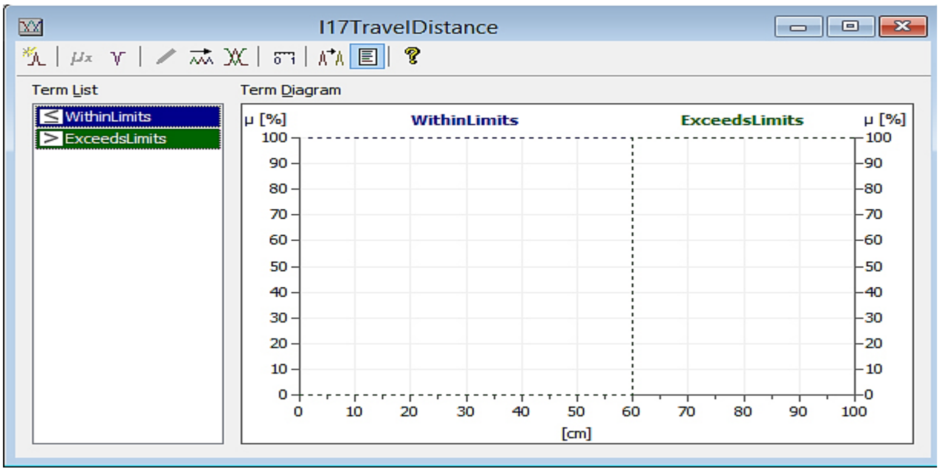
f. Escape Route Distances and Layout Vulnerability Membership Functions

Escape route distances and layout parameter has three input parameters, which are common path of travel, travel distances and dead end corridor distances. The membership functions are determined whether the escape route distance is within the limits or exceeds the limits. Membership functions are generated by using fuzzyTECH and represented in Figure 3.16.

a)



b)



c)

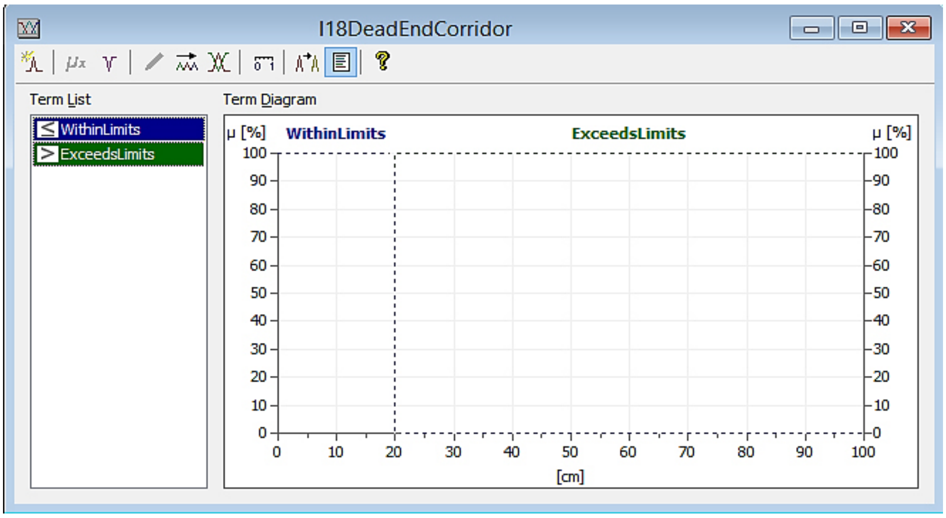


Figure 3.16 Escape route distances and layout input parameters (fuzzyTECH)

a) Common Path of Travel b) Travel Distance c) Dead End Corridor

3.2.3 Construction of Fuzzy Rules

The proposed vulnerability fuzzy expert system is rule-based so that the domain knowledge contains the rules. Rules are generated in the If-Then form to represent the expert's reasoning process. If-Then rules are the primary element of expert system language. The "If" part of a rule is defined as antecedent, while "Then" part of the rule is called consequent. Where X, Y, and Z represent fuzzy or categorical sets of input variables, the principle of the rules is in the form of:

- "**If** X **And** Y, **Then** Z"

Meaning that if the data meet certain specified conditions of X and Y, then take appropriate actions with Z. An example rule for fuzzy systems might be (Siler and Buckley, 2005)

"If Input1 is Depressive **And** Input2 is > 6 months **Then** Output is Major Depression"

a. Rule Generation Method

In terms of escape route vulnerability assessment model, use of expert system has been required for the complex interaction of parameters and their impacts cannot be effectively described by available problem solving methods. Therefore, structural interview is conducted by five fire safety experts from the architecture profession with face to face questioning method to generate rules of escape route vulnerability analysis. The structural interview conducted with the experts for data collection is presented in Appendix B, and the experiential information about five experts, with the results of structured interview is presented in Appendix C.

The output model of five sub parameters is vulnerability defined by linguistic variables. In case of vulnerability is defined by linguistic variables, the end user can understand the process without limitation of numerical algorithms (Siler & Buckley, 2005). In fuzzy expert system, input variables may be completely true, completely false or in between such as partially true. Interrelationships of 18 escape route input parameters are defined through five scale **linguistic variables;**

- <u>for vulnerability level</u>: Unqualified, Qualified, Medium Safe, Safe, Very Safe

- <u>for materials' reaction to fire:</u> Noncombustible, Very Limited Combustible, Limited Combustible, Flammable, Easily Flammable.

The weights of experts are assigned equally as "1", therefore for each linguistic decision, the rule is marked as "1", indicating that 1 expert is decided for this rule. For example; for the fuzzy system given in Table 3.14, input a, input b, and input c variables are evaluated as "qualified" by 2 experts, "safe" by 1 expert and "very safe" by 2 experts. Since there are 5 experts, total number of expert decisions are equal to 5, and total vulnerability level results are determined through weighting factors of linguistic variables. In order to find a single vulnerability level representing total expert opinion, factors for each linguistic level are converted to numeric values over 1; "0 for unqualified (U)", "0.25 for qualified (Q)", "0.50 for medium (M)", "0.75 for safe (S)" and "1 for very safe (VS)" are used for conversion. On the basis of conversion method, vulnerability level for input a, input b, and input c case is calculated as 0.65 and represented in Table 3.14.

Table 3.14 Calculation of vulnerability levels and membership degrees

<table>
<tr><th colspan="3">Input Variables</th><th colspan="5">Vulnerability Level Expert Decision Distribution "Total 5"</th><th>VL "Over 1"</th><th colspan="2">Membership Degree "Total 100%</th></tr>
<tr><td>Input a</td><td>Input b</td><td>Input c</td><td>U</td><td>Q</td><td>M</td><td>S</td><td>VS</td><td rowspan="3">0.65</td><td rowspan="3">60% Safe</td><td rowspan="3">40% Medium</td></tr>
<tr><td rowspan="2">a</td><td rowspan="2">b</td><td rowspan="2">c</td><td></td><td>2</td><td></td><td>1</td><td>2</td></tr>
<tr><td colspan="5">((0*0)+(2*0.25)+(0*0.5)+(1+0.75)+(2+1)) / 5</td></tr>
</table>

In order to convert the common vulnerability linguistic variable decided by five experts, membership degree for 0.65 vulnerability is calculated through triangular membership function equation defined in Section 3.2.1 (Equation 1).

Based on the equation (1), for the vulnerability level (x) =0.65, the membership degrees are;

In case of "Safe" membership degree defined by lower limit a=0.5, an upper limit b=1, and value m is 0.75;

$$\mu(x) = (0.65 - 0.5) / (0.75 - 0.5) = 0.6 \text{ (60\% Member of Safe Vulnerability)}$$

In case of "Medium" membership degree defined by lower limit a=0.25, an upper limit b=0.75, and value m is 0.5;

$\mu(x)= (0.75 - 0.65) / (0.75 - 0.5) = 0.4$ (40% Member of Medium Vulnerability)

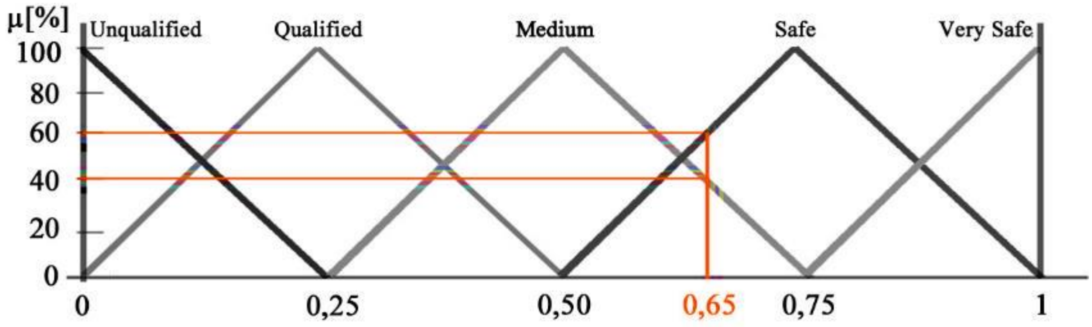


Figure 3.17 Membership degree diagram

The functional diagram showing the membership degrees is represented in Figure 3.17. The total membership degree for each x value is equal to 1 ($\mu(x)$ = %60+%40 = %100). In the following section results of literature review and structural interview to generate rule-based data is explained.

b. Escape Route Vulnerability Assessment Rule Based System

The main objective of collecting data from structural interview method is to develop the rule-based system in the fuzzy expert system structure. In addition to first two sub-parameters' (escape route finishing and escape route flow) rule data are adapted from the literature analysis, while the other three sub-parameters (escape route equipment, means of escape and escape route distances and layout) rule based system data are collected through structured interview. By using the structured interview method, vulnerability levels and membership degrees of sub-parameters are determined and listed in Table 3.17, Table 3.18, and Table 3.19. The number of rules generated for escape route finishing rule based module is 31, for escape route flow module is 125, for escape route equipment module is 12, for means of escape module is 8, and for escape route distances and layout module is 9, 185 rules in total. Rules generated for interrelations o escape route flow sub-parameters are listed in Appendix C. In the output parameter, vulnerability level (VL) linguistic variables of unqualified (U), qualified (Q), medium (M), safe (S), very safe (VS) are used that correspond to percentages.

Table 3.15 Escape route finishing material rules (Adapted from EN 13501-1)

Sub-Parameter 1: Escape Route Finishing			
Input Variables			**Fire Safety Performance Vulnerability Levels**
EuroClass	**Smoke Developed**	**Falling Parts and Droplets**	
A1			Noncombustible
A2	S1	d0	Very limited combustibility
B	S1	d0	Limited combustibility
C	S1	d0	Limited combustibility
A2	S2	d0	Limited combustibility
A2	S3	d0	Limited combustibility
B	S3	d0	Limited combustibility
C	S3	d0	Limited combustibility
A2	S1	d1	Limited combustibility
A2	S1	d2	Limited combustibility
B	S1	d1	Limited combustibility
B	S1	d2	Limited combustibility
C	S1	d1	Limited combustibility
C	S1	d2	Limited combustibility
A2	S3	d2	Limited combustibility
B	S3	d2	Limited combustibility
C	S3	d2	Limited combustibility
D	S1	d0	Flammable
D	S2	d0	Flammable
D	S3	d0	Flammable
E			Flammable
D	S1	d2	Flammable
D	S2	d2	Flammable
D	S3	d2	Flammable
E		d2	Flammable
F			Easily flammable

Table 3.16 Escape route flow rules (Adapted from Grimaz & Tosolini, 2013)

Sub-Parameter 2: Escape Route Flow						
Input Variables		**Vulnerability Level "Over 1"**	**Membership Degrees Total 1 (%100)**			
Route Height	**Route Width**					
h > 200	W ≤ 55 cm	0	0%	Qualified	100%	Unqualified
h > 200	W≤ 110 cm	0,87	48%	Very Safe	52%	Safe
h > 200	W> 110 cm	1	100%	Very Safe	0%	Safe
170< h <200	W ≤ 55 cm	0	0%	Qualified	100%	Unqualified
170< h <200	W≤ 110 cm	0,33	32%	Medium	68%	Qualified
170< h <200	W> 110 cm	0,5	0%	Safe	100%	Medium
h < 170	W ≤ 55 cm	0	0%	Qualified	100%	Unqualified
h < 170	W≤ 110 cm	0	0%	Qualified	100%	Unqualified
h < 170	W> 110 cm	0	0%	Qualified	100%	Unqualified
Route Slope						
Horizontal Plane		1	100%	Very Safe	0%	Safe
Sloping Rate		0,75	0%	Very Safe	100%	Safe
Door Swing Direction						
Outward		1	100%	Very Safe	0%	Safe
Inward		0,5	0%	Safe	100%	Medium
Route Characteristics						
Horizontal, Without Stairs		1	100%	Very Safe	0%	Safe
With Transitions		0,95	80%	Very Safe	20%	Safe
Slope		0,9	60%	Very Safe	40%	Safe
Stairway With 3-15 Steps		0,8	20%	Very Safe	80%	Safe
Not Straight or Regular Route		0,8	20%	Very Safe	80%	Safe
Stair Geometry						
Riser (cm)	**Tread (cm)**					
16,5	33	0,9	60%	Very Safe	40%	Safe
16,5	33-30	0,85	40%	Very Safe	60%	Safe
16,5-17,8	30-28	0,8	20%	Very Safe	80%	Safe
17,8-19	28-25,5	0,75	0%	Very Safe	100%	Safe
> 22	< 24	0	0%	Qualified	100%	Unqualified

Table 3.17 Escape route equipment structured interview results

Sub-Parameter 3: Escape Route Equipment Structured Interview												
Input Variables			**VL Expert Decision Distribution "Total 5"**					**VL "Over 1"**	**Membership Degrees Total 1 (%100)**			
Guidance Sign	**General Lighting**	**Emergency Lighting**	**U**	**Q**	**M**	**S**	**VS**					
Illuminating Light	Always On	Provided					5	1	100%	VS	0%	S
Illuminating Light	Always On	Not Provided		2		1	2	0,65	60%	S	40%	M
Illuminating Light	Manual	Not Provided	4	1				0,05	20%	Q	80%	U
Illuminating Light	Manual	Provided		1	1	3		0,6	40%	S	60%	M
Normal	Always On	Not Provided		3	2			0,35	40%	M	60%	Q
Normal	Always On	Provided			1	3	1	0,75	0%	VS	100%	S
Normal	Manual	Not Provided	3	1		1		0,2	80%	Q	20%	U
Normal	Manual	Provided		3		2		0,45	80%	M	20%	Q
None	Always On	Provided	1	2	2			0,3	20%	M	80%	Q
None	Always On	Not Provided	2	3	2			0,35	40%	M	60%	Q
None	Manual	Provided	2	1	1			0,15	60%	Q	40%	U
None	Manual	Not Provided	5					0	0%	Q	100%	U

Table 3.18 Means of escape structured interview results

Sub-Parameter 4: Means of Escape Structured Interview									
Input Variables		**VL Expert Decision "Total 5"**					**VL "Over 1"**	**Membership Degrees Total 1 (%100)**	
Available exit	**Alternative exit**	**U**	**Q**	**M**	**S**	**VS**			
Single	Not Provided	3	2				0,1	40% Q	60% U
Single	Single Alternative	1	3	1			0,25	0% M	100% Q
Single	At least two		2	2	1		0,45	80% M	20% Q
Multiple Leading	Single Alternative			1	2	2	0,8	20% VS	80% S
Multiple Leading	At least two				3	2	0,85	40% VS	60% S
Multiple Direct	Not Provided			1	2	2	0,8	20% VS	80% S
Multiple Direct	Provided				1	4	0,95	80% VS	20% S

Table 3.19 Escape route distances and layout structured interview results

Sub-Parameter 5: Escape Route Distances and Layout Structured Interview										
Input Variables			**VL Expert Decision "Total 5"**					**VL "Over 1"**	**Membership Degrees Total 1 (%100)**	
Common Path of Travel	**Travel Distance**	**Dead End Corridor**	**U**	**Q**	**M**	**S**	**VS**			
Within Limits	Within Limits	Within Limits				1	4	0,95	80% VS	20% S
Within Limits	Exceed Limits	Within Limits	2	2	1			0,2	80% Q	20% U
Within Limits	Within Limits	Exceed Limits		3	1	1		0,4	60% M	40% Q
Within Limits	Exceed Limits	Exceed Limits	5					0	0% Q	100% U
Exceed Limits	Within Limits	Within Limits	1	2	2			0,3	20% M	80% Q
Exceed e Limits	Within Limits	Exceed Limits	3	2				0,1	40% Q	60% U
Exceed Limits	Exceed Limits	Within Limits	5					0	0% Q	100% U
Exceed Limits	Exceed Limits	Exceed Limits	5					0	0% Q	100% U

Considering five escape route sub-parameters (route finishing, route flow, route equipment, means of escape, route distance and layout), and five scale linguistic variables (unqualified, qualified, medium safe, safe, very safe), a total of 3125 (5^5) rules are mapped. This could require an extensive amount of rule generation for the rule base, which might not be efficient in terms of applicability of the fuzzy expert system such that either some of the rules could be nonexistent in the real world. Thus, the rule bases for fuzzy vulnerability assessment model are constructed by using the priority of affecting factors by expert intuition. In the scope of this thesis, only most critical escape route input variables are tested through fuzzy expert system. Experts consulted in this study are selected from architects in fire safety profession. A comprehensive fire safety evaluation of nine building criteria is proposed as a future study, hence the evaluation criteria of all parameters are developed and compiled in section 3.1.

3.2.4 Encode the Fuzzy Sets and Fuzzy Rules to Perform Fuzzy Inference

In database and membership function phase, vulnerability level evaluation tables are generated and input parameters of escape route vulnerability system are determined by using categorical and fuzzy diagrams. In consequence of data collection, five sub parameters of escape route parameter with eighteen input parameters are structured the escape route vulnerability assessment model structure. These **input parameters** are;

- <u>for the escape route finishing sub-parameter</u>; materials reaction to fire class (I01), smoke development class (I02), droplet class (I03),
- <u>for the escape route flow sub-parameter</u>; route height (I04), route width (I05), route slope (I06), door swing direction (I07), route characteristics (I08), step rise (I09) and tread width (I10),
- <u>for escape route equipment sub-parameter</u>; guidance sign (I11), general lighting (I12), emergency lighting (I13),
- <u>for means of escape sub-parameter</u>; available exit (I14), alternative exit (I15),
- <u>for route distances and layout sub-parameter;</u> common path of travel distance (I16), travel distance (I17), dead end corridor distance (I18).

Based on the rules generated by fire safety experts in architecture profession, vulnerability model is structured in fuzzyTECH software and presented in Figure 3.18.

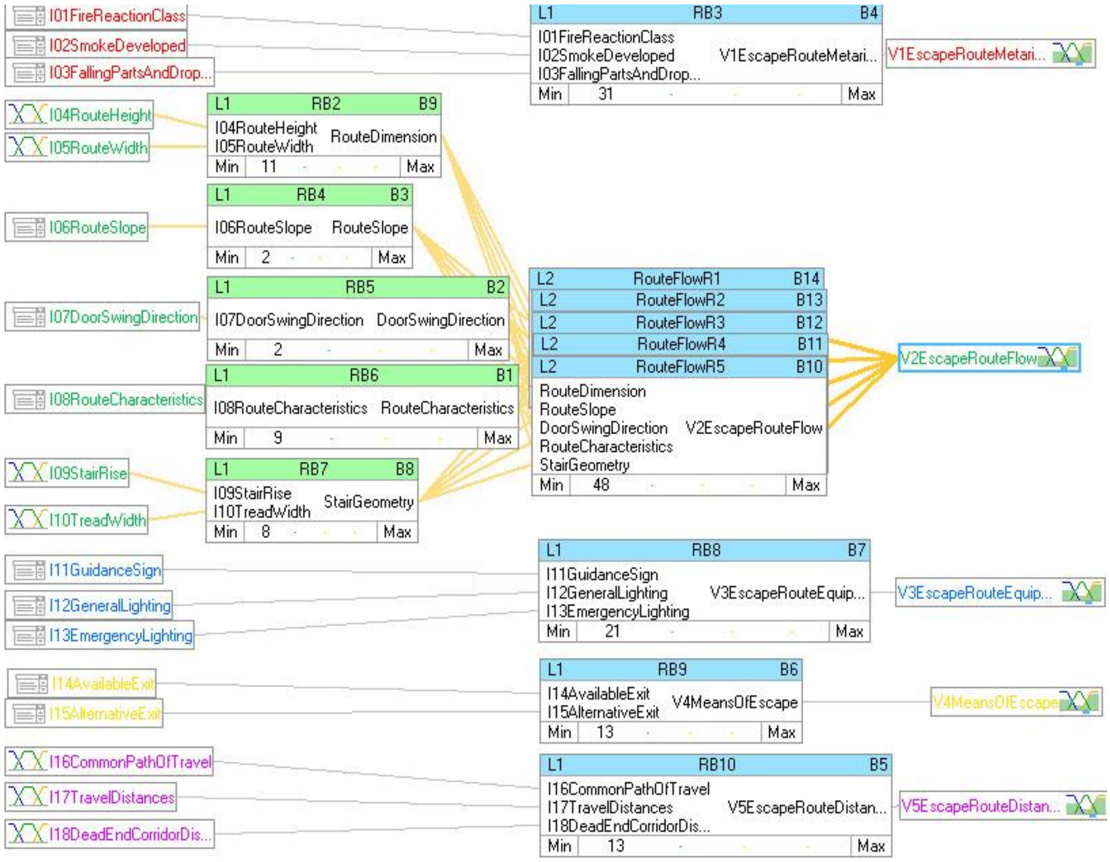


Figure 3.18 Escape route vulnerability model structure

3.2.5 Evaluate the System

In the defuzzification phase of the escape route fuzzy expert system, in which the evaluated fuzzy input variables through rule-based module are extracted in the form of combined fuzzy diagrams, the centroid method is used. Centroid method is based on finding one crisp number corresponding to the center of mass of fuzzy output. The fast and approximate way of calculating system output is defined by following equation (2) based on Figure 3.19.

$$z = \frac{\sum_{i=1}^{8} x_i \, u(x_i)}{\sum_{i=1}^{8} u(x_i)} \quad \text{(Equation 2)}$$

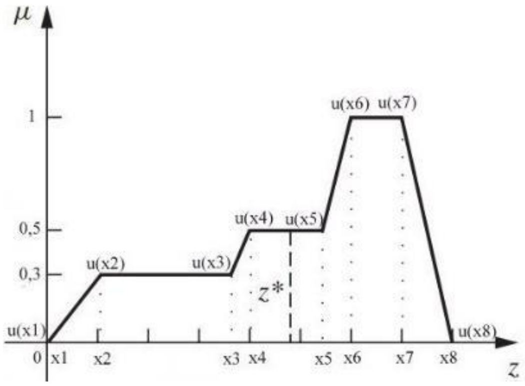


Figure 3.19 Center of area method for defuzzification (Adapted from Ross, 2010)

In the evaluation module, based on center of area output functions, input variables are entered and the numeric values of vulnerability levels are displayed through a dialog window in fuzzyTECH (Figure 3.20).

