# LITERATURE REVIEW OF FIRE RISK ASSESSMENT METHODOLOGIES

**G.V. Hadjisophocleous and Z. Fu**
Department of Civil and Environmental Engineering, Carleton University, 1125 Colonel By Drive, Ottawa, Ontario K1S 5B6, Canada

*(Received 27 December 2002; Accepted 26 November 2003)*

## ABSTRACT

This paper provides a review of recent work in the area of fire risk assessment and its application. For completeness, the paper covers the following areas: basics of fire risk assessment, types of fire risk assessment methods, and comprehensive fire risk assessment models. The first section provides information on the definition of fire risk, measures of fire risk, acceptable fire risk levels, and the relationship between fire risk assessment and performance-based codes. In the following section, the types of fire risk assessment methods, such as qualitative and semi-quantitative, are briefly introduced, while more emphasis is given to quantitative methods. A number of existing comprehensive fire risk assessment models are described in more detail, including CESARE-Risk in Australia, FiRECAM and FIERAsystem in Canada, CRISP in UK, and the quantitative risk assessment model of Lund University. In addition, a brief description of a risk assessment model currently being developed at Carleton University is presented.

## 1. BASICS OF FIRE RISK ASSESSMENT

### 1.1 Definition of Fire Risk

The definition of risk is one that varies from area to area and even between members in the same area. Watts and Hall [1] use the following definition of risk, which is based on the definition of the Society for Risk Analysis [2]: risk is the potential for realization of unwanted, adverse consequences to human life, health, property, or the environment. Estimation of risk (for an event) is usually based on the expected value of the conditional probability of the event occurring times the consequence of the event, given that it has occurred. It follows that risk for a building, a process, or some other entity would be the probability distribution of events and associated consequences relevant to that building, process, or entity.

In Meacham [3-4], a comprehensive definition of fire risk is given as follows: fire risk can be viewed as the possibility of an unwanted fire hazard in an uncertain situation, where loss or harm may be induced to the valued, typically life, property, business continuity, heritage, and/or environment. The key factors include unwanted outcomes or consequences, uncertainty, valuation, and likelihood of occurrence. Building fire risk analysis can be considered as the process of understanding and characterizing fire hazard in a building, unwanted outcomes that may result from a fire, and the likelihood of fire and unwanted outcomes occurring [3].

### 1.2 Measures of Fire Risk

Before quantitatively assessing fire risk, it is essential to determine its measure. As Bukowski mentioned [5], it is difficult to express risk to life in a way that can be understood by the public. This leads to the consideration of other metrics for risk. Financial loss is the perfect metric for the property-related risk, however, the primary focus of fire codes is life safety, which then requires that risk to life must include a measure of the value of human life. This regards the economic value of an individual as the present value of the stream of income that he or she expects to earn during the rest of his or her working life [6]. The concept that some people have less value to society than others has encountered great objection, especially by those, whose value is deemed lower. Thus risk to life is usually separately assessed to avoid the difficulty of assigning a monetary value to human life.

In Beck's work as well as in the relevant fire risk assessment models such as CESARE-Risk and FiRECAM, fire risk is measured separately using two comprehensive parameters: the expected risk-to-life (ERL) and the fire cost expectation (FCE). ERL is defined as the expected number of deaths over the design life of a building, divided by the population of the building and the design life of the building. FCE is defined as the expected total fire cost, divided by the cost of the building and its contents. The ERL value and FCE value can be used for making decisions [7-8].

Frantzich [9] divides life risk into two types, individual risk and societal risk. The individual risk is defined as the risk to which any particular occupant is subjected at the location defined by a scenario, usually expressed in terms of a probability per year of being subjected to an undesired event, i.e. hazard. The societal risk is concerned with the risk of having multiple fatalities, often described as an FN curve (frequency-number curve) or a risk profile. The FN curve can be used to define tolerable risk levels and can also be used to choose a design alternative.

## 1.3 Acceptable Fire Risk Levels

As Dungan mentioned [10], absolute risk is more difficult to declare as acceptable because it requires the acceptance of a known risk. Applying risk measures as a relative ranking to establish priorities or to compare cost-benefit of different approaches makes effective use of the methods without becoming mired down in the acceptability of any one risk.

In a relative risk assessment method, the risk of the subject building is usually assessed and compared with the risk of a similar building designed in accordance with the prescriptive code. The justification of the relative risk approach usually states that the public appears to be satisfied with the safety levels of buildings designed to the current regulations, although some argue that this statement is debatable [5]. The draft code of practice from the British Standards Institution (BSI) is the only method which has attempted to set acceptable levels of risk. They suggest a value for the risk of death per individual per year at home or elsewhere, and for the risk of multiple deaths per building per year. The problem is that risk to life is too abstract to be understood by the public.

