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FIRE SAFETY IN BUILDINGS

Abstract: Contemporary Fire Safety Engineering is based on the application of scientific research and engineering principles, using calculations, measurements, empiricism and judgment. Simplified and often uniform solutions, which were formerly proposed, resulted in the univocal rules, focused on the simplest of solutions, which were then extrapolated to larger models, could have double negative effect: it isn't well known whether these extrapolations are still acceptable for the newest technical evolutions of buildings, materials and user domains and a large part of the actual research is not applied to new concepts, where they could possible bring about savings, without harming the required comfort and security level.

Fire Safety Engineering entails the application of design principles, regulation and an expert evaluation, based on a scientific concept of the fire phenomenon, thus resulting in: the saving of lives, the protection of goods and the protection of the environment and patrimony. The determination of risk, dangers and consequences of fire and the analytic evaluation of the optimal protection and prevention measurements is necessary to limit the consequences of a fire within certain determined limits.

Fire risk assessment is an assessment of the fire risks, or the levels of fire safety, that are provided to the occupants and property in a performance-based fire safety design.

Key words: fire safety, fire risk assessment

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1. INTRODUCTION

The practice of fire safety designs is changing in many countries. The change is from traditional practice that simply follows the prescriptive code requirements to those that are based on fire safety analysis to obtain the required level of fire safety for the occupants. The change is a result of many countries moving towards the more flexible performance-based codes, which allow flexibility in fire safety designs as long as the designs can provide the required level of fire safety to the occupants.

Fire risk assessment is an assessment of the fire risks, or the levels of fire safety, that are provided to the occupants and property in a performance-based fire safety design. Fire safety designs involve the use of fire protection measures to control fire growth and smoke spread and to expedite occupant evacuation and fire department response. None of these fire protection measures, however, is 100% effective. For example, sprinklers do not have a 100% reliability in controlling fires, nor do fire alarms have 100% reliability in getting occupants to leave immediately. As a result, certain levels of fire risks to the occupants and property are implied in each fire safety design. The assessment of these levels of fire risks is the subject of fire risk assessment.

If designers are to explicitly consider the levels of fire safety and protection in buildings designs, then there must be a fundamental change in the methods that are used to design buildings for fire safety and protection [1], [2]. In addition, there must be recognition that societal levels of fire safety and protection in buildings are the result of a large number of fire scenarios, multiple responses of building fire safety and protection subsystems to these fire scenarios and a multitudinous number of human behavior responses to these scenarios. A rigorous and systematic approach to the assessment of explicit levels of fire safety and protection requires a comprehensive risk analysis to be undertaken of building fire safety and protection systems [3]. Fundamentally, this requires explicit consideration of multiple fire scenarios, response of building fire safety systems and human behavioral responses [4].

Risk assessment models are needed to identify those combinations of building subsystems which provide the requisite level of safety in a cost-effective manner. Deterministic fire-engineering design methods cannot be used for that purpose because it is necessary to estimate both the likelihood of the possible fire scenarios and their consequences, and then combine the results in order to evaluate the likely cost and safety level. Risk analysis is defined as the process of estimating magnitudes of consequences and probabilities of the adverse effects resulting from fire in a building. It provides rational criteria for the choice of remedial actions, including explicit considerations of uncertainty. It is obviously the preferred base for decision making.

Fire safety objectives and basic characteristics of traditional fire risk assessment methods (including case study) and fire risk assessment methods based on a fundamental approach are discussed in these paper.

2. FIRE SAFETY OBJECTIVES

The primary goal of fire protection is to limit, to acceptable levels, the probability of death, injury, and property loss in an unwanted fire.

The life safety has been given more emphasis by recent national codes than property protection [5]. Many codes consider that fire damage to a building is the problem of the building owner or insurer, with the code provisions only intended to provide life safety and protection to the property of other people. Automatic sprinkler systems, as many other measures, provide both life safety and property protection. It is important for the owner of the building to understand the distinction between life safety and property safety, because there is a possibility for fire damage extension to the building and contents, even if the building complies with minimum code requirements.