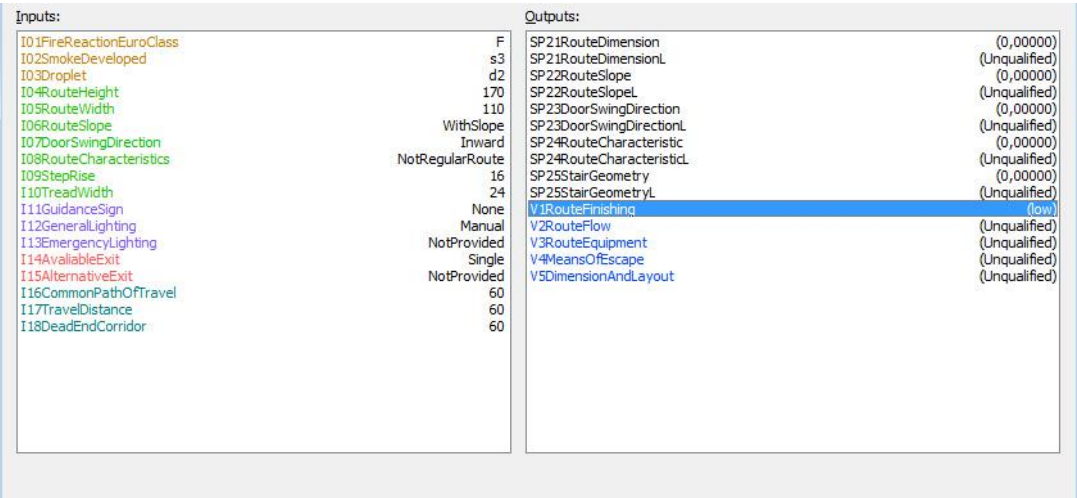


Figure 3.20 Dialog window for inputs and output variable operations (fuzzyTECH)

3.3 Material

The main objective of this research is determining fire safety vulnerability level of the building based on performance evaluation methods rather than deterministic, rule based approaches, and providing prevention measures starting from the preliminary architectural design process. Based upon the objective, the framework of fuzzy fire safety vulnerability assessment is structured throughout the previous method sections. In brief, the framework has eight critical building parameters affecting fire safety, which are escape route, door, structural separation, compartmentation, vertical openings, combustible contents and furnishings, interior finishes, and façade. In the scope of this research, vulnerability assessment of most critical escape route parameter is performed through expert evaluation and İzmir Opera House building is analyzed based on fuzzy expert vulnerability assessment structure.

İzmir Opera House is the located on the Aegean coastline of İzmir, with 50.000m^2 area, including the main hall with a capacity of 1450 people, black box of a capacity 450 people and multipurpose open-air courtyard with 400 people. The huge occupant capacity allows multi-level access and egress represented in Figure 3.21. At the back of the house, there are rehearsal rooms for orchestra, ballet, and opera, ateliers, offices and storage areas, which are open to visitors. After it is constructed, the Izmir Opera House will be the largest opera venue in the country (Teğet Architecture, 2010).

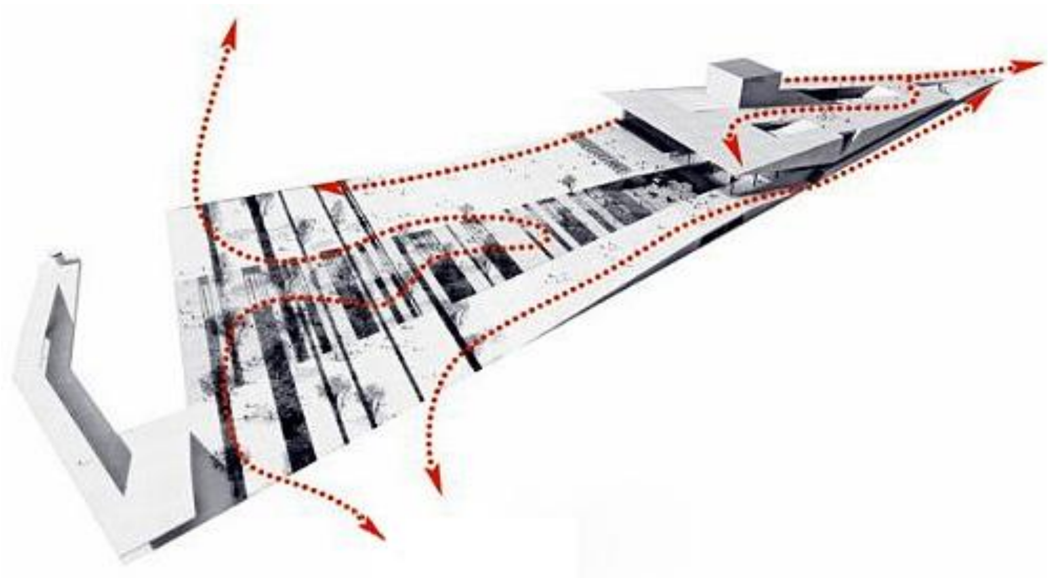


Figure 3.21 İzmir Opera House pedestrian access diagram

(Teğet Architecture, 2010)

Due to its huge capacity, and the complex and multi-levelled pedestrian route design, which affects occupant flow and escape, route distribution the İzmir Opera House is selected as a case study for this dissertation. Important design concerns that affect building occupancy are:

- Main entrance and main foyer are from the coastline of the building at ground floor level. Main foyer is planned to be used as a bookstore, souvenir shop, bistro, and a ticket booth.
- The building is planned to be used as a public space during non-exhibition hours.
- The roof area is used as open-air landscape and for the final exit for some of the exit stairs.
- Stairs and final exits from the ground floor level are represented in Figure 3.22. Multilevel evacuation levels of enclosed exit stairs are as follows; S4 and S9 from ground floor level (+0.00 level), S7 and S8 from the first floor level (+4.50 level), S5 and S6 from the third floor level (+13.40 level) by an exit passageway to roof level (+17.00level), and S1, S2 and S3 from the fourth floor level (+18.00 level).

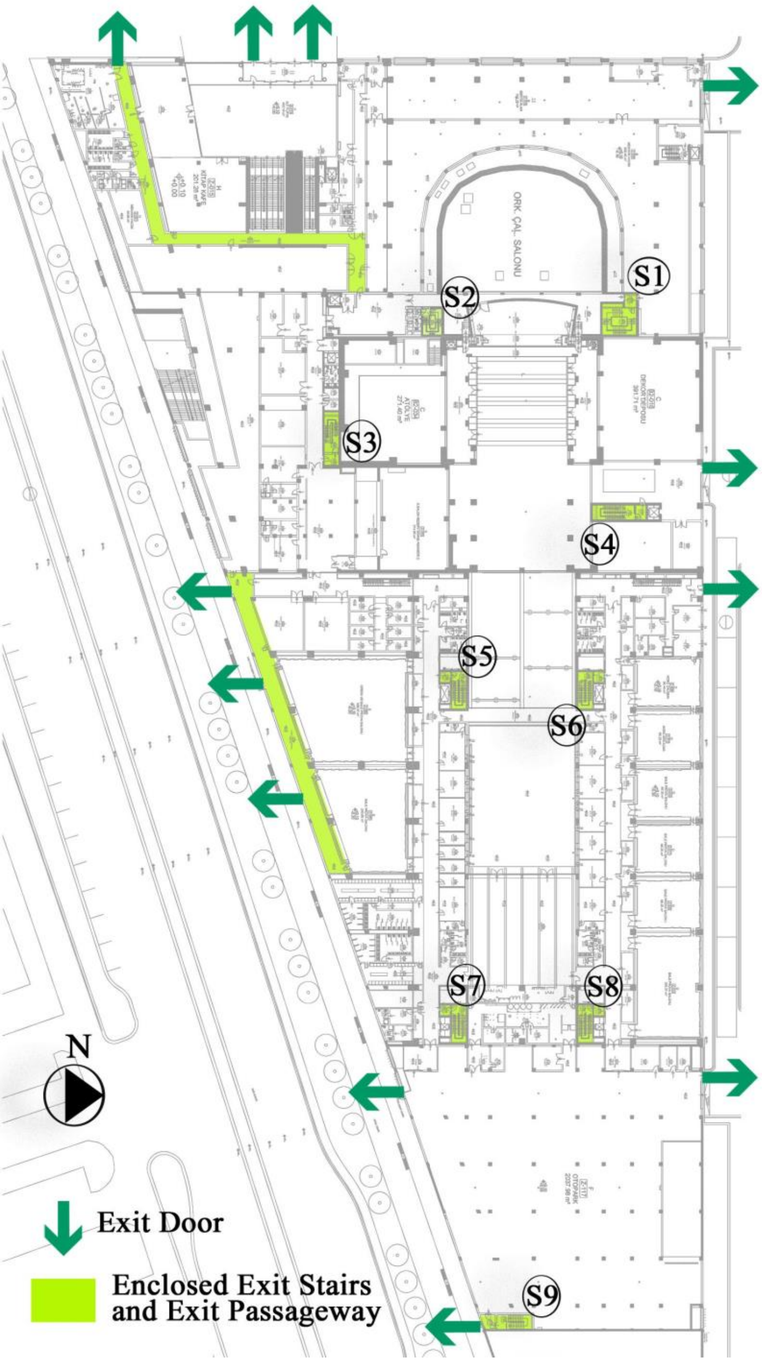


Figure 3-22 Enclosed exit stairs and final exits distribution on ground floor plan

The vulnerability assessment of escape routes is evaluated in terms of interior finishing, route flow, route equipment, means of escape, and distance and layout input variables based on expert opinion. The expert evaluation criteria and analyses of input variables are explained in following results and discussion chapter of the research.

CHAPTER 4

RESULTS AND DISCUSSION

In this chapter, escape route vulnerability results of the İzmir Opera House are assessed and discussed. In the first section, vulnerability analysis of interior finishing material, escape route flow, escape route equipment, means of escape components, and distance and layout input variables are conducted in İzmir Opera House case to get vulnerability level output variables. The methodology used in this evaluation is fuzzy expert rule-based system. The proposed evaluation system aims to perform quick-response analysis based on the expert judgement and experience, to ensure an acceptable fire safety level starting from the preliminary design phase. The rule-based system is designed through structured interviews, and used for in conversion of input variables to output variables. The structured interview data were taken from the architects working in the fire safety field. Although the input variables consist both of numerical and linguistic variables, the output variable is the vulnerability, which is a linguistic variable. In the results section, the vulnerability analysis results of the İzmir Opera House ground floor are presented. Analysis of the first, the second, the third, and the fourth floor plans are presented in Appendix D. In the discussion section, the vulnerability assessment results of the case study are discussed through comparison of juxtaposition methodologies in order to get a single value for the escape route parameter.

4.1 Izmir Opera House Escape Route Vulnerability Assessment

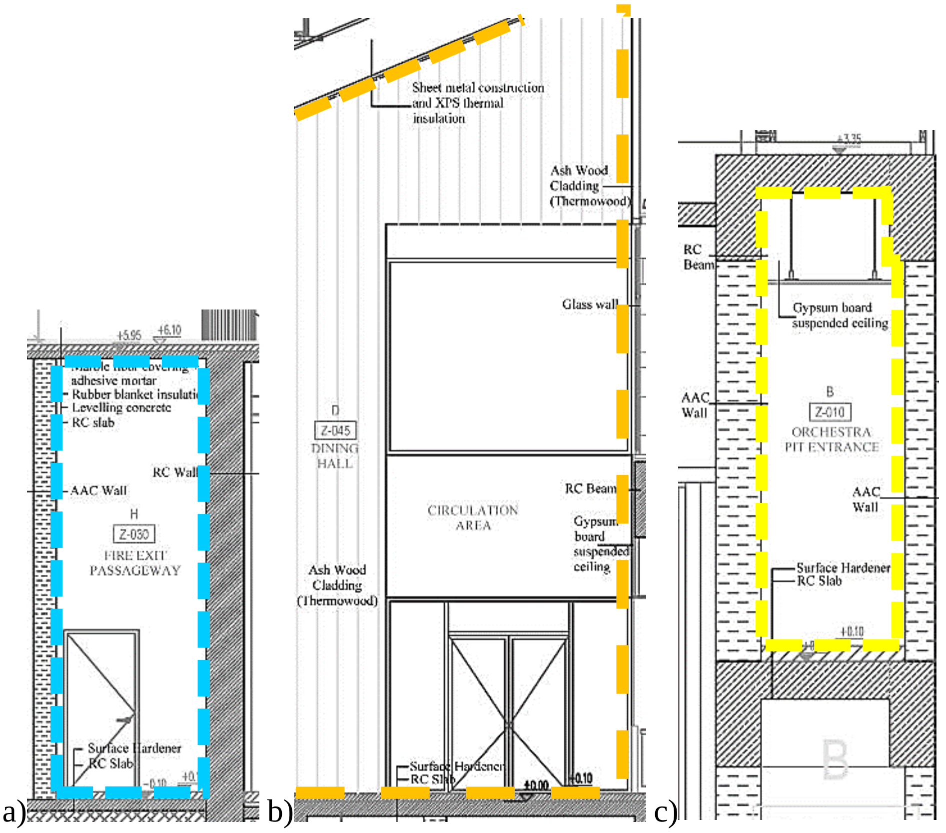
The first part of the escape route vulnerability analysis includes five sub parameter analyses, carried out for the ground floor plan of the İzmir Opera House. The vulnerability analyses are performed for each route separately in the fuzzyTECH software based on the fuzzy expert rule system. The results are shown in the form of numerical data in 0-1 scale, and transferred into linguistic data by using conversion Table 3.13. The assessment of escape routes is conducted in the form of route spaces for finishing material and route flow analysis, since any defect in the route properties effect the enclosed space in terms of material and flow characteristics. On the other hand, for route equipment availability, alternative means of egress, and route distance and layout analysis, results are represented in the form of route direction lines. For the vulnerability levels determined as linguistic variables, a color code scale is determined. The representations of vulnerability levels are transferred to plan drawings with color codes from most vulnerable (unqualified) to least vulnerable (very safe). The color coding legend used in the evaluated plans is shown in Table 4.1. In finishing material vulnerability linguistic variables, the combustibility is used as a scale, while in other parameters of escape route flow, equipment, means of escape and distances the safety levels are used.

Table 4.1 Vulnerability levels color legend

Vulnerability Levels	Material Vulnerability	Color Code
Unqualified	Easily Flammable	
Qualified	Flammable	
Medium	Limited Combustible	
Safe	Very Limited Combustible	
Very Safe	Noncombustible	

4.1.1 Escape Route Finishing Material Vulnerability Assessment

In the ground floor plan, for each route space planned to be used for the evacuation purposes is analyzed in terms of finishing material vulnerability. The analysis was based on the most vulnerable finishing material in the enclosed route cell (corridor, hall, enclosed exit passageway) to be on the safe side. Levels were determined through the material reaction to fire classes (Table 3.15), corresponding to the technical specifications of the building materials. In order to conduct the finishing material vulnerability analysis, the route cells in ground floor plan of İzmir Opera. Then, the finishing material of each escape route with their reaction to fire classes is determined through the technical specifications, and through the literature review. Accordingly, vulnerabilities of escape route finishing materials in İzmir Opera House ground floor plan are grouped under three levels; *noncombustible*, *limited combustible* and *flammable*. The example of each vulnerability level of escape route is represented in the sections in Figure 4.1. In the typical sections, critical materials with the highest combustibility are determinant elements to assess vulnerability. In the Section A, noncombustible (A1) reinforced concrete (RC) slab, noncombustible (A1) autoclaved aerated concrete (AAC) materials are used as a finishing, so that the route cell vulnerability is at the safest level. In the Section B, flammable (E) XPS thermal insulation materials and flammable (D, s2, d0) ash wood cladding (thermowood) are used so that the route cell has flammable vulnerability level. In the Section C, limited combustible (B, s1, d0) gypsum board suspended ceiling and noncombustible (A1) AAC wall and noncombustible (A1) RC slab are used. Therefore, the route cell has limited combustibility. Based on the most vulnerable material vulnerability levels, escape route finishing materials on the ground floor is evaluated by using fuzzy rule based structure. The levels are determined for each route cell in decision making tool and transferred on the plan drawing which is represented in Figure 4.2.



Noncombustible ▬ ▬ Very Limited Combustible ▬ ▬

Limited Combustible ▬ ▬ Flammable ▬ ▬ Easily Flammable ▬ ▬

Figure 4.1 Vulnerability level descriptions of escape route sections a) Fire Exit Passageway / Noncombustible (Scale 1/100) b) Circulation Area / Flammable (Scale 1/100) c) Orchestra Entrance / Limited Combustible (Scale 1/50)

Figure 4.2 Ground floor escape route finishing material vulnerability (Scale ~ 1/1000)

4.1.2 Escape Route Flow Vulnerability Assessment

Escape route flow vulnerability was assessed by rule-based relationships of route dimension (height / width), route slope (horizontal / sloping), swing direction of the doors on the route (outward / inward), route characteristics (transitions /stairs) and stair geometry (riser/tread dimensions), in case a stair exists. The evaluation table showing the input variables is listed in the method section (Table 3.16), while the rules showing interrelationships between input variables and the vulnerability output are listed in Appendix C. In the ground floor plan of the İzmir Opera House, routes that are planned to be used in the evacuation process are examined by using a fuzzy evaluation methodology based on the most critical factors. Route flow analysis reveals that, in the ground floor, all of the route dimensions are proper in terms of height, and all routes are planned in the horizontal plane without slope. Hence, the route width, door swing direction, and stair and transition availability on the route axis are determinant factors in terms of route flow.

The route flow analyses depend on the geometry and layout of routes. Route cells on İzmir Opera House ground floor are determined in the plan drawing, and the route flow vulnerability levels for each cell are determined in fuzzyTECH software based on Table 3.16. Then, for each combination of route flow vulnerability variable, a single escape route flow level is attained as a rule (Table C.3). Since the system is generated through the software, the final route flow vulnerability value is directly calculated within 0-1 range. Depending on the severity of safety level, corresponding linguistic variables and color codes described in Table 4.1 are selected and visualized in the plan drawing. According to İzmir Opera House ground floor plan route flow vulnerability assessment represented in Figure 4.3, routes with inward door swing direction, with width less than 110 cm, and with transition paths to achieve exit ways are evaluated as a limited safety (safe), while other routes provide adequate safety for each route flow variable are evaluated as “very safe”.

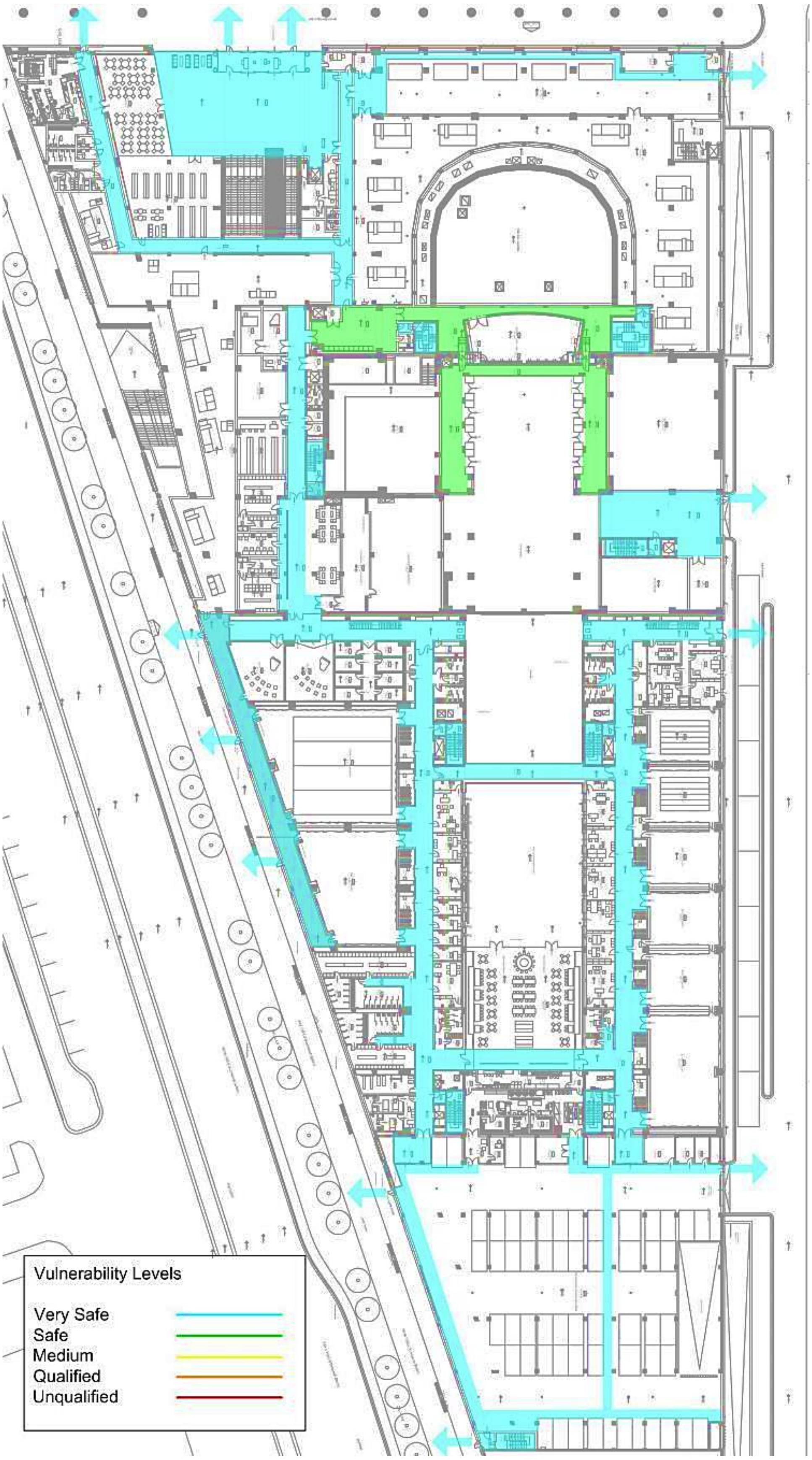


Figure 4.3 Ground floor escape route flow vulnerability (Scale ~1/1000)

4.1.3 Escape Route Equipment Vulnerability Assessment

Evaluation of escape route equipment including guidance sign, general lighting, and emergency lighting is generated through fire scenario and guidance sign plan designed by fire safety engineers. According to the fire scenario of the İzmir Opera House, emergency lighting system, and guidance sign illuminations are kept "always on" regardless of emergency case. In addition, scenario indicates that in case of a power blackout, alternative storage batteries are required to be used. Accordingly, in the evaluation phase, general lighting is accepted as always on and emergency lighting is accepted as provided, so that the position and availability of guidance signs on the route axis and doors (stairway, exit passageway, and final exit doors) are determinant factors in terms of escape route equipment vulnerability.

In order to conduct the analysis, the route axis from the room spaces and intermediate spaces to means of egress components (stairs, exit passageways, and exit doors) are drawn on the plan drawing. The guidance signs indicating the orientation of users are placed on the axis by using reference plan prepared by fire safety professionals. The evaluation of the route axis on the particular routes is assessed according to availability of guidance on the travel paths, exit doors, and exit stair entrances. According to the rules determined by structured interviews and defined in Table 3.17, in case of existence of guidance signs, the ground floor plan of the building either provides proper guidance and evaluated as "very safe," or does not provide the guidance and evaluated as "medium safe". Assessment of escape routes in terms of equipment vulnerability is shown in Figure 4.4. The evaluation is done by using software structure, and the linguistic vulnerability levels with corresponding color-codes are transferred to plan drawing.

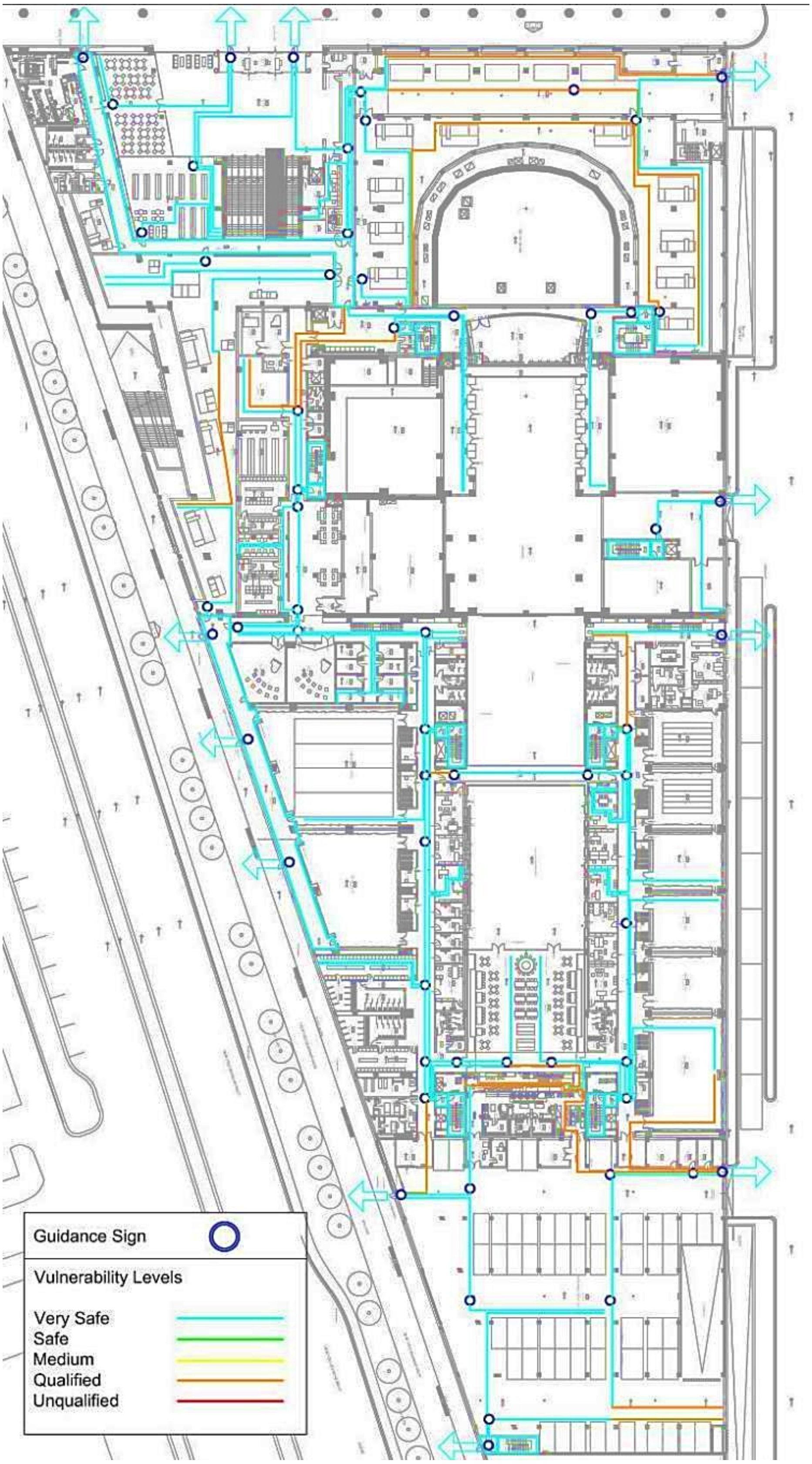


Figure 4.4 Ground floor escape route equipment vulnerability (Scale ~ 1/1000)

4.1.4 Means of Escape Vulnerability Assessment

In the assessment phase of means of egress vulnerability, availability and quantity of egress components and alternative means of egress components' availability are used. In order to carry on İzmir Opera House ground floor plan means of egress evaluation, an egress route axis plan showing the travel paths is used. The route axes following from any point of the building to the nearest means of egress components are accepted as an available means of egress. On the other hand, the means of egress alternatives that are provided as a third or more alternative, and that are within the range of travel distances are accepted as alternative means of escape.

The ground floor plan route paths are drawn and analyzed through the rule based system generated by expert opinion, listed in Table 3.18, and the vulnerability levels are determined. The escape routes are selected from the most critical point of the building, such as the corner and intermediate points. As a result of vulnerability assessment, ground floor vulnerability levels regarding means of egress are grouped under three levels as; unqualified, safe and very safe. Accordingly, the route axis linguistic variables and color codes are determined on the basis of these rules;

- If escape routes available with single exit and without alternative means of egress, then vulnerability level is unqualified, with red color representation,
- If escape routes with multiple means of egress leading to exit and with an alternative exit, then vulnerability level is safe, with green color representation,
- If escape routes with multiple means of egress and without alternative exit, then vulnerability level is safe, with green color representation,
- If escape routes with multiple means of egress and with alternative exit components, then vulnerability level is very safe, with blue color representation.

In consideration of the rules, the ground floor means of escape vulnerability analysis are performed through fuzzy expert model structure and represented on the plan drawing in Figure 4.5.

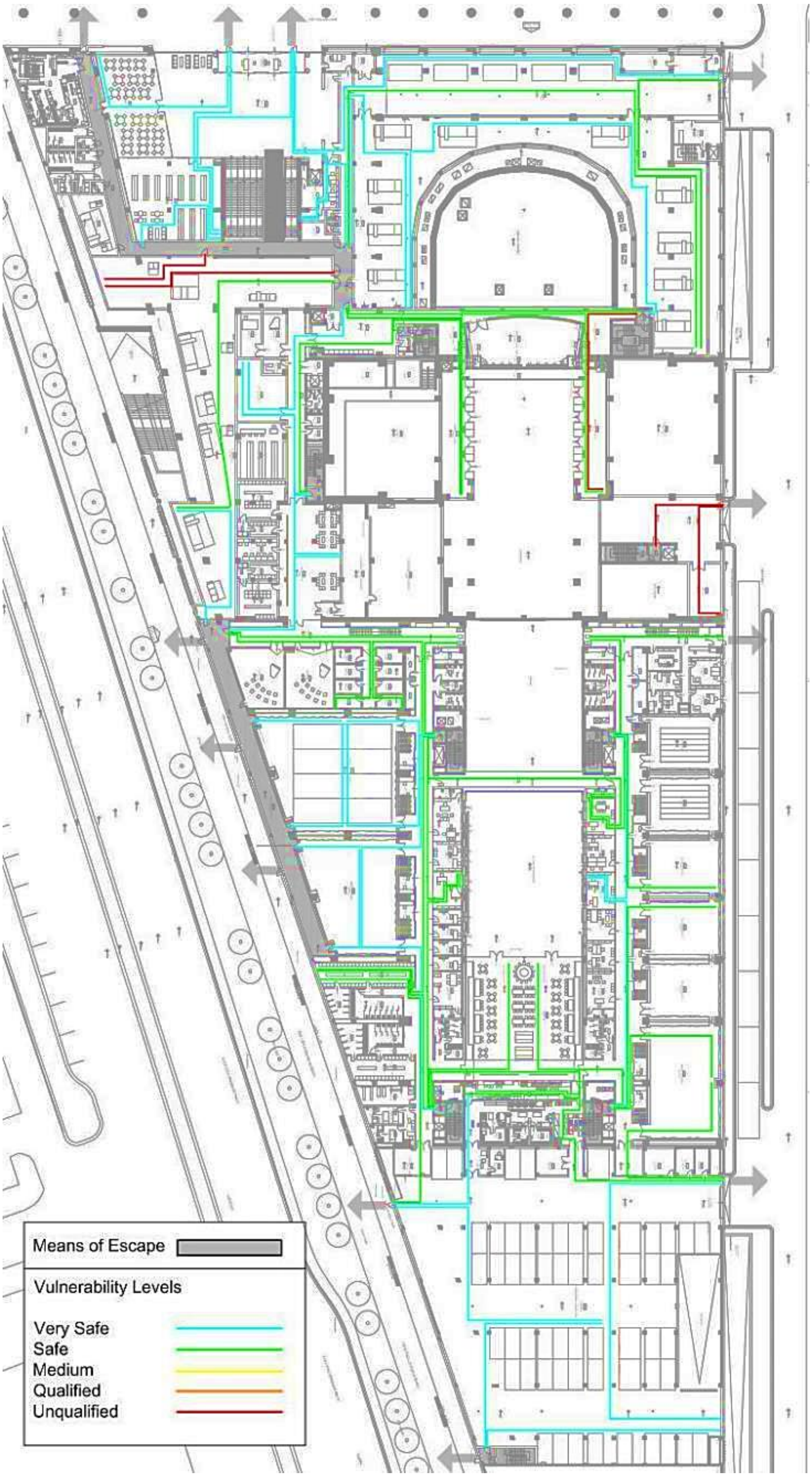


Figure 4.5 Ground floor means of escape vulnerability (Scale ~ 1/1000)

4.1.5 Escape Route Distances and Layout Vulnerability Assessment

The last part of the escape route analysis includes the measurement of common path distances, travel distances, and dead end corridor distances in terms of remaining or exceeding the limits determined through the building fire regulations. In order to perform route distance and layout vulnerability assessment, escape route axes from critical rooms and corridors to means of egress components are drawn in the ground floor plan drawing. Travel distances comprise the route from the any point of the building to a protected path of egress, to the exit discharge or to a public way. Drawings of route path are done in the orthographic representation technique, while the distances are measured as shortest accessible path between any points. In case of more than one means of egress component availability, all egress route paths are drawn to differentiate the proper means of egress alternatives. For each route axes common path distances, travel distances and dead end corridor distances are assessed according to regulation limits. According to Turkish Fire Safety Regulation travel distance limits, for assembly occupancies with the sprinkler protection common path of travel is limited to 25m, travel distance is limited to 60m, and dead end corridor is limited to 20m. After the distances are determined, the vulnerability level of the route is generated from the rule based structure model, which is listed in Table 3.19. Escape route distance and layout vulnerability level assessment for the İzmir Opera House ground floor is categorized under three safety groups; unqualified, medium and very safe, according to rule based system as follows;

- If the route distances are kept under the limits for all three input variables, then the escape route the vulnerability level is very safe, with blue color representation,
- If the route path provides an adequate common path and travel distances, but exceeds the dead end corridor length, the vulnerability level is medium, with yellow color representation,
- If the route path exceeds any of the two input variable distances lengths, the vulnerability level is unqualified, with red color representation.

In consideration of the rules, the ground floor escape route distance and layout vulnerability analysis are performed through fuzzy expert model structure and represented on the plan drawing in Figure 4.6.

Figure 4.6 Ground floor escape route distance and layout vulnerability (Scale ~ 1/1000)

4.2 Discussion

The proposed vulnerability assessment system aims to assess eight parameters with 20 sub parameters and 39 input variables in total to detect most critical fire safety vulnerabilities in building design. In addition, one of the main objectives of designing the vulnerability assessment tool is to minimize the gaps between architect and fire safety engineer by providing architects a quick fire safety analysis method. By using the evaluation tool, safety concerns of building can be emphasized and the probable modification of proposed architectural design can be minimized.

In the first part of comprehensive assessment, escape route vulnerability is applied in the case study to identify the advantages and limitations of the method. Based on the fuzzy expert method, in the escape route vulnerability analysis, evaluation of route material, route flow, route equipment arrangement and availability, route means and route distance are carried on in separate plans of case study. One of the objectives of the study is to result with single escape route vulnerability value for each route cell, reflecting effects of all sub parameters. To do so, first, the vulnerability distribution of escape route sub parameters is prepared by the juxtaposition of overlapping ground floor plan vulnerability analysis figures presented in section 4.1. The juxtaposed plan is used to understand whether the single vulnerability level can express the overlapped vulnerabilities. Therefore, in Figure 4.7 juxtaposed vulnerable parts are represented by color codes. Detected weakness in ground floor analyses is discussed through juxtaposed plans. Escape routes with intense red lines are the most vulnerable spaces, which are entrance foyer, orchestra study room, mechanical rooms, car parking area and kitchen service spaces. In the entrance foyer area, the most vulnerable parameter is finishing material (ash wood cladding) with qualified safety level, which should be protected by fire retardant treatments. In orchestra study room area, although the route flow and means of escape components are safe, the finishing material is medium safe, the equipment is qualified, and distances are unqualified. Therefore, enclosed escape route corridors with proper guidance and fire resistance is needed to provide life safety. In the two mechanical room area, the travel distances and route equipment are unqualified and qualified levels, so additional means of escape components and proper placement of guidance sign is needed in that area.

Figure 4.7 Juxtaposition of ground floor escape route sub parameter vulnerabilities (Scale ~ 1/1000)

For the car parking area, the material, route flow, and means of escape requirements are very safe, however the equipment and travel distances of east side are evaluated as qualified and unqualified. Therefore, the additional pedestrian route between car parking spaces with proper guiding need to be provided. In the kitchen service spaces, including the dining hall area, finishing material and route equipment is combustible, while the means of egress components are safe, and distance and route flow vulnerability levels are very safe. For these spaces, guidance sign placement for safe wayfinding and fire retardant protection of ash wood cladding is required.

In order to assess single vulnerability output based on five separate analyses the juxtaposed plan can be used by attaining the most severe vulnerability value as a single vulnerability level for each route. On the other hand, center of area and structured interview data collection from expert can be other ways of producing single vulnerability data for each escape route. In this research, in order to discuss applicability of escape route fire safety design precautions, the ground floor plan is analyzed by using two methods; (1) center of area method, (2) expert opinion method. These two methods are compared with each other and with a juxtaposed vulnerability assessment plan.

The first method is center of area method, using sub-parameter membership degrees over 100% and vulnerability levels between 0-1 by using equation 2 described in section 3.2.5. By using this method, approximate analysis of five sub parameters is assessed in one vulnerability value with a membership degree. The rule based system based on possibilities of ground floor escape route vulnerabilities is generated and represented in Appendix C Table C.4. The escape route vulnerability expression of ground floor plan by using the center of area method is indicated in Figure 4.8. The second method is using expert opinion to create rule-based data, to include expert intuition in the differentiating significance of the parameters. Expert rules for single output is generated by using structured interview as a test methodology for ground floor analysis and to compare the outputs of expert rules and center of area rules. The result of expert evaluation is represented in Figure 4.9.

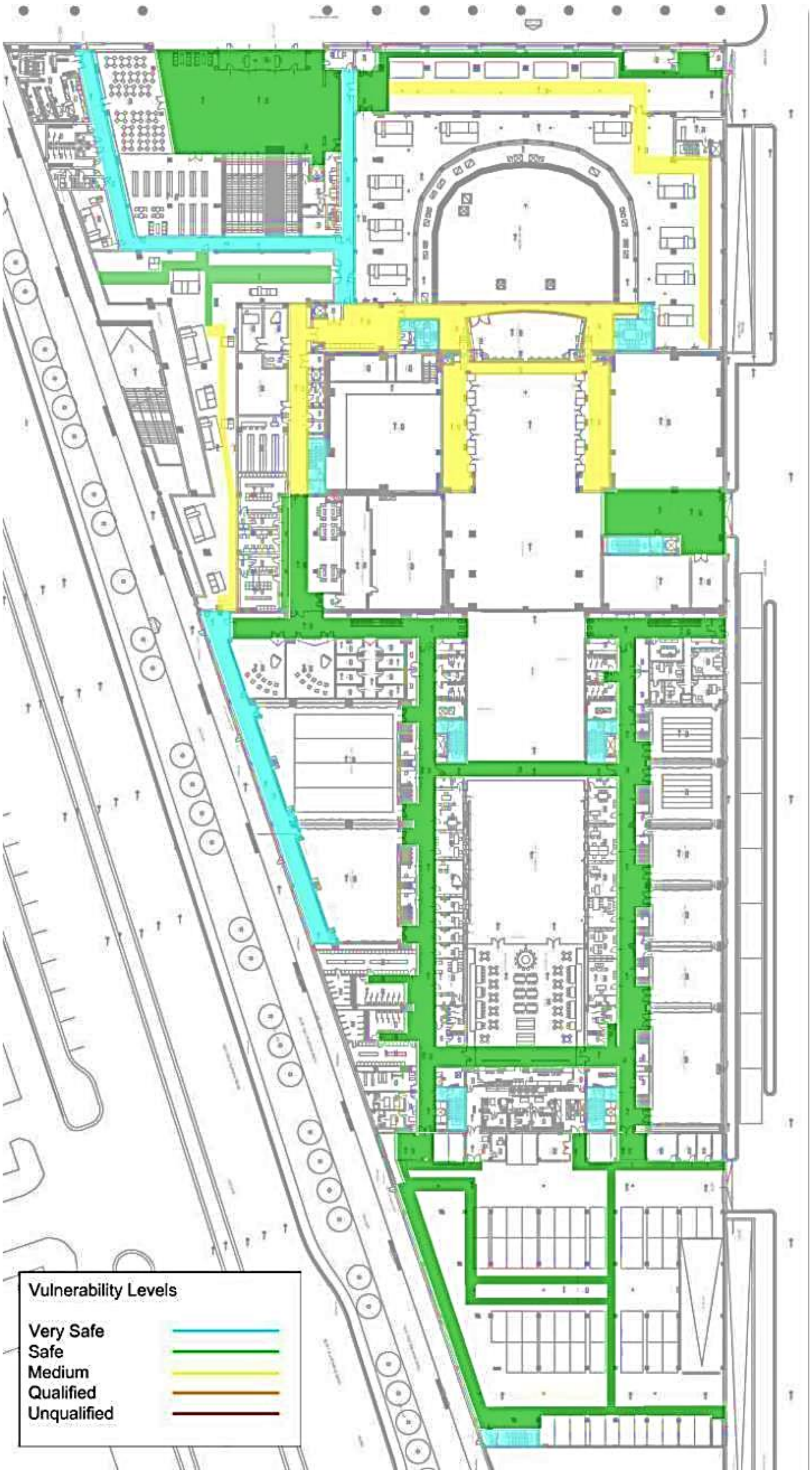


Figure 4.8 Ground floor escape route vulnerability by center of area method

(Scale ~ 1/1000)

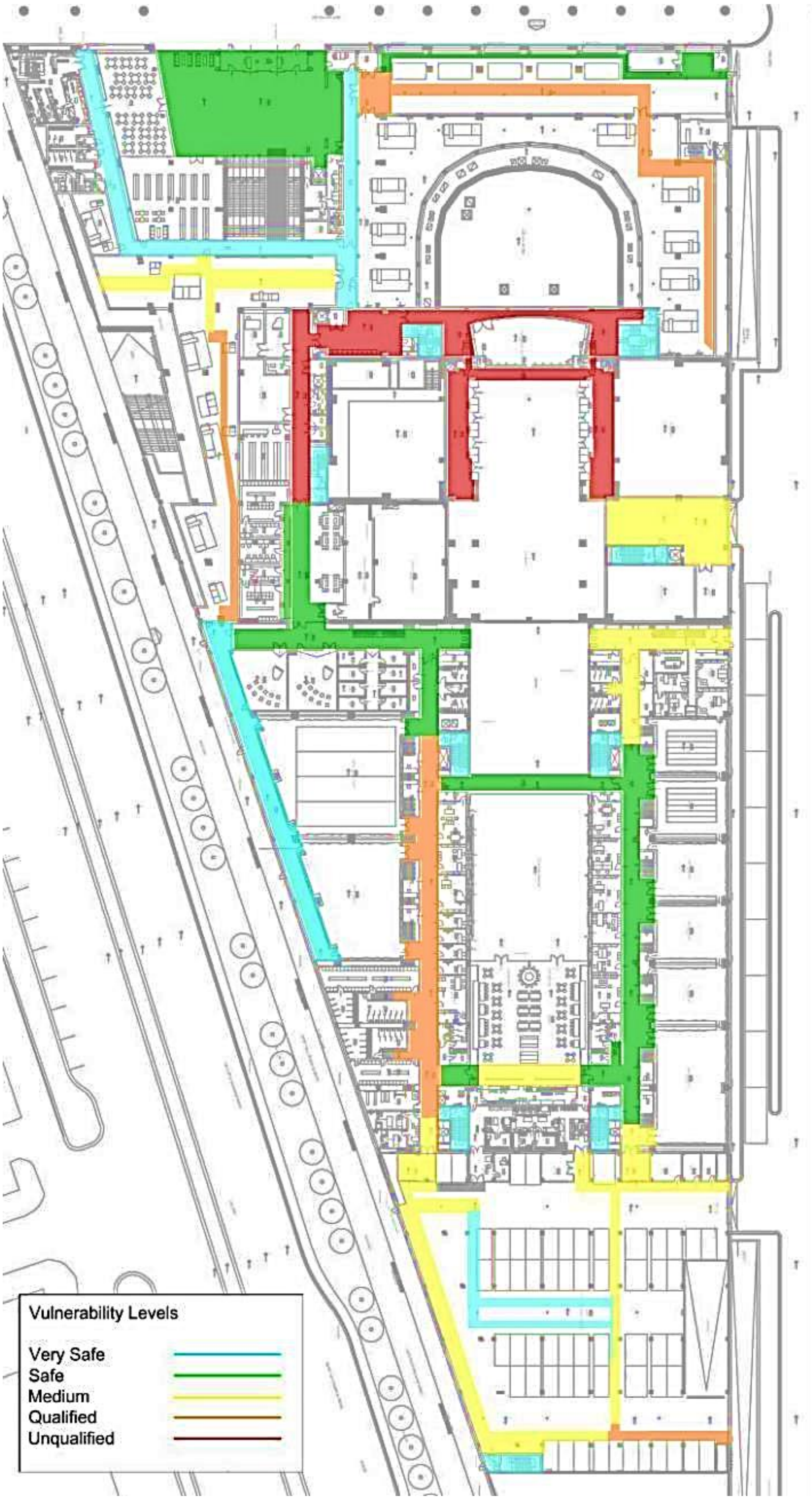


Figure 4.9 Ground floor escape route vulnerability by expert rule based

(Scale ~ 1/1000)

To compare two methodologies, the center of area method is systematical and easy to construct rules. However, the disadvantage of using the center of area method may be absorbing one the most severe vulnerability in case of other safe vulnerabilities, so that the results tend to accumulate at medium levels. On the other hand, the expert opinion method represents a wide range of vulnerability levels depending on importance levels of sub parameters. However, the construction of comprehensive rule based system with five escape route sub- parameters and five scale linguistic variables requires a total of 3125 (5^5) rules. This is an excessive amount of rule generation and might not be efficient in terms of the applicability of the system. Therefore, in terms of applicability the rule-based system by its own cannot be used for comprehensive evaluation. More detailed system with learning and generalization capacities need to be used. Moreover, for more accuracy, the sub parameters need differentiation, by assignment of weighting factors for each.