Ensuring the safe escape is the most important goal in providing life safety. First of all, it is necessary to alert people to the fire, provide suitable escape paths, and make them safe of fire and smoke, so people can not be injured while escaping through those paths to a safe place. It is also necessary to provide safety for people unable to escape, as well as people in adjacent buildings. There are also provisions to be made for fire-fighters who enter the building for rescue or fire control purposes.

Property protection includes protecting the structure and fabric of building, and the moveable contents. Protection also must apply to neighbouring buildings. If there is a possibility of irreplaceable loss of heritage values or major damage to main infrastructures, it is necessary to apply an extra level of fire protection.

Environmental protection is an additional objective, formulated in a way to limit environmental damage in the event of major fire. Emissions of gaseous pollutants in smoke and liquid pollution in fire-fighting run-off water can both have major environmental impacts.

All of above listed objectives can be met if any fire is extinguished before growing large, which depends on the reliability of predicted fire protection measures.

3. TRADITIONAL FIRE RISK ASSESSMENT METHODS

Fire risk assessment is the assessment of the risks to the people and property as a result of unwanted fires. A simple risk assessment considers the probability of the occurrence of a certain unwanted fire scenario and the consequence of that scenario. A comprehensive risk assessment considers all probable unwanted fire scenarios and their consequences.

If the assessment of the expected risk to life to the occupants in a building is considered as a result of one single fire scenario, the expected risk to life can be expressed by the following equation:

$$\text{Expected risk to life} = P \cdot C, \quad (1)$$

where P is the probability of a certain fire scenario and C is the expected number of deaths as a consequence of that fire scenario. If the probability of a certain fire scenario occurring in a building is once every five years, then P = 0.2 fires per year. If the consequence of that fire scenario is two deaths, then C = 2 deaths per fire. From Equation (1), the expected risk to life as a result of that fire scenario is equal to 0.4 deaths per year, or 2 deaths every 5 years.

Because fires can occur in a building in more ways than one, the risk to the occupants is usually assessed based on all probable fire scenarios. A comprehensive fire risk assessment can be expressed by the following equation:

$$\text{Expected risk to life} = \Sigma i\ (Pi \cdot Ci), \quad (2)$$

where Σi represents the summation of all probable fire scenarios, Pi is the probability of one fire scenario (i), and Ci is the expected number of deaths as a consequence of that fire scenario (i).

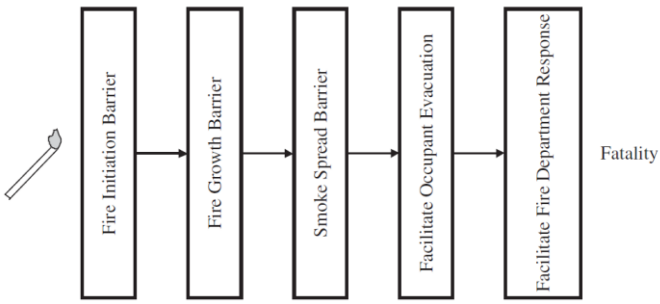

Figure 1 –Five major fire barriers between fire source and fatality [6]

A fire scenario is a set of fire events that are linked together by the success or failure of fire protection measures. There are basically five major hazardous events that must occur before a fire can cause harm to the occupants (Fig. 1). They are: (1) fire ignition, (2) fire growth, (3) smoke spread, (4) failure of occupants to evacuate and (5) failure of fire department to respond. Each of these five hazardous events can be prevented by fire protection measures, or barriers.

The probability of a fire scenario that can lead to harm to the occupants depends on the combined probability of failure of all fire protection measures, or barriers. The lower the individual probabilities of failure of fire protection measures are, the lower is the probability of the fire scenario that can lead to harm to the occupants. Fire risk assessment concerns not only the number of fire protection measures that are put in place, but also how reliable and effective these fire protection measures are.

The risk to the occupants depends not only on the probability of the fire scenario that can lead to harm to the occupants, but also the level of harm to the occupants as a result of the consequence of that scenario. The consequence of a fire scenario can be assessed by using time-dependent modeling of fire and smoke spread, occupant evacuation and fire department response.