These methodologies help to describe the overall fire safety of evaluation factors, by answering “how safe is safe enough” to define the acceptable fire safety level. Since the selected sub-parameters are the most critical factors to provide safe evacuation and to protect building property, the vulnerability should not be evaluated in average levels; on the contrary, any weakness detected by analyses should be reflected in the results. Therefore, for overall the vulnerability level assessment value reflecting the defects is required to take the lowest and the most critical vulnerability level. For instance, for the orchestra study hall in the ground floor plan, with medium safe finishing material, safe route flow, very safe route equipment, and unqualified means of escape and distances, the evaluation should be concluded as “unqualified,” in other words “not acceptable” until the vulnerabilities are handled.

CHAPTER 5

CONCLUSIONS

In this chapter, the scope of the study, the literature review critics on fire safety evaluation methods, and the proposed fuzzy expert system methodology is summarized. In addition, the breakdown of the advantages and the main results of the study are explained. In the final part, the limitations of the study and the future work recommendations are proposed.

5.1 Summary of the Research

The scope of the study comprises checking fire safety vulnerabilities by arguing the direct relationship between building characteristics and fire spread, and identification of building vulnerabilities in the design process. Literature review shows that if the fire safety design results in unacceptable design, the system directs designers to modification of the original building design proposal. Therefore, acceptability of proper fire safety design directly depends on the suitability of building design input with general fire safety objectives. In order to find building design input that affects the fire safety, critical literature analysis was conducted. In critical literature analysis, fire safety parameters are identified by examining fire safety evaluation methods, most of which are ranking systems. In this study, suitable for the uncertain nature of fire safety evaluation, fuzzy expert system method is selected to find out vulnerability level of building characteristics in terms of fire safety and possible measures to decrease it. By using a fuzzy expert method, expert knowledge is converted to a decision-making tool, which brings experts' skills to solve specific problems and provide structure to deal with uncertainties. Moreover, using expert system based on fuzzy logic has the advantages of using linguistic terms to deal with complex interactions. In the methodology, after finding out common architectural and fire safety design parameters by a literature review, as a first phase of fuzzy expert system, the problem and the linguistic variables are defined. In order to conduct the fuzzy expert system, building parameters with the highest priority are selected as the input parameters among the ranking methods, and the fire safety vulnerability system is proposed. The parameters are; escape route, structure-separating/building height, doors, compartmentation/hazard protection, vertical openings, furnishing, interior finishes, and external envelope / façade. Accordingly, the proposed vulnerability assessment system aims to assess eight parameters with 20 sub parameters and 39 input variables in total to detect most critical fire safety vulnerabilities in building design. In the scope of this thesis, a comprehensive method is proposed, but only escape route parameter is evaluated in terms of checking the applicability of the method. The purpose of the vulnerability assessment model and verbal evaluation scale is to develop and to provide quick response fire safety check in design process, and to minimize the gaps between architect and fire safety engineer. In the second phase, fuzzy membership functions of these parameters are determined. Then, in the following phase, if-then fuzzy rules are constructed by using structured interviews conducted by fire safety experts. In the last two steps, the fuzzy rules are encoded to a computer tool, named fuzzyTECH, and the evaluation of a case study is performed. As a case study material, İzmir Opera House building is evaluated by fuzzy based vulnerability assessment and the weaknesses in terms of escape route parameters are identified.

5.2 Main Results

The escape route vulnerability analyses are performed as an alternative method to regulation-based escape route evaluation. The system is designed for architects to enter the project data in terms of numerical and linguistic variables and to detect fire safety vulnerabilities in the form of linguistic data and corresponding color codes. The route plans with color codes was prepared by using Computer-Aided Design (CAD) tool to display the output vulnerabilities. Therefore, linguistic expressions enabled easy communication among the design team, while color-coding enabled easy detection of weaknesses. For simpler analysis, it is possible to detect vulnerabilities on the results screen without displaying the color-coded plans. A total egress route evaluation was performed by entering project data to system, and results shown simultaneously by using rule-based method, so that the system has a time advantage over regulation checking methodologies.

The case study is analyzed based on the construction-drawing phase, so that the concept design phase is evaluated by the fire safety experts based on the regulations and the corrections are submitted as written report previously. Therefore, it is quite visible that initial design has too many vulnerabilities that are corrected and approved. However, it may not be possible to evaluate them in detail. By using the fuzzy expert structure, the unnoticed or unrevised weak points are detected on the escape route vulnerability analysis and presented on floor plans. In order to provide an acceptable level of safety, the lowest vulnerability level should be the determinant factor. By combining the data extracting from regulations together with expert opinion more detailed analyses were performed. The detailed analyses enable fire protection measures by detecting point sources of the vulnerabilities. The effects of each input variable change in total vulnerability can be tested on the single platform. As a result, in fire safety design process the priority was given to precautions, aiming to prevent fire before it starts.

5.3 Future Work Recommendations

There are some limitations arise from transferring fuzzy tool data to a CAD tool to show the vulnerability levels. Therefore, the integrated vulnerability level analysis of building plans is proposed for the future applications to enable collaborations and modifications from the beginning of the design process. For the future studies, evaluation data extracted from the literature and expert opinion are planned to be transferred to BIM (Building Information Modelling), as a joint database. BIM helps to bring together efficiency and accuracy systems into one single platform, in order to integrate of fire facilities with other building functions and accurately judge of fire safety vulnerabilities of the building. By doing so, the input variables used in the fuzzy model structure can be extracted from the architectural model data, and can be evaluated during the design process without using another assessment tool. The aim is to test the applicability of the methodology, to provide interoperability of fire safety objectives and building design input, and not to limit the creative basis of the practice.

Besides the advantages of fuzzy logic such as representing uncertainties of the human knowledge with linguistic variables and using expert knowledge through the rules, it has some limitations. The rule base system is applicable for a small number of parameters. The revision of parameters directs the system to modification of rule-based system. So that for comprehensive fire safety vulnerability assessment expert rule system has time and rule extension disadvantages. Therefore, rule generation is required for further development of the research. The rule generation capacity and learning capacity system methodology is recommended for future work applications of fire safety vulnerability assessment. In the scope of this dissertation, the parameters are limited to eight parameters with twelve sub parameters. By using automated rule generation methodologies, more parameters related to building construction and fire safety, such as the roof and attic vulnerability can be added to construct detailed analyses of buildings. Finally, the complex system should define relationships between parameters such as their weighting factors of relative importance, and the resilience levels, which defines how the parameter values are return and maintain their properties after the hazard event.

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APPENDICES

APPENDIX A

FIRE SAFETY EVALUATION METHODS REVIEW

In literature review of fire safety evaluation researches, the parameters related with building characteristics are explained in detail. However, evaluation and decision-making methods deal with holistic fire safety factors, including building, human and fire aspects. Therefore, list of evaluated parameters is prepared and represented in Table A1. In order to determine the most critical parameters used in the structure of vulnerability assessment, weighting ratios of parameters are used and shaded in the table. To designate parameters, if separate parameters were ranked, then most critical three building design related parameters are selected, if parameter groups are ranked, then all parameters mentioned in the group are selected. The selected parameters with their references are explained. The first parameter is mentioned as means of escape (Shields *et al.* 1990), evacuation route and width of stair (Chow 2002), number and configuration of exit routes and emergency lighting (Lo 1999 and Zhao *et al* 2004), maximum travel distances (Watts & Kaplan, 2001), smoke and fire spread in evacuation routes (Chen *et al* 2012). The second parameter is mentioned as doors (Karlsson & Larsson 2000), smoke doors (Chow 2002), and fire doors (Chen *et al* 2012). The third parameter is mentioned as structural separating (Karlsson & Larsson 2000), building height and construction (Watts & Kaplan, 2001), and fire resistance construction (Chow 2002). The fourth parameter is mentioned as compartmentation (Karlsson & Larsson 2000), horizontal fire compartments (Chen *et al* 2012), and survey volume (Donegan *et al* 1991), and building area (Watts & Kaplan, 2001). The fifth parameter is mentioned as vertical openings (Watts & Kaplan, 2001), and fire barriers with vertical openings (Chen *et al* 2012). The sixth parameter is mentioned as furnishings (Shields *et al.* 1990), contents, and hazard protection (Donegan *et al* 1991). The seventh parameter is mentioned as interior finishes (Shields *et al.* 1990**)** and internal design (Donegan *et al* 1991). Final parameter is external envelope, mentioned once by Donegan *et al* (1991).

Table A.1 Fire Safety Evaluation Model Review

Shields *et al.* (1990)	**Donegan, *et al.* (1991)**	**Watts (1992)**	**Lo (1999) and Zhao *et al* (2004)**		**Karlsson & Larsson (2000)**
Parameters (Over 100)	**Parameters (Over 500)**	**Parameters (No weight)**	**Parameters (Over 1)**		**Hierarchical System**
People	**Human (205)**	**Death and injury**	**Means of egress/warning (0.34) and (0.51)**	**Fire services (0.29) and (0.12)**	**Parameters (Over 1)**
Users (30)	Occupants and visitors	Sleeping	Width of exit routes	Hose reel	Linings (0,0576)
Means of egress (4)	Contents	Evacuation	Number of exit route	Sprinkler system	Suppression system (0,0668)
Management(12)	Management	Density	Travel distance	Detection system	Fire service (0,0681)
Passive	**Passive(205)**	Confined/ restrained	Population distribution pattern	Warning system	Compartment (0,0666)
Fire and smoke control (1)	Internal design	Impairment	Configuration of exit routes	Mech. smoke extraction	Structure-separating (0,0675
Furnishing(8)	Survey volume	Occupant control	Emergency lighting	**Building character. (0.09)**	Doors (0,0698)
Interior finishes(7)	Means of egress	**Property loss**	**Ignition prevention (0.19) and (0.16)**	Building orientation	Windows (0,0473)
Active	Hazard protection	Fuel load	Compartmentation size	Occupancy pattern	Façade (0,0492)
Building services (3)	External envelope	Response time	Fire rated doors	Management level	Attic (0,0515)
Suppression equipment (11)	**Active fire brigade(90)**	Involvement	Fire rated walls, floors, etc.	Maintenance level	Adjacent buildings (0,0396)
Detection and communication systems(24)	Detection systems	Fire control	Flame spread prevention		Smoke control (0,0609)
	First aid firefighting	**Ignition potential**	Fire load		Detection (0,063)
		Purposeful	**Vehicle access (0.09) and (0.06)**		Signal system (0,0512)
		Accidental	Emergency vehicle access		Escape routes (0,062)
			Firefighting and rescue stair		Structure-load-bearing (0,063)
			Firemen's lift (elevator)		Maintenance and info. (0,0601)
			Smoke vent		Ventilation (0,0558)

Table A.1 (Cont.)

Watts & Kaplan (2001)	**Chow (2002)**	**Chen *et al* (2012)**		
Parameters (Over 100)	**Parameters (Over 100)**	**Parameters (Over 100)**		
Vertical openings (18)	**Passive building construction (63.3)**	**Fire prevention (25.99)**	**Evacuation and mitigation (28.96)**	**Fire control and resistance (45.05)**
Building height (12)	Building height	Duties of fire management organization	Utilization of emergency equipment	Fire resistance performance of building (2.5)
Sprinklers/automatic sprinklers (10)	Evacuation route	Fire safety plans	Evacuation facilities	Material of interior decoration (3.4)
Building area (7)	Width of staircase	Fire prevention awareness	Fire escape equipment	Horizontal fire compartment (4.2)
Maximum travel distance (7)	Smoke doors	General equipment management	Utilization of evacuation facilities	Fire barriers with vertical openings (4.2)
Corridor walls (6)	Fire resistance construction	Maintenance of fire equipment	Utilization of fire escape equipment	Fire door (8.5)
Fire alarm system/fire alarm (5)	**Fire services (31.4)**	Security system	Firefighting capacity	Spatial characteristics (4.9)
Means of egress/exit system (5)	Fire hydrant/hose reel	Fire and gas equipment	Mandatory firefighting measures	Automatic alarm equipment (4.2)
Automatic fire detection/smoke detection (4)	Fire alarm	Performance of power supply equipment	Safety of openings of exterior walls	Fire extinguishing equipment (5.4)
Segregation of hazards (4)	Fire detection system	Report status of fire safety	Risk transfer measure	Smoke exhaust equipment(3.4)
Compartmentation (4)	Sprinkler system			Alarm system (4.2)
HVAC systems (4)	Fire extinguisher			
Smoke control/smoke control (2)	Smoke control			
Dead ends/exit access (2)	Emergency lighting			
Interior finish (2)	Exit sign			
Mixed use groups (2)	**Software management (5.3)**			
Occupant emergency program (2)				
Unit separations (1)				
Elevator control (1)				
Egress emergency lighting (1)				

APPENDIX B

STRUCTURED INTERVIEW OF VULNERABILITY ASSESMENT

This research is conducted by METU building Science Graduate program student Nilüfer Kızılkaya to fulfill dissertation study.

In this section, the evaluation tables for vulnerability assessment of escape route sub-parameters are represented. The sub-parameters are determined through literature analysis and presented for expert evaluation. Thank you for your contributions

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Participant Information

Name:

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Profession:

Experience in Fire Safety:

The structural interview method is used to collect data from experts and to develop a rule-based system in the fuzzy expert system structure. The rule data of the first two sub-parameters' (escape route finishing and escape route flow) are adapted from the literature analysis and listed in Section 3.1.1, so that the tables are extracted from the appendix section. In section data collection tables of other three sub-parameters (escape route equipment, means of escape and escape route distances and layout) are explained. The output model of five sub parameters is vulnerability defined by linguistic variables to provide understandable process to end user without limitation of numerical algorithms. The linguistic variables and their corresponding triangular fuzzy numbers are listed in Table B.1.

Table B.1 Linguistic variables used in vulnerability evaluation

Linguistic Variable	**Triangular Fuzzy Number**
Unqualified (U)	(0, 0, 0.25)
Qualified (Q)	(0, 0.25, 0.50)
Medium (M)	(0.25, 0.50, 0.75)
Safe (S)	(0.50, 0. 75, 1)
Very Safe (VS)	(0,75, 1, 1)

In the following part, the vulnerability assessment information of escape route equipment means of escape availability and escape route dimension and layout sub-parameters are represented.

Sub-parameter 3: Escape route equipment

Evaluation of escape route equipment sub-parameter comprises assessment of guidance sign, general lighting, and emergency lighting conditions for each escape route. In Table B.2, the vulnerability assessment of guidance sign, general lighting and emergency lighting variables are listed. Please evaluate the most suitable vulnerability level according to your experiences and observations in fire safety profession.

You are required to consider the evaluation in case of each three input variables are valid in the row. For example; if the guidance sign is "Illuminating Light" **and** general lighting is "Always On" **and** emergency lighting is "Provided"; **then** the vulnerability level is "Very Safe" *etc.* It is accepted that, in case of emergency general lighting is operated with or without utility supply power.

Table B.2 Escape route equipment vulnerability assessment

Guidance Sign	**General Lighting**	**Emergency Lighting**	**Vulnerability Levels**				
			U	**Q**	**M**	**S**	**VS**
Illuminating Light	Always On	Provided	☐	☐	☐	☐	☐
Illuminating Light	Always On	Not Provided	☐	☐	☐	☐	☐
Illuminating Light	Manual	Not Provided	☐	☐	☐	☐	☐
Illuminating Light	Manual	Provided	☐	☐	☐	☐	☐
Normal	Always On	Not Provided	☐	☐	☐	☐	☐
Normal	Always On	Provided	☐	☐	☐	☐	☐
Normal	Manual	Not Provided	☐	☐	☐	☐	☐
Normal	Manual	Provided	☐	☐	☐	☐	☐
None	Always On	Provided	☐	☐	☐	☐	☐
None	Always On	Not Provided	☐	☐	☐	☐	☐
None	Manual	Provided	☐	☐	☐	☐	☐
None	Manual	Not Provided	☐	☐	☐	☐	☐

Sub-parameter 4: Means of Escape

Evaluation of means of escape sub- parameter comprises assessment of available and alternative exit conditions for each escape route. In Table B.3, the vulnerability assessment of available and alternative exits is listed. Please evaluate the most suitable vulnerability level according to your experiences and observations in fire safety profession.

You are required to consider the evaluation in case of each two input variables is valid in the row. For example, if the available exit is "Multiple Direct" **and** alternative exit is "Provided"; **then** the vulnerability level is "Very Safe" *etc.*

Table B.3 Means of egress vulnerability assessment

Available exit	**Alternative exit**	**Vulnerability Levels**				
		U	**Q**	**M**	**S**	**VS**
Single	Not Provided	☐	☐	☐	☐	☐
Single	Single Alternative	☐	☐	☐	☐	☐
Single	At least two	☐	☐	☐	☐	☐
Multiple Leading	Single Alternative	☐	☐	☐	☐	☐
Multiple Leading	At least two	☐	☐	☐	☐	☐
Multiple Direct	Not Provided	☐	☐	☐	☐	☐
Multiple Direct	Provided	☐	☐	☐	☐	☐

Sub-parameter 5: Escape Route Distance and Layout

Evaluation of means of escape route sub-parameter comprises assessment of common path, travel, and dead end corridor distances of each escape route. In Table B.4, the vulnerability assessment of common path, travel and dead end corridor distance variables are listed. Please evaluate the most suitable vulnerability level according to your experiences and observations in fire safety profession.

You are required to consider the evaluation in case of each three input variables is valid in the row. For example; if the common path distance is "Within Limits" **and** of travel distance is "Within Limits" **and** dead end corridor distance is "Within Limits"; **then** the vulnerability level is "Very Safe" *etc.*

Table B.4 Escape route distance and layout vulnerability assessment

Common Path of Travel	Travel Distance	Dead End Corridor	Vulnerability Levels				
			U	Q	M	S	VS
Within Limits	Within Limits	Within Limits	☐	☐	☐	☐	☐
Within Limits	Exceed Limits	Within Limits	☐	☐	☐	☐	☐
Within Limits	Within Limits	Exceed Limits	☐	☐	☐	☐	☐
Within Limits	Exceed Limits	Exceed Limits	☐	☐	☐	☐	☐
Exceed Limits	Within Limits	Within Limits	☐	☐	☐	☐	☐
Exceed Limits	Within Limits	Exceed Limits	☐	☐	☐	☐	☐
Exceed Limits	Exceed Limits	Within Limits	☐	☐	☐	☐	☐
Exceed Limits	Exceed Limits	Exceed Limits	☐	☐	☐	☐	☐

Ground Floor Escape Route Vulnerability Assessment Rules

In this section rule based system for ground floor escape route evaluation sub-parameters are asked to assess single value for each route axis. The rule alternatives are generated based on analysis in Section 4.1. Please complete Table B.5 based on your experiences and observations in fire safety profession

Table B.5 Ground floor vulnerability rules based on expert opinion

	Route Material	**Route Flow**	**Route Equipment**	**Means of Escape**	**Route Distance Layout**	**Escape Route Vulnerability Level**				
	IF	**AND**	**AND**	**AND**	**THEN**	**U**	**Q**	**M**	**S**	**VS**
1	VS	VS	VS	VS	VS	☐	☐	☐	☐	☐
2	M	S	VS	VS	VS	☐	☐	☐	☐	☐
3	M	VS	VS	VS	VS	☐	☐	☐	☐	☐
4	Q	VS	VS	VS	VS	☐	☐	☐	☐	☐
5	VS	VS	Q	VS	VS	☐	☐	☐	☐	☐
6	M	S	Q	VS	VS	☐	☐	☐	☐	☐
7	M	VS	Q	VS	VS	☐	☐	☐	☐	☐
8	Q	VS	Q	VS	VS	☐	☐	☐	☐	☐
9	VS	VS	VS	S	VS	☐	☐	☐	☐	☐
10	M	S	VS	S	VS	☐	☐	☐	☐	☐
11	M	VS	VS	S	VS	☐	☐	☐	☐	☐
12	Q	VS	VS	S	VS	☐	☐	☐	☐	☐
13	VS	VS	Q	S	VS	☐	☐	☐	☐	☐
14	M	S	Q	S	VS	☐	☐	☐	☐	☐
15	M	VS	Q	S	VS	☐	☐	☐	☐	☐
16	Q	VS	Q	S	VS	☐	☐	☐	☐	☐
17	VS	VS	VS	U	VS	☐	☐	☐	☐	☐
18	M	S	VS	U	VS	☐	☐	☐	☐	☐
19	M	VS	VS	U	VS	☐	☐	☐	☐	☐
20	Q	VS	VS	U	VS	☐	☐	☐	☐	☐

Table B.5 (Cont.)

21	VS	VS	Q	U	VS	□	□	□	□	□
22	M	S	Q	U	VS	□	□	□	□	□
23	M	VS	Q	U	VS	□	□	□	□	□
24	Q	VS	Q	U	VS	□	□	□	□	□
25	VS	VS	VS	VS	U	□	□	□	□	□
26	M	S	VS	VS	U	□	□	□	□	□
27	M	VS	VS	VS	U	□	□	□	□	□
28	Q	VS	VS	VS	U	□	□	□	□	□
29	VS	VS	Q	VS	U	□	□	□	□	□
30	M	S	Q	VS	U	□	□	□	□	□
31	M	VS	Q	VS	U	□	□	□	□	□
32	Q	VS	Q	VS	U	□	□	□	□	□
33	VS	VS	VS	S	U	□	□	□	□	□
34	M	S	VS	S	U	□	□	□	□	□
35	M	VS	VS	S	U	□	□	□	□	□
36	Q	VS	VS	S	U	□	□	□	□	□
37	VS	VS	Q	S	U	□	□	□	□	□
38	M	S	Q	S	U	□	□	□	□	□
39	M	VS	Q	S	U	□	□	□	□	□
40	Q	VS	Q	S	U	□	□	□	□	□
41	VS	VS	VS	U	U	□	□	□	□	□
42	M	S	VS	U	U	□	□	□	□	□
43	M	VS	VS	U	U	□	□	□	□	□
44	Q	VS	VS	U	U	□	□	□	□	□
45	VS	VS	Q	U	U	□	□	□	□	□
46	M	S	Q	U	U	□	□	□	□	□
47	M	VS	Q	U	U	□	□	□	□	□
48	Q	VS	Q	U	U	□	□	□	□	□

APPENDIX C

RULES GENERATED FOR FUZZY VULNERABILITY ASSESSMENT

In this section, results of structured interview and center of area defuzzification method are listed to construct rule-based structure of escape route vulnerability assessment. In the first part, participant information in terms of profession and experience are listed (Table C.1). In the following part, the structured interview responses in the form of if-then rules for ground floor analysis are listed (Table C.2). The results of structured interview to construct sub-parameter rules are given in Section 3.2.3, so that the tables are not repeated in the appendix part.

The center of area defuzzification based on equation 2 is used to construct route flow rules including route dimension, route slope, door swing direction, route characteristics, and stair geometry (Table C.3). In addition to route flow analysis, center of area method is used to compare unified ground floor analysis with structured interview method (Table C.4). For the output parameters, vulnerability level (VL) linguistic variables of unqualified (U), qualified (Q), medium (M), safe (S), very safe (VS) are used that correspond to percentages.

Table C.1 Expert information

Expert Number	Profession	Experience in Fire Safety
Expert 1	Architect	> 20 years
Expert 2	Architectural Technician	4 years
Expert 3	Interior Architect	2,5 years
Expert 4	Architect	2,5 years
Expert 5	Interior Architect	7 months

Table C.2. Structured interview result for vulnerability rules

Route Material	Route Flow	Route Equipment	Means of Escape	Distance Layout	Escape Route VL				
IF	**AND**	**AND**	**AND**	**THEN**	**U**	**Q**	**M**	**S**	**VS**
VS	VS	VS	VS	VS	☐	☐	☐	☐	☒
M	S	VS	VS	VS	☐	☐	☐	☒	☐
M	VS	VS	VS	VS	☐	☐	☐	☒	☐
Q	VS	VS	VS	VS	☐	☐	☐	☒	☐
VS	VS	Q	VS	VS	☐	☐	☐	☒	☐
M	S	Q	VS	VS	☐	☐	☒	☐	☐
M	VS	Q	VS	VS	☐	☐	☐	☒	☐
Q	VS	Q	VS	VS	☐	☐	☒	☐	☐
VS	VS	VS	S	VS	☐	☐	☐	☐	☒
M	S	VS	S	VS	☐	☐	☐	☒	☐
M	VS	VS	S	VS	☐	☐	☐	☒	☐
Q	VS	VS	S	VS	☐	☐	☒	☐	☐
VS	VS	Q	S	VS	☐	☐	☐	☒	☐
M	S	Q	S	VS	☐	☐	☒	☐	☐
M	VS	Q	S	VS	☐	☐	☒	☐	☐
Q	VS	Q	S	VS	☐	☐	☒	☐	☐
VS	VS	VS	U	VS	☐	☐	☒	☐	☐
M	S	VS	U	VS	☐	☐	☒	☐	☐
M	VS	VS	U	VS	☐	☐	☒	☐	☐
Q	VS	VS	U	VS	☐	☒	☐	☐	☐
VS	VS	Q	U	VS	☐	☒	☐	☐	☐
M	S	Q	U	VS	☐	☒	☐	☐	☐
M	VS	Q	U	VS	☐	☒	☐	☐	☐
Q	VS	Q	U	VS	☐	☒	☐	☐	☐
VS	VS	VS	VS	U	☐	☐	☒	☐	☐
M	S	VS	VS	U	☐	☐	☒	☐	☐

Table C.2 (Cont.)

Route Material	Route Flow	Route Equipment	Means of Escape	Route Distance Layout	Escape Route Vulnerability Level				
IF	**AND**	**AND**	**AND**	**THEN**	**U**	**Q**	**M**	**S**	**VS**
M	VS	VS	VS	U	☐	☐	☒	☐	☐
Q	VS	VS	VS	U	☐	☒	☐	☐	☐
VS	VS	Q	VS	U	☐	☒	☐	☐	☐
M	S	Q	VS	U	☐	☒	☐	☐	☐
M	VS	Q	VS	U	☐	☒	☐	☐	☐
Q	VS	Q	VS	U	☒	☐	☐	☐	☐
VS	VS	VS	S	U	☐	☒	☐	☐	☐
M	S	VS	S	U	☐	☒	☐	☐	☐
M	VS	VS	S	U	☐	☒	☐	☐	☐
Q	VS	VS	S	U	☒	☐	☐	☐	☐
VS	VS	Q	S	U	☐	☒	☐	☐	☐
M	S	Q	S	U	☒	☐	☐	☐	☐
M	VS	Q	S	U	☒	☐	☐	☐	☐
Q	VS	Q	S	U	☒	☐	☐	☐	☐
VS	VS	VS	U	U	☒	☐	☐	☐	☐
M	S	VS	U	U	☒	☐	☐	☐	☐
M	VS	VS	U	U	☒	☐	☐	☐	☐
Q	VS	VS	U	U	☒	☐	☐	☐	☐
VS	VS	Q	U	U	☒	☐	☐	☐	☐
M	S	Q	U	U	☒	☐	☐	☐	☐
M	VS	Q	U	U	☒	☐	☐	☐	☐
Q	VS	Q	U	U	☒	☐	☐	☐	☐

Table C.3 Route flow vulnerability rules

Route Dimension			Route Slope			Door Swing Direction			Route Characteristics			Stair Geometry			Route Flow Vulnerability				
x	μ(x)	VL	x	μ(x)	VL	x	μ(x)	VL	x	μ(x)	VL	x	μ(x)	VL	Cent. of Area	Membership Degrees (Total %100)			
0	100	U	1	100	VS	1	100	VS	1	100	VS				0,75	0%	VS	100%	S
0	100	U	1	100	VS	1	100	VS	0,95	80	VS	0,9	60	VS	0,75	0%	VS	100%	S
0	100	U	1	100	VS	1	100	VS	0,95	80	VS	0,75	100	S	0,73	93%	S	8%	M
0	100	U	1	100	VS	1	100	VS	0,8	80	S	0,9	60	VS	0,72	89%	S	11%	M
0	100	U	1	100	VS	0,5	100	M	0,95	80	VS	0,9	60	VS	0,64	55%	S	45%	M
0	100	U	0,75	100	S	1	100	VS	0,95	80	VS	0,9	60	VS	0,69	77%	S	23%	M
0	100	U	0,75	100	S	0,5	100	M	0,95	80	VS	0,9	60	VS	0,58	32%	S	68%	M
0	100	U	0,75	100	S	1	100	VS	0,8	80	S	0,9	60	VS	0,67	66%	S	34%	M
0	100	U	0,75	100	S	1	100	VS	0,95	80	VS	0,75	100	S	0,68	72%	S	28%	M
0	100	U	1	100	VS	0,5	100	M	0,8	80	S	0,9	60	VS	0,61	44%	S	56%	M
0	100	U	1	100	VS	0,5	100	M	0,95	80	VS	0,75	100	S	0,63	51%	S	49%	M
0	100	U	1	100	VS	1	100	VS	0,8	80	S	0,75	100	S	0,71	83%	S	18%	M
0	100	U	0,75	100	S	0,5	100	M	0,8	80	S	0,9	60	VS	0,55	21%	S	79%	M
0	100	U	0,75	100	S	0,5	100	M	0,95	80	VS	0,75	100	S	0,58	30%	S	70%	M
0	100	U	1	100	VS	0,5	100	M	0,8	80	S	0,75	100	S	0,60	41%	S	59%	M
0	100	U	0,75	100	S	1	100	VS	0,8	80	S	0,75	100	S	0,65	62%	S	38%	M
0	100	U	0,75	100	S	0,5	100	M	0,8	80	S	0,75	100	S	0,55	20%	S	80%	M
0	100	U	1	100	VS	1	100	VS	0,95	80	VS	0	100	U	0,58	30%	S	70%	M
0	100	U	0,75	100	S	1	100	VS	0,95	80	VS	0	100	U	0,52	9%	S	91%	M
0	100	U	1	100	VS	0,5	100	M	0,95	80	VS	0	100	U	0,47	88%	Q	12%	U
0	100	U	1	100	VS	1	100	VS	0,8	80	S	0	100	U	0,55	20%	S	80%	M
0	100	U	0,75	100	S	0,5	100	M	0,95	80	VS	0	100	U	0,42	68%	Q	33%	U
0	100	U	1	100	VS	0,5	100	M	0,8	80	S	0	100	U	0,45	78%	Q	22%	U
0	100	U	0,75	100	S	1	100	VS	0,8	80	S	0	100	U	0,50	0%	S	100%	M
0	100	U	0,75	100	S	0,5	100	M	0,8	80	S	0	100	U	0,39	58%	Q	43%	U
0,33	68	Q	1	100	VS	1	100	VS	1	100	VS				0,88	50%	VS	50%	S
0,33	68	Q	1	100	VS	1	100	VS	0,95	80	VS	0,9	60	VS	0,86	46%	VS	54%	S
0,33	68	Q	1	100	VS	1	100	VS	0,95	80	VS	0,75	100	S	0,83	33%	VS	67%	S
0,33	68	Q	1	100	VS	1	100	VS	0,8	80	S	0,9	60	VS	0,83	34%	VS	66%	S
0,33	68	Q	1	100	VS	0,5	100	M	0,95	80	VS	0,9	60	VS	0,74	97%	S	3%	M
0,33	68	Q	0,75	100	S	1	100	VS	0,95	80	VS	0,9	60	VS	0,80	21%	VS	79%	S
0,33	68	Q	0,75	100	S	0,5	100	M	0,95	80	VS	0,75	100	S	0,67	66%	S	34%	M
0,33	68	Q	1	100	VS	0,5	100	M	0,8	80	S	0,75	100	S	0,70	78%	S	22%	M
0,33	68	Q	0,75	100	S	1	100	VS	0,8	80	S	0,75	100	S	0,75	100	S	0%	M
0,33	68	Q	0,75	100	S	0,5	100	M	0,8	80	S	0,75	100	S	0,64	56%	S	44%	M
0,33	68	Q	1	100	VS	1	100	VS	0,95	80	VS	0	100	U	0,67	66%	S	34%	M
0,33	68	Q	0,75	100	S	1	100	VS	0,95	80	VS	0	100	U	0,61	44%	S	56%	M

Table C.3 (Cont.)

x	μ(x)	VL	x	μ(x)	VL	x	μ(x)	VL	x	μ(x)	VL	x	μ(x)	VL	Cent. of Area	Membership Degrees (Total %100)			
0,33	68	Q	1	100	VS	0,5	100	M	0,95	80	VS	0	100	U	0,55	22%	S	78%	M
0,33	68	Q	1	100	VS	1	100	VS	0,8	80	S	0	100	U	0,64	56%	S	44%	M
0,33	68	Q	0,75	100	S	0,5	100	M	0,95	80	VS	0	100	U	0,50	0%	S	100	M
0,33	68	Q	1	100	VS	0,5	100	M	0,8	80	S	0	100	U	0,53	11%	S	89%	M
0,33	68	Q	0,75	100	S	1	100	VS	0,8	80	S	0	100	U	0,58	33%	S	67%	M
0,33	68	Q	0,75	100	S	0,5	100	M	0,8	80	S	0	100	U	0,47	89%	M	11%	Q
0,5	100	M	1	100	VS	1	100	VS	1	100	VS				0,88	50%	VS	50%	S
0,5	100	M	1	100	VS	1	100	VS	0,95	80	VS	0,9	60	VS	0,86	45%	VS	55%	S
0,5	100	M	1	100	VS	1	100	VS	0,95	80	VS	0,75	100	S	0,84	34%	VS	66%	S
0,5	100	M	1	100	VS	1	100	VS	0,8	80	S	0,9	60	VS	0,84	35%	VS	65%	S
0,5	100	M	1	100	VS	0,5	100	M	0,95	80	VS	0,9	60	VS	0,75	0%	VS	100	S
0,5	100	M	0,75	100	S	1	100	VS	0,95	80	VS	0,9	60	VS	0,81	23%	VS	77%	S
0,5	100	M	0,75	100	S	0,5	100	M	0,95	80	VS	0,9	60	VS	0,69	77%	S	23%	M
0,5	100	M	0,75	100	S	1	100	VS	0,8	80	S	0,9	60	VS	0,78	12%	VS	88%	S
0,5	100	M	0,75	100	S	1	100	VS	0,95	80	VS	0,75	100	S	0,78	13%	VS	87%	S
0,5	100	M	1	100	VS	0,5	100	M	0,8	80	S	0,9	60	VS	0,72	89%	S	11%	M
0,5	100	M	1	100	VS	0,5	100	M	0,95	80	VS	0,75	100	S	0,73	93%	S	8%	M
0,5	100	M	1	100	VS	1	100	VS	0,8	80	S	0,75	100	S	0,81	24%	VS	76%	S
0,5	100	M	0,75	100	S	0,5	100	M	0,8	80	S	0,9	60	VS	0,67	66%	S	34%	M
0,5	100	M	0,75	100	S	0,5	100	M	0,95	80	VS	0,75	100	S	0,68	72%	S	28%	M
0,5	100	M	1	100	VS	0,5	100	M	0,8	80	S	0,75	100	S	0,71	83%	S	18%	M
0,5	100	M	0,75	100	S	1	100	VS	0,8	80	S	0,75	100	S	0,76	3%	VS	97%	S
0,5	100	M	0,75	100	S	0,5	100	M	0,8	80	S	0,75	100	S	0,65	62%	S	38%	M
0,5	100	M	1	100	VS	1	100	VS	0,95	80	VS	0	100	U	0,68	72%	S	28%	M
0,5	100	M	0,75	100	S	1	100	VS	0,95	80	VS	0	100	U	0,63	51%	S	49%	M
0,5	100	M	1	100	VS	0,5	100	M	0,95	80	VS	0	100	U	0,58	30%	S	70%	M
0,5	100	M	1	100	VS	1	100	VS	0,8	80	S	0	100	U	0,65	62%	S	38%	M
0,5	100	M	0,75	100	S	0,5	100	M	0,95	80	VS	0	100	U	0,52	9%	S	91%	M
0,5	100	M	1	100	VS	0,5	100	M	0,8	80	S	0	100	U	0,55	20%	S	80%	M
0,5	100	M	0,75	100	S	1	100	VS	0,8	80	S	0	100	U	0,60	41%	S	59%	M
0,5	100	M	0,75	100	S	0,5	100	M	0,8	80	S	0	100	U	0,50	0%	S	100%	M
0,87	52	S	1	100	VS	1	100	VS	1	100	VS				0,98	92%	VS	8%	S
0,87	52	S	1	100	VS	1	100	VS	0,95	80	VS	0,9	60	VS	0,96	83%	VS	17%	S
0,87	52	S	1	100	VS	1	100	VS	0,95	80	VS	0,75	100	S	0,92	67%	VS	33%	S
0,87	52	S	1	100	VS	1	100	VS	0,8	80	S	0,9	60	VS	0,93	71%	VS	29%	S
0,87	52	S	1	100	VS	0,5	100	M	0,95	80	VS	0,9	60	VS	0,83	32%	VS	68%	S
0,87	52	S	0,75	100	S	1	100	VS	0,95	80	VS	0,9	60	VS	0,89	57%	VS	43%	S
0,87	52	S	0,75	100	S	0,5	100	M	0,95	80	VS	0,9	60	VS	0,77	6%	VS	94%	S
0,87	52	S	0,75	100	S	1	100	VS	0,8	80	S	0,9	60	VS	0,86	45%	VS	55%	S

Table C.3 (Cont.)

x	μ(x)	VL	x	μ(x)	VL	x	μ(x)	VL	x	μ(x)	VL	x	μ(x)	VL	Cent. of Area	Membership Degrees (Total %100)			
0,87	52	S	0,75	100	S	1	100	VS	0,95	80	VS	0,75	100	S	0,86	44%	VS	56%	S
0,87	52	S	1	100	VS	0,5	100	M	0,8	80	S	0,9	60	VS	0,80	20%	VS	80%	S
0,87	52	S	1	100	VS	0,5	100	M	0,95	80	VS	0,75	100	S	0,80	21%	VS	79%	S
0,87	52	S	1	100	VS	1	100	VS	0,8	80	S	0,75	100	S	0,89	56%	VS	44%	S
0,87	52	S	0,75	100	S	0,5	100	M	0,8	80	S	0,9	60	VS	0,73	94%	S	6%	M
0,87	52	S	0,75	100	S	0,5	100	M	0,95	80	VS	0,75	100	S	0,74	97%	S	3%	M
0,87	52	S	1	100	VS	0,5	100	M	0,8	80	S	0,75	100	S	0,77	9%	VS	91%	S
0,87	52	S	0,75	100	S	1	100	VS	0,8	80	S	0,75	100	S	0,83	33%	VS	67%	S
0,87	52	S	0,75	100	S	0,5	100	M	0,8	80	S	0,75	100	S	0,72	86%	S	14%	M
0,87	52	S	1	100	VS	1	100	VS	0,95	80	VS	0	100	U	0,74	97%	S	3%	M
0,87	52	S	0,75	100	S	1	100	VS	0,95	80	VS	0	100	U	0,69	74%	S	26%	M
0,87	52	S	1	100	VS	0,5	100	M	0,95	80	VS	0	100	U	0,63	51%	S	49%	M
0,87	52	S	1	100	VS	1	100	VS	0,8	80	S	0	100	U	0,72	86%	S	14%	M
0,87	52	S	0,75	100	S	0,5	100	M	0,95	80	VS	0	100	U	0,57	28%	S	72%	M
0,87	52	S	1	100	VS	0,5	100	M	0,8	80	S	0	100	U	0,60	40%	S	60%	M
0,87	52	S	0,75	100	S	1	100	VS	0,8	80	S	0	100	U	0,66	63%	S	37%	M
0,87	52	S	0,75	100	S	0,5	100	M	0,8	80	S	0	100	U	0,54	17%	S	83%	M
1	100	VS	1	100	VS	1	100	VS	1	100	VS				1,00	100	VS	0%	S
1	100	VS	1	100	VS	1	100	VS	0,95	80	VS	0,9	60	VS	0,98	91%	VS	9%	S
1	100	VS	1	100	VS	1	100	VS	0,95	80	VS	0,75	100	S	0,94	76%	VS	24%	S
1	100	VS	1	100	VS	1	100	VS	0,8	80	S	0,9	60	VS	0,95	80%	VS	20%	S
1	100	VS	1	100	VS	0,5	100	M	0,95	80	VS	0,9	60	VS	0,86	45%	VS	55%	S
1	100	VS	0,75	100	S	1	100	VS	0,95	80	VS	0,9	60	VS	0,92	68%	VS	32%	S
1	100	VS	0,75	100	S	0,5	100	M	0,95	80	VS	0,9	60	VS	0,81	23%	VS	77%	S
1	100	VS	0,75	100	S	1	100	VS	0,8	80	S	0,9	60	VS	0,89	57%	VS	43%	S
1	100	VS	0,75	100	S	1	100	VS	0,95	80	VS	0,75	100	S	0,89	55%	VS	45%	S
1	100	VS	1	100	VS	0,5	100	M	0,8	80	S	0,9	60	VS	0,84	35%	VS	65%	S
1	100	VS	1	100	VS	0,5	100	M	0,95	80	VS	0,75	100	S	0,84	34%	VS	66%	S
1	100	VS	1	100	VS	1	100	VS	0,8	80	S	0,75	100	S	0,91	66%	VS	34%	S
1	100	VS	0,75	100	S	0,5	100	M	0,8	80	S	0,9	60	VS	0,78	12%	VS	88%	S
1	100	VS	0,75	100	S	0,5	100	M	0,95	80	VS	0,75	100	S	0,78	13%	VS	87%	S
1	100	VS	1	100	VS	0,5	100	M	0,8	80	S	0,75	100	S	0,81	24%	VS	76%	S
1	100	VS	0,75	100	S	1	100	VS	0,8	80	S	0,75	100	S	0,86	45%	VS	55%	S
1	100	VS	0,75	100	S	0,5	100	M	0,8	80	S	0,75	100	S	0,76	3%	VS	97%	S
1	100	VS	1	100	VS	1	100	VS	0,95	80	VS	0	100	U	0,78	13%	VS	87%	S
1	100	VS	0,75	100	S	1	100	VS	0,95	80	VS	0	100	U	0,73	93%	S	8%	M
1	100	VS	1	100	VS	0,5	100	M	0,95	80	VS	0	100	U	0,68	72%	S	28%	M
1	100	VS	1	100	VS	1	100	VS	0,8	80	S	0	100	U	0,76	3%	VS	97%	S
1	100	VS	0,75	100	S	0,5	100	M	0,95	80	VS	0	100	U	0,63	0%	S	100	M

Table C.3 (Cont.)