3.1. Fire risk assessment based on past fire experience

Fire risk assessments can be performed based on past fire experiences. Such fire risk assessments, however, are valid only if the situation in the past and that to be assessed at the present are the same. This requires that the controlling parameters that govern the fire scenarios in both situations are the same. Often, they are not the same because of changes over time such as the introduction of new furnishing materials or new fire protection systems. Controlling parameters include fire protection systems, such as sprinklers that control the development of a fire or alarm systems that expedite the evacuation of the occupants. Controlling parameters also include physical parameters, such as the type and amount of combustibles that govern the development of a fire or the number and length of the egress routes that govern the required evacuation time. If these controlling parameters are not the same, then a fire risk assessment based on the past experience can be quite wrong.

Fire statistics e.g. fire loss information from fire incident reports, stored in databases that can be extracted for various statistical analyses (access to databases in our country requires special permission from Ministry of Interior), could provide valuable information for risk assessment. For example, data can be extracted for certain type of occupancy, such as residential buildings. Within that occupancy type, further breakdown of the information can be obtained. For example, fire loss information can be obtained based on the area of fire origin, or source of ignition, or object first ignited and so on. Fire loss information can also be obtained based on the presence or absence of fire protection systems, such as smoke alarms or sprinklers. Following this approach, one can extract statistical information for a specific set of controlling parameters. For example, one can extract statistical information on fires originating in the kitchen in apartment building, with or without alarms or any other preventive measure. This allows the results to be applicable to situations with similar controlling parameters.

3.2. Qualitative fire risk assessment

Qualitative fire risk assessment is based on subjective judgment of not only the probability of a fire hazard or fire scenario occurring, but also the consequence of such a fire hazard or fire scenario. The term fire hazard generally describes any fire situation which is dangerous and which may have potentially serious consequences; whereas the term fire scenario was defined previously as a sequence of fire events that are linked together by whether the fire protection measures succeeded or failed. Qualitative fire risk assessment is usually employed in order to obtain a quick assessment of the potential fire risks in a building and to consider various fire protection measures to minimize these risks.

In qualitative fire risk assessments, there are no numerical values for the probability or consequence that can be used to obtain the product. Instead, the product is assessed using a simple two-dimensional risk matrix (Tab. 1), with one axis representing the level of the probability of occurrence and the other representing the severity of the consequence.

Table 1- Risk matrix diagram, after [7]

PROBABILITY	Anticipated	Negligible Risk	Moderate Risk	High Risk	High Risk
	Unlikely	Negligible Risk	Low Risk	Moderate Risk	High Risk
	Extremely unlikely	Negligible Risk	Low Risk	Low Risk	Moderate Risk
	Beyond extremely unlikely	Negligible Risk	Negligible Risk	Negligible Risk	Negligible Risk
		Negligible	Low	Moderate	High
	CONSEQUENCE				

In general qualitative fire risk assessments may be performed in two ways: (1) a checklist is used to go through the potential fire hazards, the fire protection measures to be considered and the subjective assessment of their fire risks; (2) an event tree is used to go through the potential fire scenarios and the fire protection measures to be considered and the subjective assessment of their fire risks. The outcome in both cases, is a list of potential fire hazards or fire scenarios, the fire protection measures to be considered and their assessed fire risks. In this context, assessed risks are described in qualitative rather than quantitative terms.

The checklist method employs the creation of a checklist of potential fire hazards and the consideration of fire protection measures, either in place or to be added, to arrive at a subjective judgment of the fire risks. The creation of a checklist of potential fire hazards allows a systematic check of potential fire hazards that are in place. The listing of fire protection measures alongside with the potential fire hazards allows a quick check of any safety deficiencies and any need to provide additional fire protection measures to minimize the risk. The checklist method, therefore, is an enumeration of potential fire hazards, fire protection measures, either in place or to be added, and the subjective judgment of the residual fire risks. It is used to identify any deficiencies and any corrective measures needed to minimize the fire risks. It does not include, however, the consideration of the logical development of fire events, which can be discussed using an event tree.