1	100	VS	1	100	VS	0,5	100	M	0,8	80	S	0	100	U	0,65	62%	S	38%	M
1	100	VS	0,75	100	S	1	100	VS	0,8	80	S	0	100	U	0,71	83%	S	18%	M
1	100	VS	0,75	100	S	0,5	100	M	0,8	80	S	0	100	U	0,60	41%	S	59%	M

Table C.4 Ground floor escape route rules with center of area method

R	Route Material			Route Flow			Route Equipment			Means of Egress			Route Dimension			Escape Route Vulnerability Result				
	x	μ(x)	VL	x	μ(x)	VL	x	μ(x)	VL	x	μ(x)	VL	x	μ(x)	VL	Cent. of Area	Membership Degrees			
1	1	100	VS	1	100	VS	1	100	VS	1	100	VS	1	100	VS	1,00	100%	VS	0%	S
2	0,5	100	M	0,75	100	S	1	100	VS	1	100	VS	1	100	VS	0,85	40%	VS	60%	S
3	0,5	100	M	1	100	VS	1	100	VS	1	100	VS	1	100	VS	0,90	60%	VS	40%	S
4	0,25	100	Q	1	100	VS	1	100	VS	1	100	VS	1	100	VS	0,85	40%	VS	60%	S
5	1	100	VS	1	100	VS	0,25	100	Q	1	100	VS	1	100	VS	0,85	40%	VS	60%	S
6	0,5	100	M	0,75	100	S	0,25	100	Q	1	100	VS	1	100	VS	0,70	80%	S	20%	M
7	0,5	100	M	1	100	VS	0,25	100	Q	1	100	VS	1	100	VS	0,75	100%	S	0%	M
8	0,25	100	Q	1	100	VS	0,25	100	Q	1	100	VS	1	100	VS	0,70	80%	S	20%	M
9	1	100	VS	1	100	VS	1	100	VS	0,75	100	S	1	100	VS	0,95	80%	VS	20%	S
10	0,5	100	M	0,75	100	S	1	100	VS	0,75	100	S	1	100	VS	0,80	20%	VS	80%	S
11	0,5	100	M	1	100	VS	1	100	VS	0,75	100	S	1	100	VS	0,85	40%	VS	60%	S
12	0,25	100	Q	1	100	VS	1	100	VS	0,75	100	S	1	100	VS	0,80	20%	VS	80%	S
13	1	100	VS	1	100	VS	0,25	100	Q	0,75	100	S	1	100	VS	0,80	20%	VS	80%	S
14	0,5	100	M	0,75	100	S	0,25	100	Q	0,75	100	S	1	100	VS	0,65	60%	S	40%	M
15	0,5	100	M	1	100	VS	0,25	100	Q	0,75	100	S	1	100	VS	0,70	80%	S	20%	M
16	0,25	100	Q	1	100	VS	0,25	100	Q	0,75	100	S	1	100	VS	0,65	60%	S	40%	M
17	1	100	VS	1	100	VS	1	100	VS	0	100	U	1	100	VS	0,80	20%	VS	80%	S
18	0,5	100	M	0,75	100	S	1	100	VS	0	100	U	1	100	VS	0,65	60%	S	40%	M
19	0,5	100	M	1	100	VS	1	100	VS	0	100	U	1	100	VS	0,70	80%	S	20%	M
20	0,25	100	Q	1	100	VS	1	100	VS	0	100	U	1	100	VS	0,65	60%	S	40%	M
21	1	100	VS	1	100	VS	0,25	100	Q	0	100	U	1	100	VS	0,65	60%	S	40%	M
22	0,5	100	M	0,75	100	S	0,25	100	Q	0	100	U	1	100	VS	0,50	0%	S	100%	M
23	0,5	100	M	1	100	VS	0,25	100	Q	0	100	U	1	100	VS	0,55	20%	S	80%	M
24	0,25	100	Q	1	100	VS	0,25	100	Q	0	100	U	1	100	VS	0,50	0%	S	100%	M
25	1	100	VS	1	100	VS	1	100	VS	1	100	VS	0	100	U	0,80	20%	VS	80%	S

Table C.4 (Cont.)

R	x	μ(x)	VL	x	μ(x)	VL	x	μ(x)	VL	x	μ(x)	VL	x	μ(x)	VL	Cent. of Area	Membership Degrees			
26	0,5	100	M	0,75	100	S	1	100	VS	1	100	VS	0	100	U	0,65	60%	S	40%	M
27	0,5	100	M	1	100	VS	1	100	VS	1	100	VS	0	100	U	0,70	80%	S	20%	M
28	0,25	100	Q	1	100	VS	1	100	VS	1	100	VS	0	100	U	0,65	60%	S	40%	M
29	1	100	VS	1	100	VS	0,25	100	Q	1	100	VS	0	100	U	0,65	60%	S	40%	M
30	0,5	100	M	0,75	100	S	0,25	100	Q	1	100	VS	0	100	U	0,50	0%	S	100%	M
31	0,5	100	M	1	100	VS	0,25	100	Q	1	100	VS	0	100	U	0,55	20%	S	80%	M
32	0,25	100	Q	1	100	VS	0,25	100	Q	1	100	VS	0	100	U	0,50	0%	S	100%	M
33	1	100	VS	1	100	VS	1	100	VS	0,75	100	S	0	100	U	0,75	100%	S	0%	M
34	0,5	100	M	0,75	100	S	1	100	VS	0,75	100	S	0	100	U	0,60	40%	S	60%	M
35	0,5	100	M	1	100	VS	1	100	VS	0,75	100	S	0	100	U	0,65	60%	S	40%	M
36	0,25	100	Q	1	100	VS	1	100	VS	0,75	100	S	0	100	U	0,60	40%	S	60%	M
37	1	100	VS	1	100	VS	0,25	100	Q	0,75	100	S	0	100	U	0,60	40%	S	60%	M
38	0,5	100	M	0,75	100	S	0,25	100	Q	0,75	100	S	0	100	U	0,45	80%	M	20%	Q
39	0,5	100	M	1	100	VS	0,25	100	Q	0,75	100	S	0	100	U	0,50	0%	S	100%	M
40	0,25	100	Q	1	100	VS	0,25	100	Q	0,75	100	S	0	100	U	0,45	80%	M	20%	Q
41	1	100	VS	1	100	VS	1	100	VS	0	100	U	0	100	U	0,60	40%	S	60%	M
42	0,5	100	M	0,75	100	S	1	100	VS	0	100	U	0	100	U	0,45	80%	M	20%	Q
43	0,5	100	M	1	100	VS	1	100	VS	0	100	U	0	100	U	0,50	0%	S	100%	M
44	0,25	100	Q	1	100	VS	1	100	VS	0	100	U	0	100	U	0,45	80%	M	20%	Q
45	1	100	VS	1	100	VS	0,25	100	Q	0	100	U	0	100	U	0,45	80%	M	20%	Q
46	0,5	100	M	0,75	100	S	0,25	100	Q	0	100	U	0	100	U	0,30	20%	M	80%	Q
47	0,5	100	M	1	100	VS	0,25	100	Q	0	100	U	0	100	U	0,35	40%	M	60%	Q
48	0,25	100	Q	1	100	VS	0,25	100	Q	0	100	U	0	100	U	0,30	20%	M	80%	Q

APPENDIX D

The complete analysis of İzmir Opera House floors in terms of escape route finishing material, escape route flow, escape route equipment, means of escape availability and escape route distances and layout are represented in this section. Route cells and route axis are evaluated by using the structure in fuzzy-TECH software, and transferred to CAD program to for representation. The color codes used to represent vulnerability levels attained in the form of route cells for finishing material and route flow analysis, and in the form of route direction lines for route equipment, availability and alternative means of egress, and route distance and layout analysis (Table D.1)

Table D.1 Vulnerability level color codes

Vulnerability Levels	**Material Vulnerability**	**Color Code**
Unqualified	Easily Flammable	
Qualified	Flammable	
Medium	Limited Combustible	
Safe	Very Limited Combustible	
Very Safe	Noncombustible	

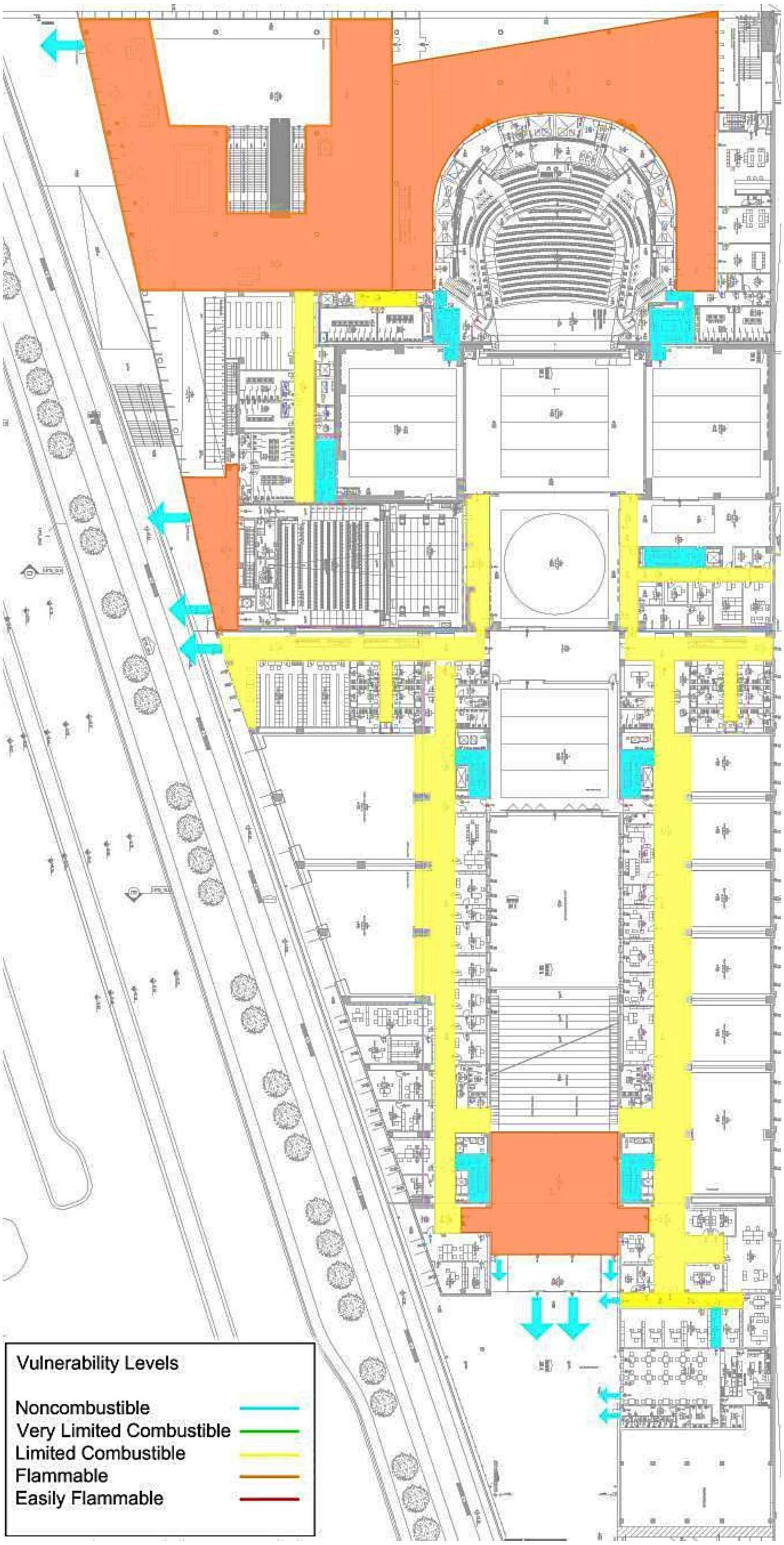

Figure D-1 First floor finishing material vulnerability (Scale ~ 1/1000)

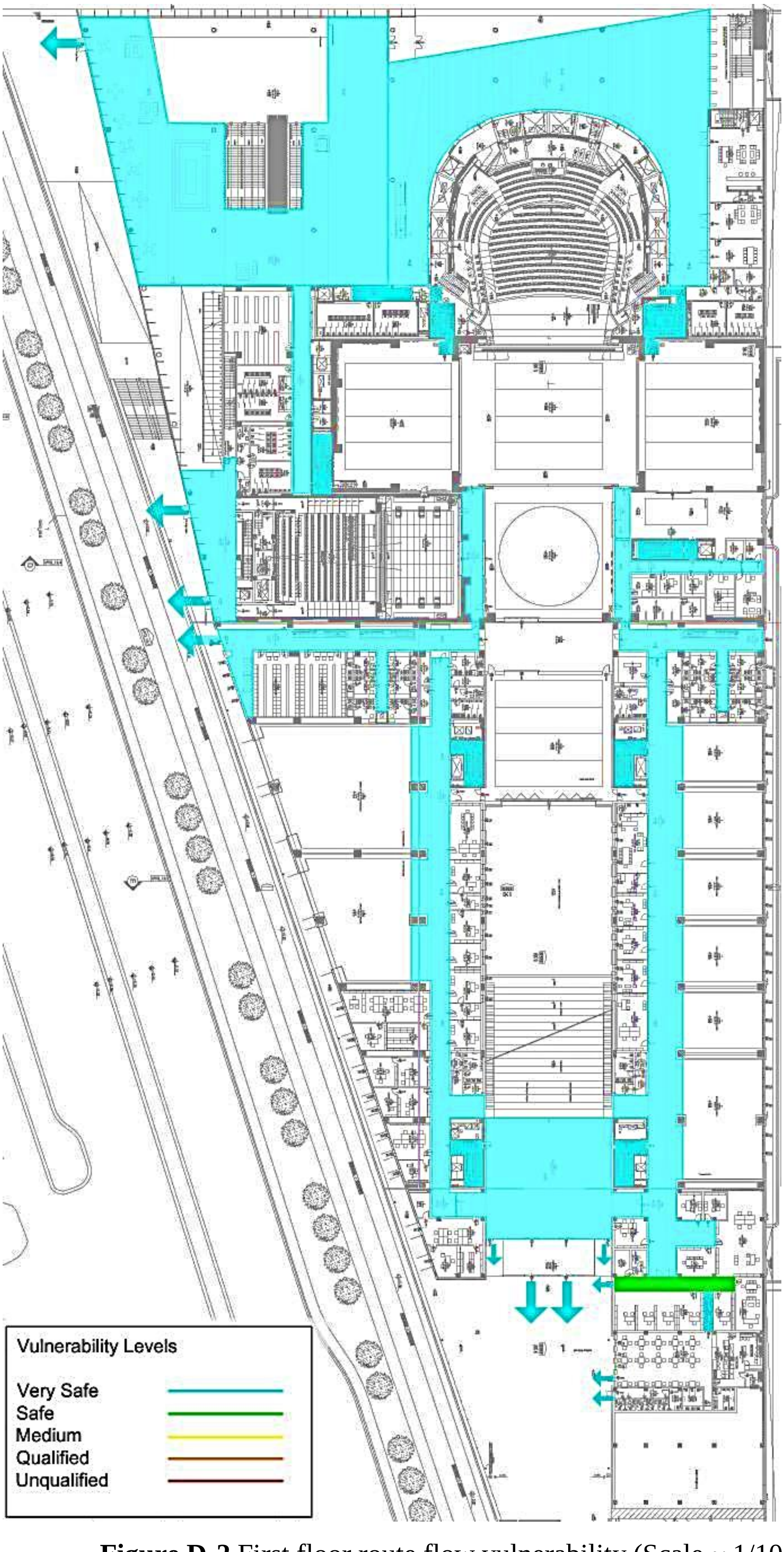

Figure D-2 First floor route flow vulnerability (Scale ~ 1/1000)

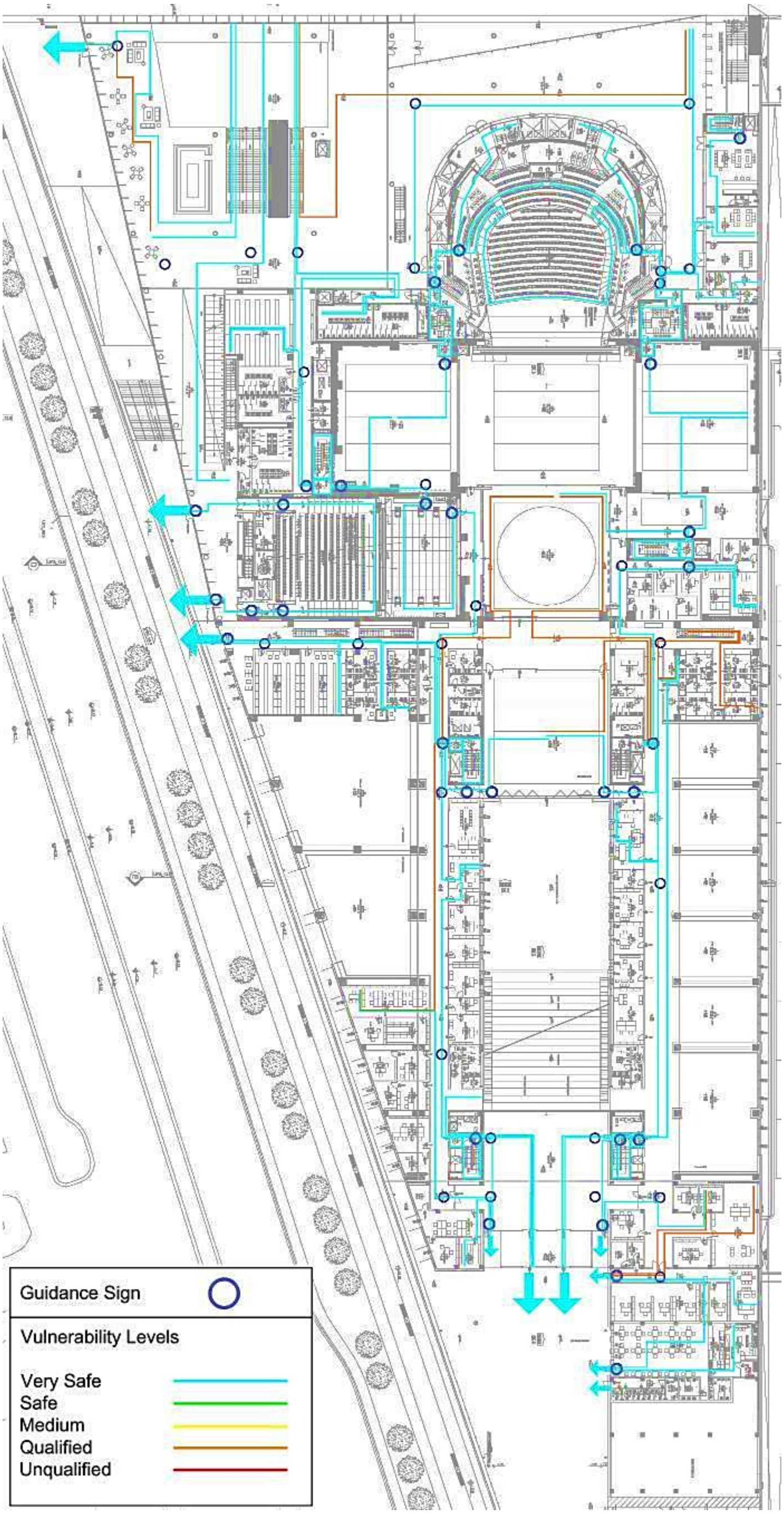

Figure D-3 First floor equipment vulnerability (Scale ~ 1/1000)

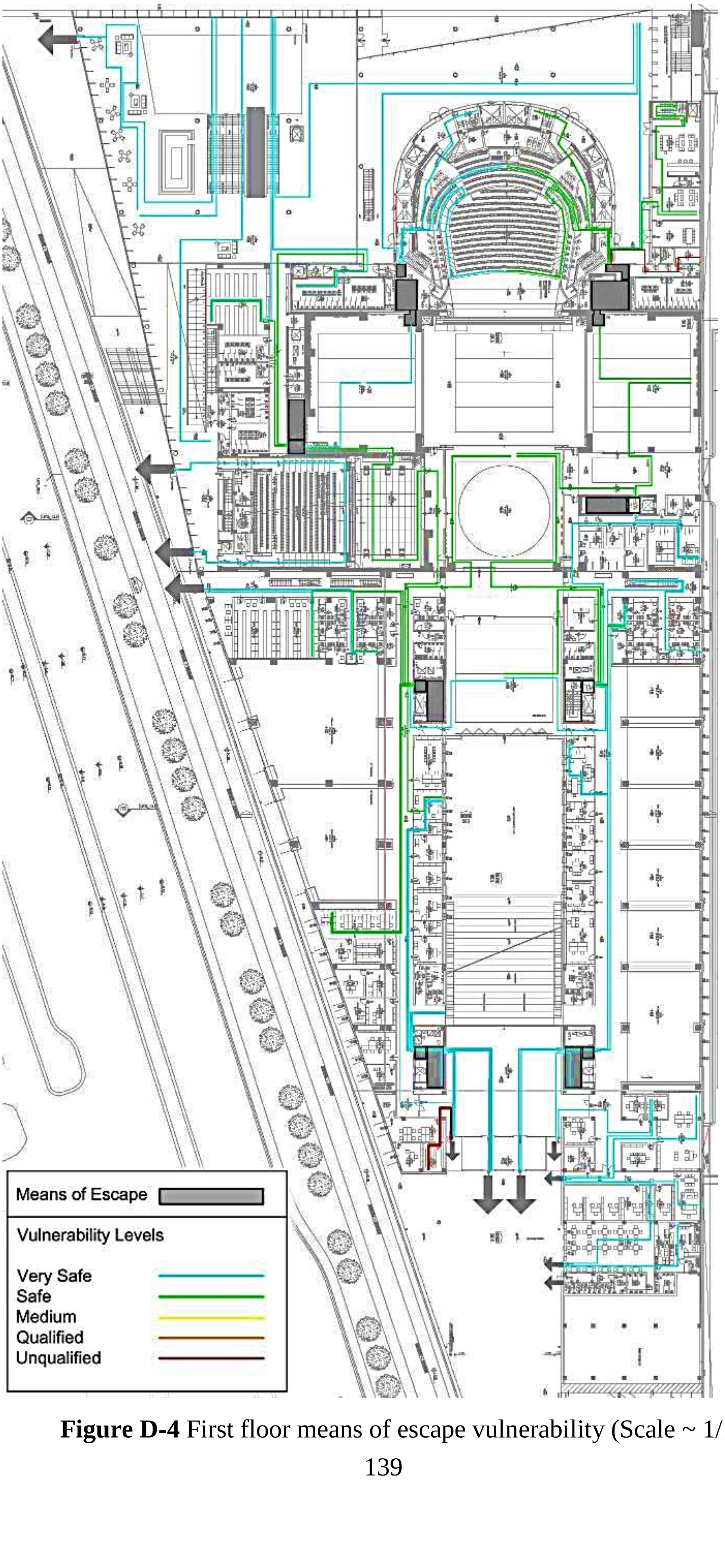

Figure D-4 First floor means of escape vulnerability (Scale ~ 1/1000)

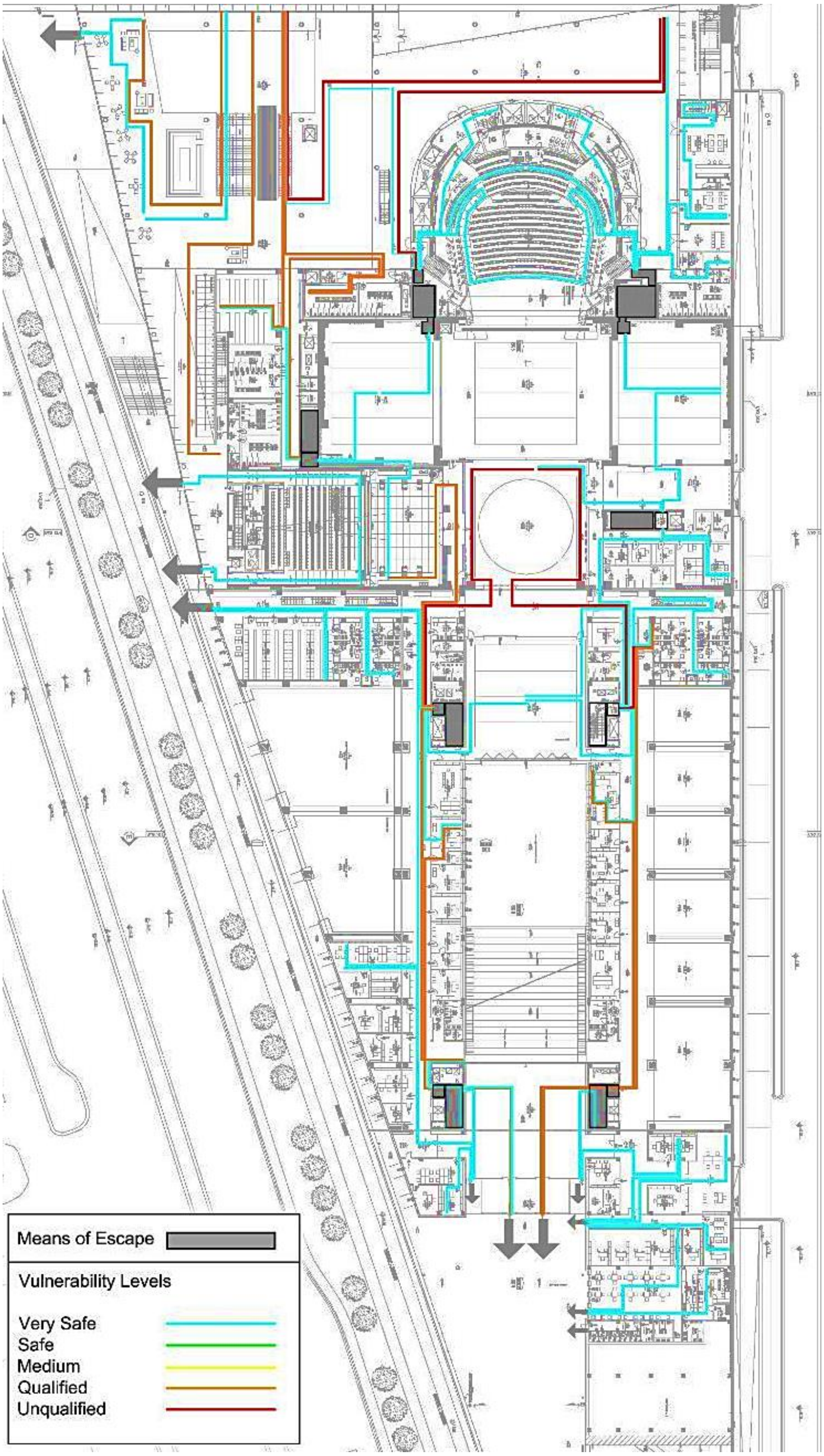

Figure D-5 First floor route distances and layout vulnerability (Scale ~ 1/1000)

Figure D-6 Second floor finishing material vulnerability (Scale ~ 1/1000)

Figure D-7 Second floor route flow vulnerability (Scale ~ 1/1000)

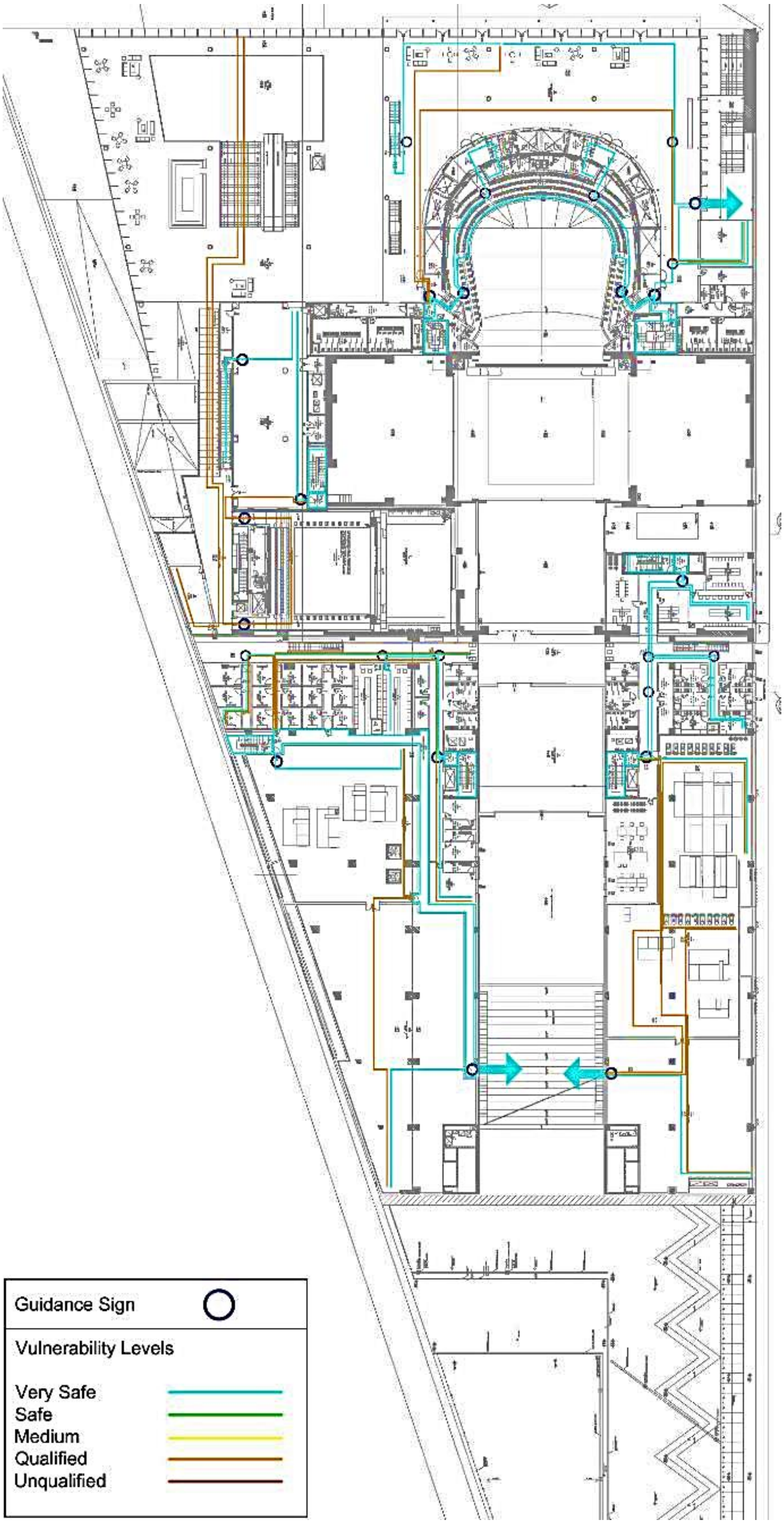

Figure D-8 Second floor route equipment vulnerability (Scale ~ 1/1000)

Figure D-9 Second floor means of escape vulnerability (Scale ~ 1/1000)

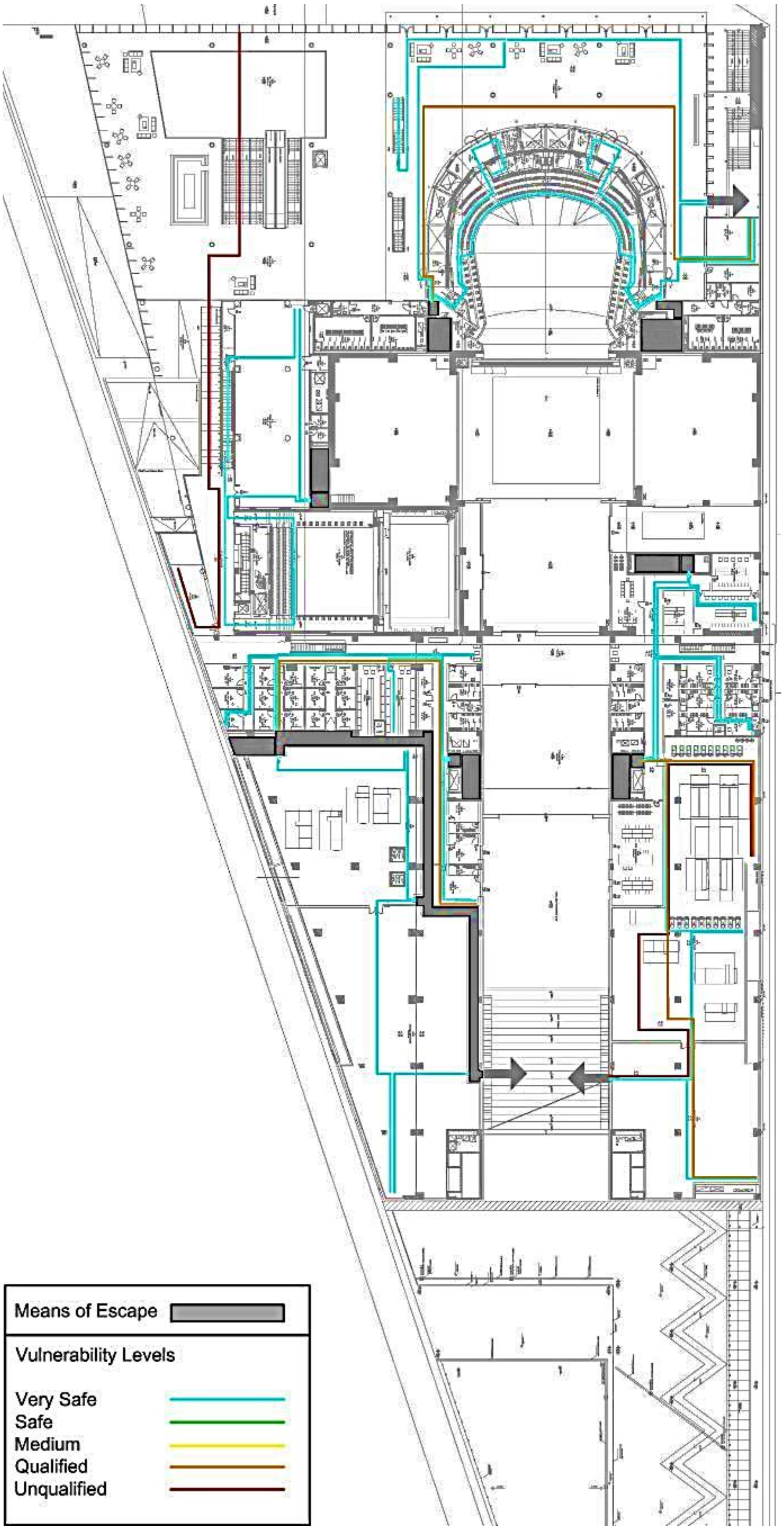

Figure D-10 Second floor distances and layout vulnerability (Scale ~ 1/1000)

Figure D-11 Third floor finishing material vulnerability (Scale ~ 1/1000)

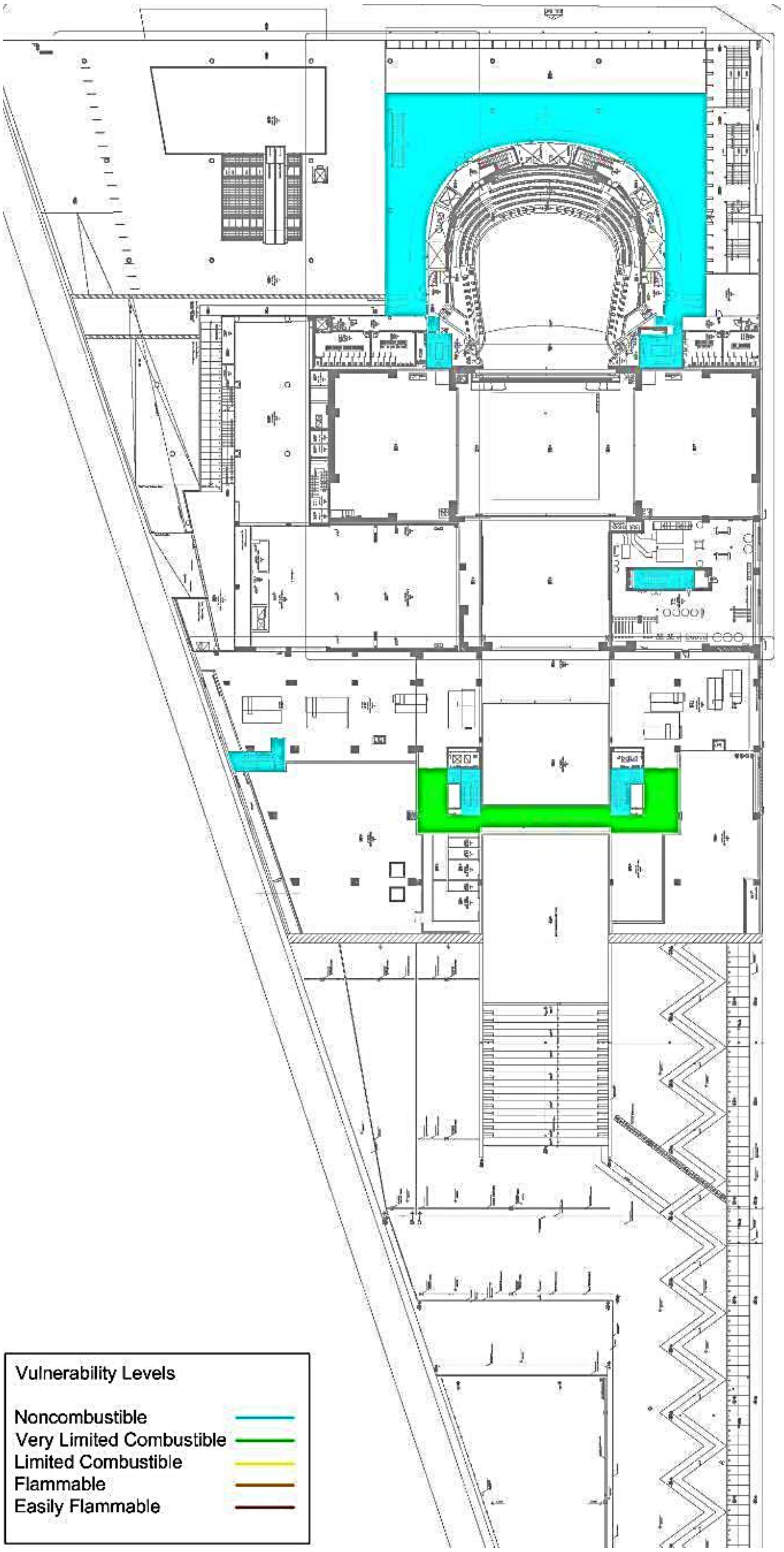

Figure D-12 Third floor escape route flow vulnerability (Scale ~ 1/1000)

Figure D-13 Third Floor escape route equipment vulnerability (Scale ~ 1/1000)

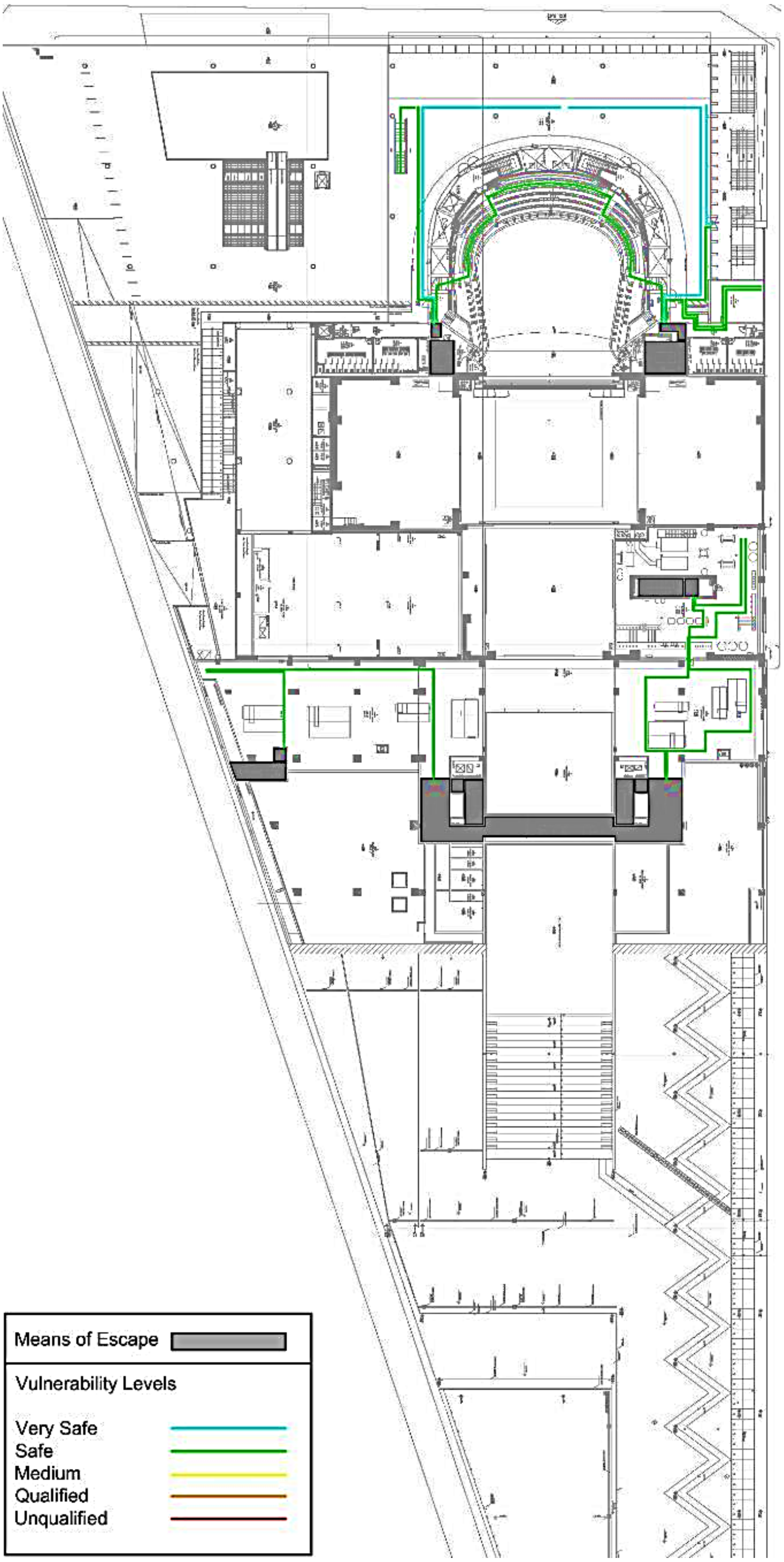

Figure D-14 Third floor means of escape vulnerability (Scale ~ 1/1000)