An event tree is another way to identify potential fire hazards, judge their probabilities and consequences and arrive at risk ratings. Different from the checklist method, an event tree shows more than a list of potential fire hazards and fire protection measures for the judgment of the probabilities, consequences and eventually the risk ratings. The event-tree method constructs an event-tree subsequent to the initiation of a fire hazard, which provides more information for the judgment of probability, consequence and risk rating.

3.3. Quantitative fire risk assessment

Quantitative fire risk assessment is an assessment involving numerical quantifications of both the probability of occurrence of a fire hazard or fire scenario, and the consequence of that fire hazard or scenario. The multiplication of the numerical values of probability and consequence gives each fire scenario a numerical fire risk value. The cumulative sum of the risk values from all probable fire scenarios gives an overall fire risk value. The assessed risk can be risk to life, loss of property and so on. Quantitative fire risk assessment allows a numerical comparison of the overall fire risk values of different fire safety designs in a building. It also allows the assessment of equivalency by comparing the fire risk of an alternative fire safety design with that of a code-compliant design.

There are two ways in general of conducting systematic quantitative fire risk assessments: (1) using a checklist to go through a list of potential fire hazards and the quantitative assessment of their fire risks; (2) using an event tree to go through a set of the potential fire scenarios and the quantitative assessment of their fire risks. Within the checklist method, there are specific methods that have been developed by various organizations for their own use. The risk indexing method uses well-defined schedules or tables to rate the risks.

In both the checklist and event-tree methods, the outcome is a list of potential fire hazards or fire scenarios, and their assessed fire risk values. Summation of all these individual risk values gives an overall fire risk value in a building that can be used for comparisons with those of alternative fire safety designs. The quantification of both the parameters was based on statistical data, if they are available, or subjective judgment, if such data are not available. More fundamental and rational approaches to quantification, includes the use of mathematical modeling.

4. HIGH RISE RESIDENTIAL BUILDING FIRE SCENARIO

The group of residential high rise buildings, observed in the case-study, includes three buildings with cellar, ground floor and 14 stories (Fig 2, Fig. 3). Similar groups of two or three buildings with 9 to 14 floores are built at four other locations in Novi Sad city area. These buildings were built in the period from 1968 to 1976, applying „IMS“ prefabricated building technology – prestressed reinforced concrete elements, skeleton system. The load bearing construction is designed to be stable in case of fire for at least 2 hours [8].

Possible Fire scenario event tree (Fig. 4) was formulated based on available statistics, building performance, field investigation, survey and findings completed during fire drills, using event-tree method.

According to the available statistics data from 2009 of Fire Brigade Novi Sad (Republic of Serbia, Ministry of Interior, Sector for Emergency Management), 881 fire events, 215 in buildings, were recorded in Novi Sad: 67% residential, 22% offices and

11% others. In residential buildings, 37% fires started in kitchens (forgotten meal on stove or malfunction of kitchen apparatus), and 23% fires started on electrical installations in apartments. In the period 2000-2004 in Novi Sad, the year average number of fires was 750 and 19 deaths in fire. According to that data, the inherent rate of risk for human life in a fire is 0.02533.

Based on statistics of fire events in Serbia in the period 2001 – 2009 (Republic of Serbia Ministry of Interior, Sector for Emergency Management), two main fire hazards in apartment buildings are human negligence and inaccurate or untested electrical installations. Consequently, the inherent rates of fire occurrence for those hazards are 37% and 23% respectively. In both cases, fire initiation barrier can be formulated as fire prevention education for residents in order to raise awareness about fire events and to apply prevention measures: (1) to examine the apartment before leaving it and (2) to test electrical installations regularly, especially when the building is over 40 years old and there are no records of regular maintaining activities or testing.