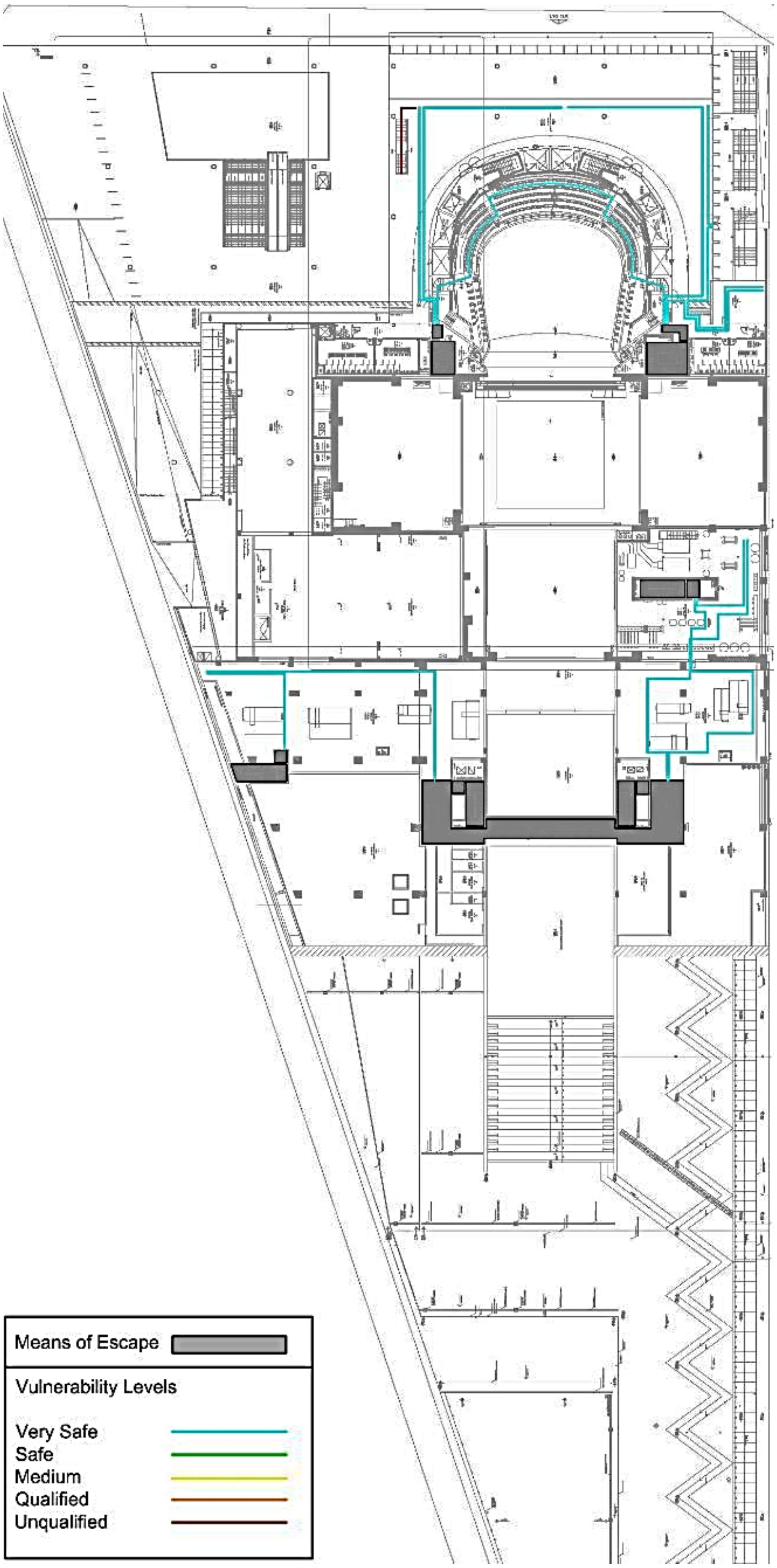

Figure D-15 Third floor distances and layout vulnerability (Scale ~ 1/1000)

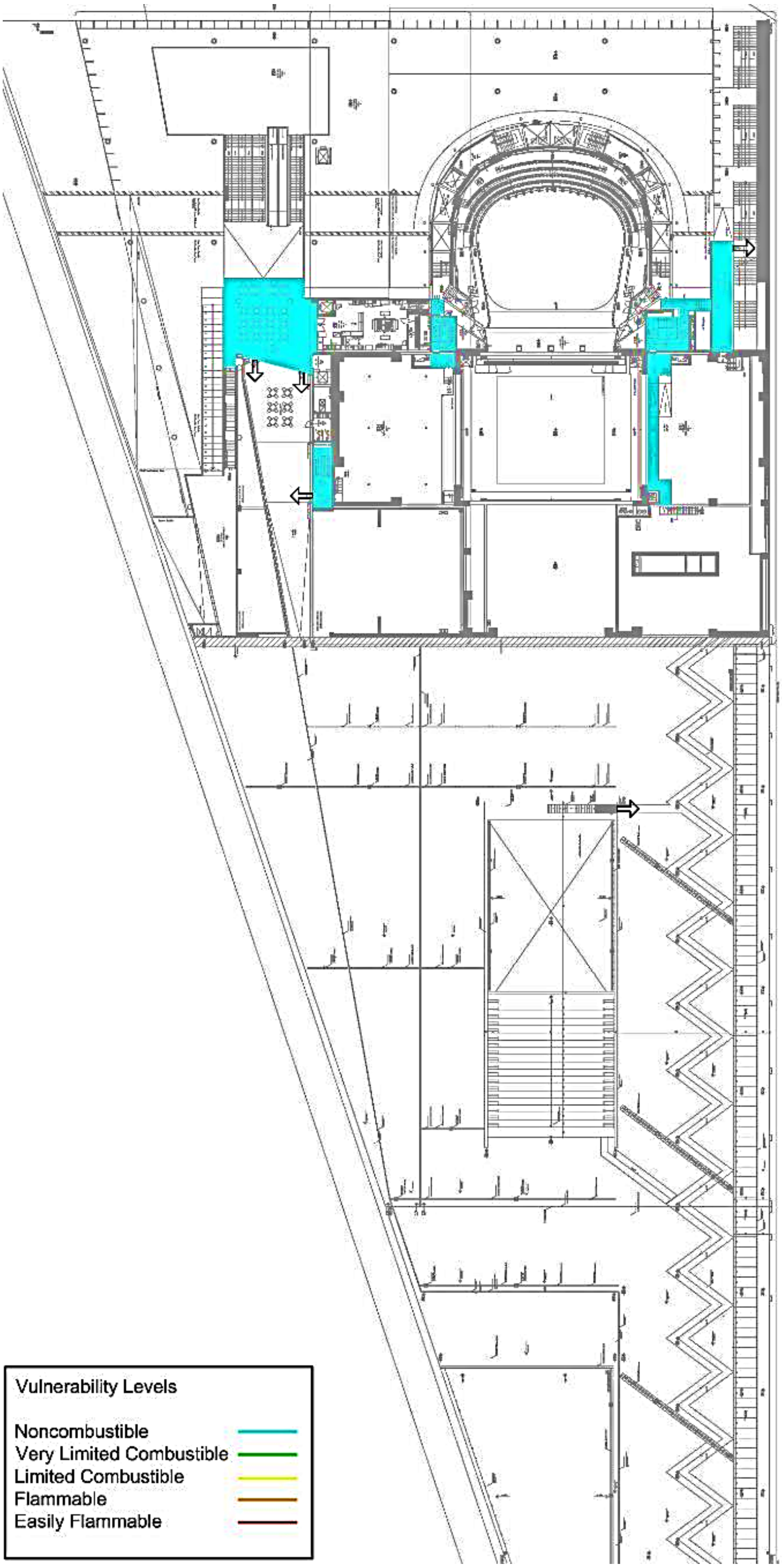

Figure D-16 Fourth floor finishing material vulnerability (Scale ~ 1/1000)

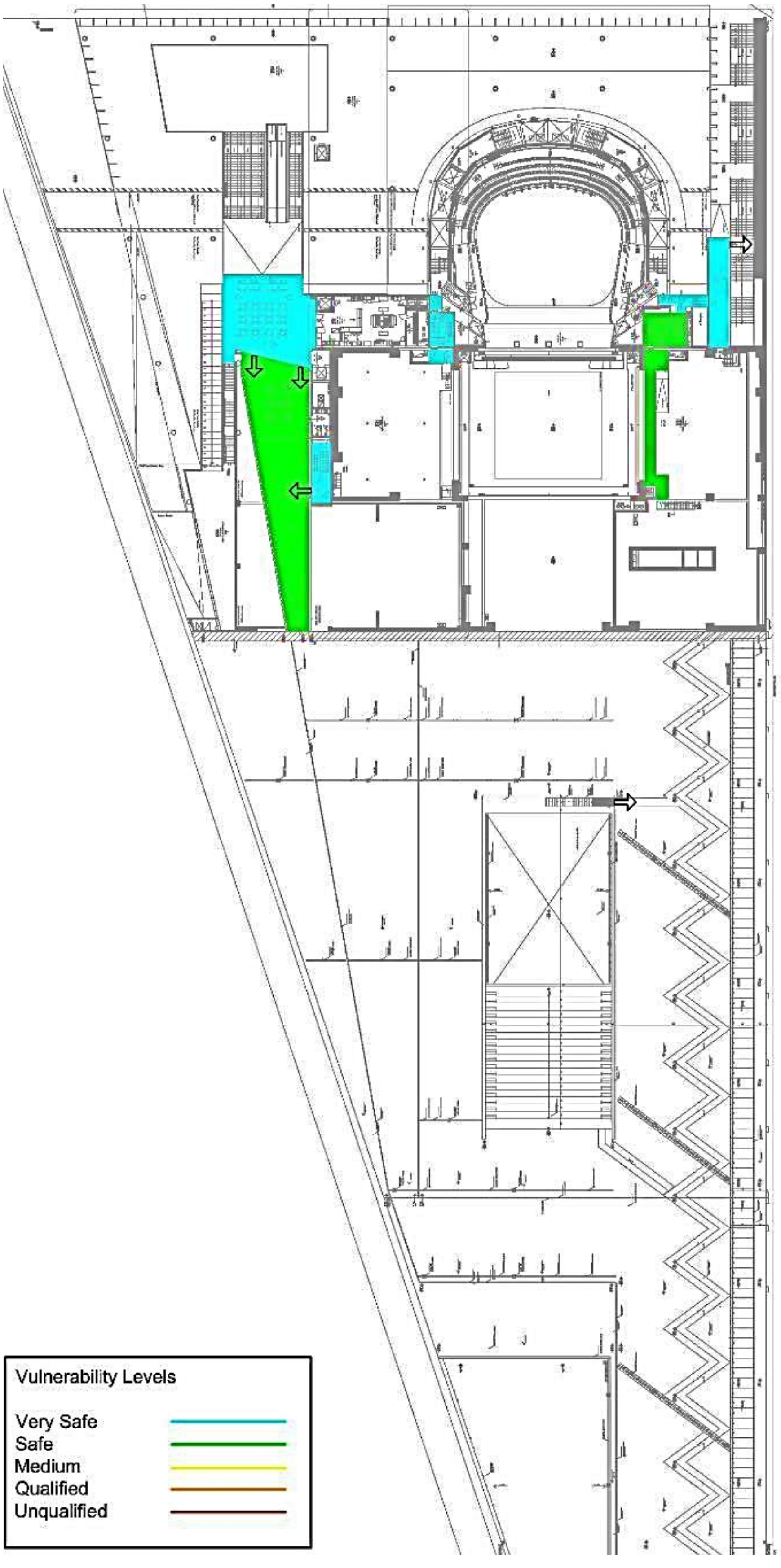

Figure D-17 Fourth floor escape route flow vulnerability (Scale ~ 1/1000)

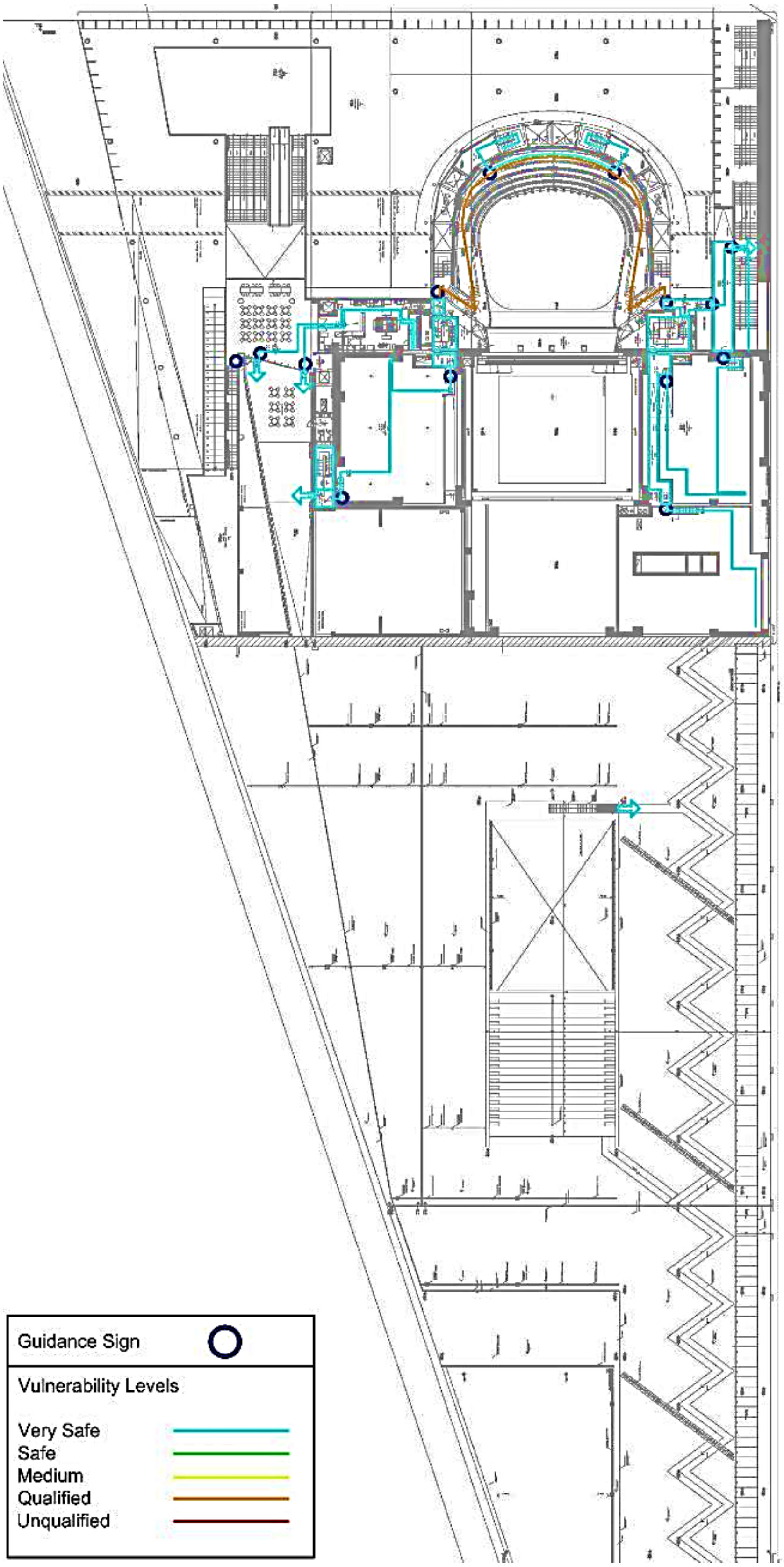

Figure D-18 Fourth floor escape route equipment vulnerability (Scale ~ 1/1000)

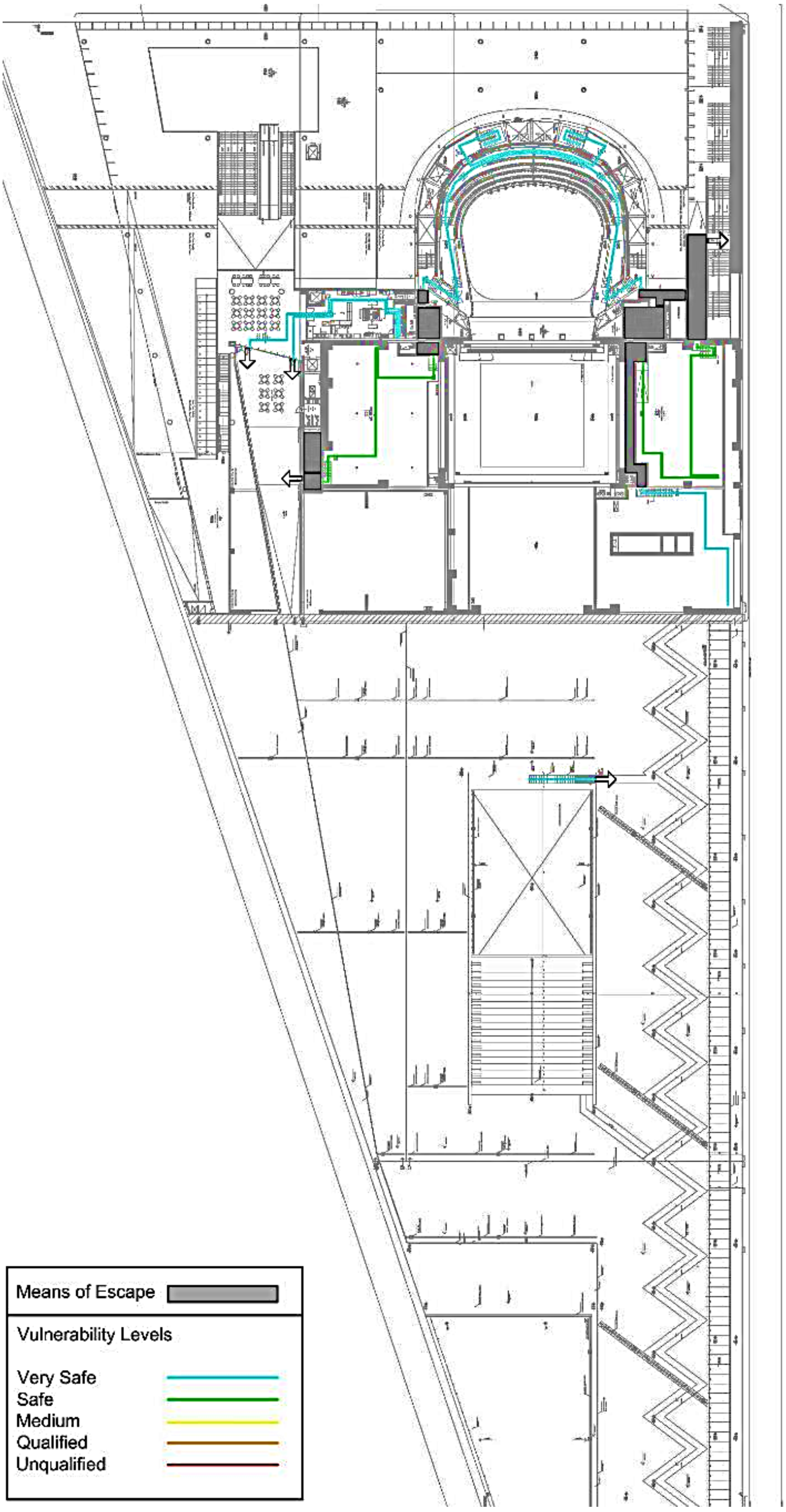

Figure D-19 Fourth floor means of escape vulnerability (Scale ~ 1/1000)

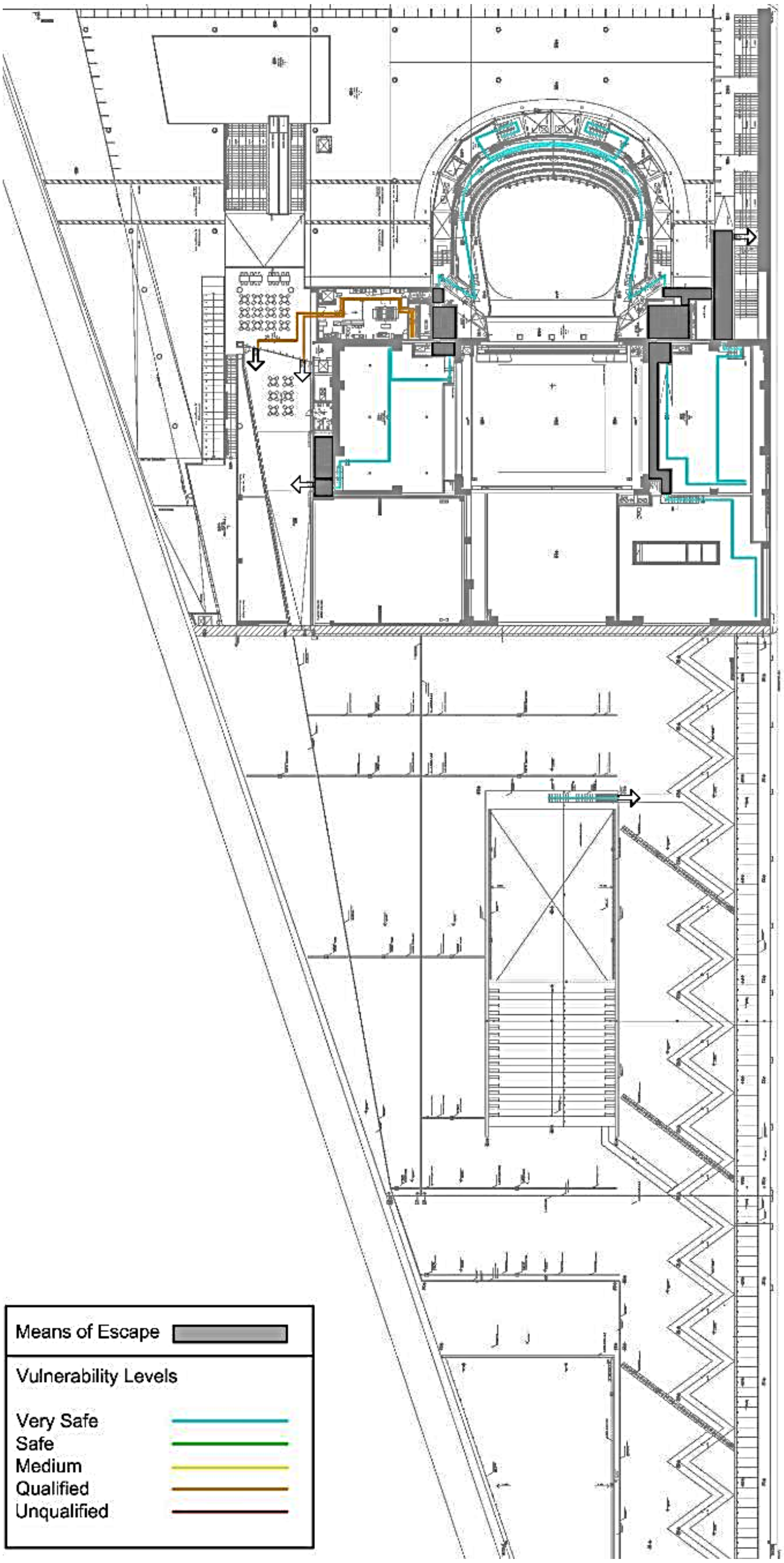

Figure D-20 Fourth floor distances and layout vulnerability (Scale ~ 1/1000)