Figure 2 – High-rise residential building with no fire stairs

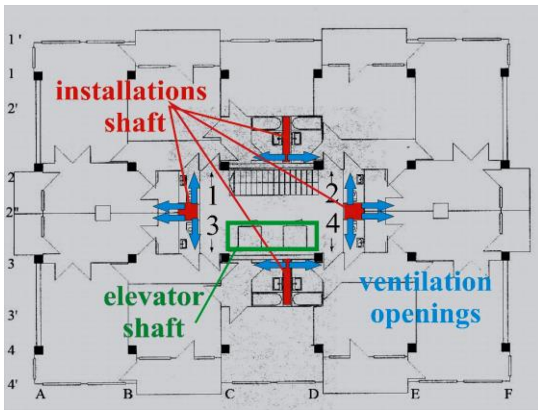

Figure 3 – Typical floor layout – 4 apartments

Assumed fire ignition source in fire event scenario is forgotten meal on stove or malfunction of kitchen apparatus when no one is at home.

During the research work on fire safety of residential towers, many contacts with residents, including interviews and polls were included. Only 10% are of opinion that residents are well informed about fire prevention and evacuation, but 5% thinks that residents are trained well about actions in the case of fire and 80% are aware that they are neither prepared nor trained for fire event. So far, fire drills were performed every month in residential towers in Novi Sad city area, but residents lacked attention, although they were notified in advance and supplied by information leaflets about fire preventive measures. In one specific building, only 10% of residents responded to an appeal to take part in the drill and education process. It is assumed that all of them would apply recommended measures and the probability of successful implementation of measures is 10% while the residual probability multiplier for low fire occurrence is 0.9.

The apartment door is locked. No one is at home to extinguish the initial fire. There are no sprinklers to prevent fire growth to flashover in the apartment.

The whole building is one fire sector: there are no fire or smoke compartments separated or any additional fire barriers. In the case of fire, in every apartment, fire and smoke are easy to spread around and get into the neighbour's apartment and the whole staircase in at least three ways:

- through four vertical installation shafts, each linking half of building’s apartments through ventilation openings in bathrooms and commons, and are separated from staircase with a wooden plate;
- through apartment doors made of a wooden plate, into staircase;
- through elevator shaft which is separated from staircase with a 4mm glass wall.

Fire spreading is also possible through apartment walls and façade, but it would take more time then former listed ways. The floor layout design includes no fire stairs, so the only evacuation route is down the main staircase, or they can be trapped in apartments, until the fire brigade comes and rescues them.

Smoke is spreading through ventilation and installation shafts into other apartments in the building.

In time, someone would notice the smoke or fire and try to alarm the residents in other apartments and the Fire brigade. The fire alarm system - manual pull stations were installed once, but some of them disappeared and the rest of them were never checked, so it is incomplete and unreliable. A manual fire alarm system depends on a human factor, which is in most cases unpredictable, but in these circumstances there are no other options to include fire alarms in event scenario. Based on investigation, it can be assumed that the reliability of the fire alarm is 35%.

The most of house fire hydrants (80%) are also damaged and incomplete, so their reliability is questionable, too. Fire brigade, during previous drill, excluded them as a fire protection supply.

Smoke evacuation from staircase is possible only through a one-square-meter large exit opening on the flat roof. Smoke spreading after flashover develops fast into main staircase through apartment door. Single smoke vent on the roof is usually locked, so it cannot be taken into account in event scenario. Staircase becomes a deadly trap, soon after flashover [9]. Emergency light and signalization is badly damaged and incomplete, so it can slow down people movement during evacuation and increase disorientation. Elevators are as old as the buildings, so they are still in function in the case of fire (without an automatic shutdown system), and there is a possibility that someone could try to go down with the elevator. Its shaft would be soon filled up with smoke, and even if the fire does not damage it, it is another trap to residents. It is positive that poll results showed that no one would take a lift in the case of fire.

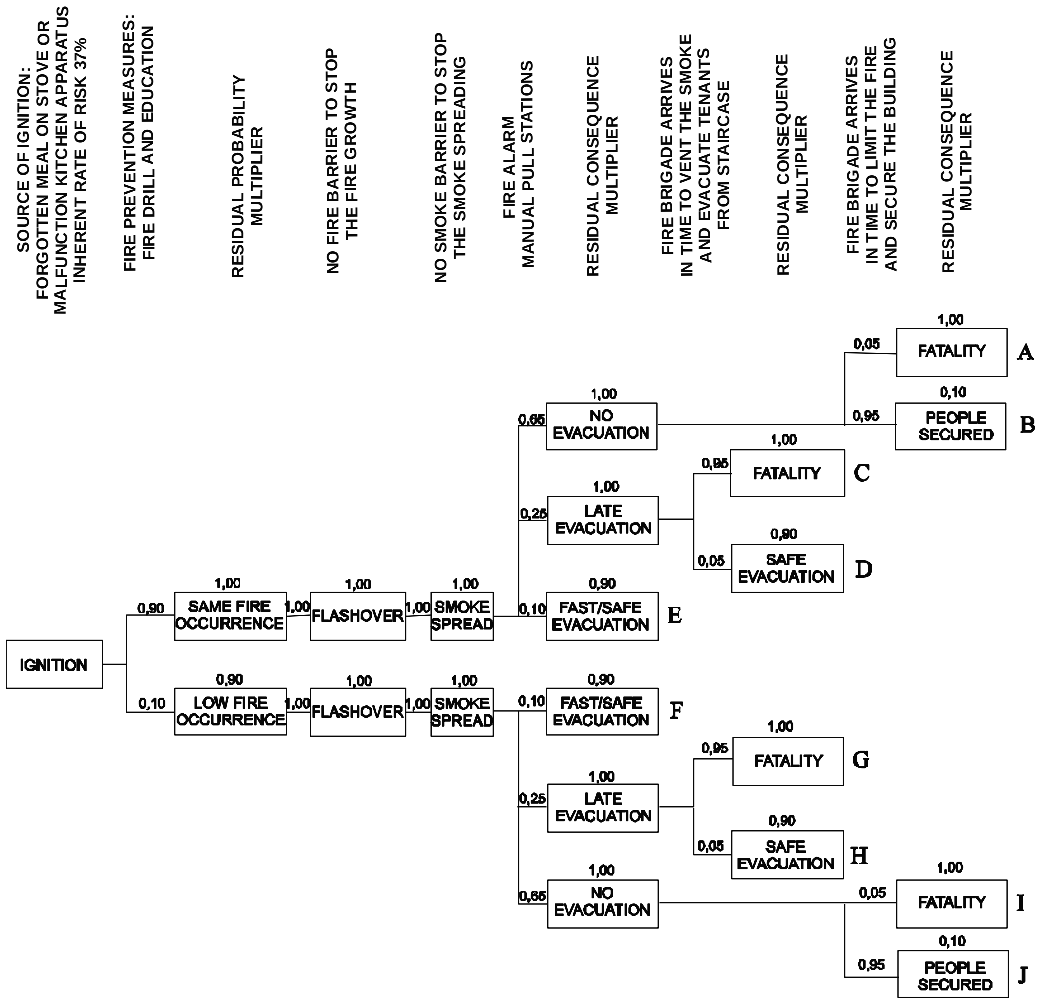

Figure 4 – Fire Scenario Event Tree - High-rise residential building with no fire stairs

Residents who took part in the drill and education process knew about it, but the others did not know that it was recommended to evacuate immediately when they spot first signs of smoke and fire, or to block the apartment door and the ventilation openings with wet blankets and stay in their apartments until fire brigade arrives [10]. For that reason, it is assumed that there is only a 10% possibility for fast/safe evacuation.

The results of the poll conducted among residents of high-rise residential building showed that only 25% paid attention on evacuation routes and the sign in their buildings, therefore it is assumed that they will try to take the main staircase. Poll results also showed that 90% of residents will use fire stairs for evacuation - if there is one, and 65% thinks that the fire brigade will come in time to rescue them and they will be waiting in their apartments in the case of fire.

According to the fire department dates and time measuring during the drill, it takes 8 to 10 minutes for the Fire brigade to arrive. Additionally, difficult circumstances are included in arrival time: inappropriate building position regarding approach possibility for fire squad interventions - parked cars or other barriers at access routes, or impossibility to approach some sides of buildings. Their activities are focused on saving lives and limiting fire on actual stage and extinguishing it. Smoke can also slow down fire-fighter teams' intervention and make life-saving operations more difficult. For that reason, first activity the fire brigade takes is to open the roof door and engage mobile smoke ventilation and suppression facilities.

Fire scenario development after fire brigade arrived is possible in two deferent ways – depending on protection measures: (1) fire brigade came in time to limit and extinguish the fire, but too late to save residents who started late evacuation and (2) Fire brigade came in time to save the residents who started late evacuation through staircase filled with smoke.

The most probable scenario is Scenario B: the best chances to save their lives have the residents who stay in their apartments and wait for fire brigade to come to rescue them.

The most probable fatal consequence scenario is in the case the residents try to evacuate with delay – late evacuation, when the stairway is filled with smoke (Scenario C).

The results of quantitative fire risk assessment for the various fire scenarios in high rise building with no fire stairs, based on event-tree method are presented in Table 2.

Table 2- Assessment of probability, consequence and residual risk values for the various fire scenarios in high rise building with no fire stairs based on event-tree method

Fire Scenario	Scenario Probability	Residual Probability Multiplier	Residual Consequence Multiplier	Residual Risk Multiplier
A	0.02925	1.00	1.00	0.02925
B	0.55575	1.00	0.90	0.50018
C	0.21375	1.00	1.00	0.21375
D	0.01125	1.00	0.10	0.00112
E	0.09000	1.00	0.90	0.08100
F	0.01000	0.90	0.81	0.00729
G	0.02375	0.90	0.90	0.01924
H	0.00125	0.90	0.09	0.00010
I	0.00325	0.90	0.90	0.00263
J	0.06475	0.90	0.81	0.04502
	1.00			**0.89958**

The fire scenario was formulated according to the present state of building and its fire safety performance (structure, materialization, floor layout, existing route of escape, fume ventilation, etc) and recorded fire protection measures applied: (1) fire drill and education, (2) manual fire alarm, (3) fire brigade intervention. Combined residual risk multiplier of implementing these three fire protection measures is 0.89958; which means that the residual risk to human lives is reduced to 89.96% of its inherent value. That is, in the case of a fire, protection measures applied so far are insufficient to reduce the risk to an acceptable level.

5. CONCLUSIONS

Every building is unique for its location, structure, building material and floor layouts, so the fire risk assessment based on fire scenario event tree method assesses different combinations and provides detailed information about success or failure of proposed protection measures, as well as comparison of different combinations.

The assessment of expected occupant fatalities and property loss in a building for a particular fire scenario is achieved by modeling fire growth, smoke spread, fire spread, occupant evacuation and fire department response. Expected risk to life for the occupants is the sum of all expected occupant fatalities from all probable fire scenarios that may occur in a building during the building designed lifetime.

Regular inspection and maintenance of fire protection systems is required in risk-based, or performance-based, fire safety designs. Without such regular maintenance and evacuation drills, the consequence is that the expected risk to life to the occupants is higher than that assumed by the fire safety design. The reliability of fire protection systems can be modeled based on failure rate and service time interval.

The various fire scenarios that a fire initiation can develop into are governed by the success and failure of fire protection measures. The sequence of fire events that follows the course of an actual fire development includes fire growth, smoke spread, occupant evacuation and fire department response. The performance based approach is to follow the logical development of these fire events in specific building.

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7. QUESTIONS FOR DISCUSSION WITH STUDENTS

1. Draw a basic fire scenario event tree: *Five major fire barriers between fire source and fatality*?
2. Explain the *Fire initiation barrier*, with an example from your everyday experience? What could be the fire source at home or at faculty premises?
3. What could be the *Fire grouth barrier* in the buildings?
4. Do you recognize any *Smoke spread barriere* in the buildings you visit or spend your time every day?
5. Are there *evacuation signes* in the building you live in? Do you pay attantion on possible escape rutes when you entrance the buildings?
6. Is it possible for firebrigade to aproach to the buildings in your neigbourhood?
7. Do you know how much time it takes for firefighters to come to your university building? Or your residential building?
8. Can you assum how much time it takes to get the full development of a fire in the apartment today? What do you tnihk it dependes on?
9. Do you know how to use fire extinguisher? Do your parents know? Or your teachers?
10. What would you do to rise the awarenes about fire safety among your familly, friends and colleagues?