To make decisions about the appropriate level of fire safety or risk, it is necessary to balance the benefits of safety and costs of achieving it. From this view, risks should be reduced until the marginal cost equals the marginal benefits. The cost of fire protection measures is fairly straightforward and can be calculated in the same way as any other building cost. However, it is more difficult to quantify the benefits. A number of studies have been made to estimate acceptable or tolerable risk level in terms of costs and benefits as well as human capital [6].

Armin [11-12] studies the issue of acceptable fire risk level in terms of the public perceptions of risk. When developing a fire safety code, developers have to consider the acceptable level of risk for various occupancies, which is closely related to the perceptions of risk. Human perceptions of risk can be quantified in terms of human factors or risk factors. They include volition, severity, effect manifestation, familiarity, controllability, benefit, necessity, exposure pattern and origin. Each risk factor is associated with a scale. Each risk factor is also assumed to have an acceptable risk level, which was obtained from historical data. Furthermore, a risk conversion factor for each risk factor can be used to calculate the mathematical difference from one end of a risk factor scale to the opposite.

## 1.4 Performance-Based Codes and Fire Risk Assessment

Risk assessment is also closely related to performance-based codes, which are gradually replacing existing prescriptive-based codes. The traditional building fire safety design was highly dependent on compliance of individual building elements with specific prescriptive rules. The major advantage of prescriptive codes is that they are easy to use, enforce and implement. Prescriptive rules were developed mainly on the basis of trial and error experiences, and not on scientific and systematic methodologies and strict engineering disciplines. They are not flexible, restricting innovation and cost-effectiveness. Compliance with prescriptive code requirements does not ensure that all buildings are constructed to the same level of safety or risk [13,14].

In order to encourage more flexible and cost-effective designs, there is a worldwide trend to switch from prescriptive codes to performance-based codes. Performance-based codes include a set of clear fire safety objectives, functional requirements of fire safety systems or components, and approaches to achieve these objectives. To facilitate the transition from prescriptive codes, performance codes usually include “deemed to satisfy” provisions, which are approaches shown to provide acceptable solutions based on prescriptive solutions. Contrary to prescriptive-based codes, the advantage of performance-based codes is that they promote flexibility, equitability, innovativeness and cost-effectiveness [5,14,15]. Together with the development of performance-based codes, several design guidelines have been published, which describe how to use engineering approaches for fire safety designs [16,17]. What is absent, however, in these documents are guidelines regarding methods to quantify and verify the safety or risk levels achieved by fire safety designs [18,19].

In performance-based fire safety designs, a definite numerical criterion of fire safety in building design should be established. The natural choice for this criterion is the fire risk to either life or property. Two things are necessary to put fire safety design on a firm quantitative footing; a method for measuring fire risk and a criterion of acceptable risk, which designers would be expected to conform. In fact, every draft performance evaluation system is risk based, thus fire risk assessment can play an important role in performance-based fire protection design [6].

## 2. TYPES OF FIRE RISK ASSESSMENT METHODS

As pointed out by Watts [1,20,21], methods of fire risk analysis may be classified into four categories, narratives, checklists, indexing, and probabilistic methods. Narratives do not attempt to evaluate the fire risk quantitatively; instead, a risk is judged acceptable if it complies with published recommendations. An obvious limitation to the narratives approach is that it cannot cover the myriad conditions of human activity. A common accessory of fire protection is a listing of hazards and recommended practices. These checklists comprise valuable tools for identifying fire risk factors but they do not distinguish among the importance of these factors. Fire risk indexing methods assign values to selected variables based on professional judgment and past experience. The selected variables represent both positive and negative fire protection features and the assigned values are then operated on by some combination of arithmetic functions to arrive at a single value. This single value can be compared to other similar assessments or to a standard. This method is a useful and powerful cost-effective tool that can provide valuable fire risk assessment, especially when an in-depth analysis is not appropriate. Probabilistic methods are the most informative approaches to fire risk assessment in that they produce quantitative values, typically produced by methods that can be traced back through explicit assumptions, data, and mathematical relationships to the underlying risk distribution that all methods are presumably seeking to address.

Fraser-Mitchell discussed three methods of fire risk assessment: point schemes, state transition models, and simulation models [22]. Point scheme methods are equivalent to indexing methods mentioned above, which correlate fire statistics with parameters such as size of building and fire load. It is difficult to assign numerical values to some of the parameters, so the correlations are probably rather weak. The method is also not applicable to novel buildings or techniques. A more sophisticated approach is based on state transition models, with probabilities assigned to each event. The determination of the probabilities may also be a rather subjective process, or may use deterministic models to examine the consequences of various starting conditions. Fire realm models are more complex than but similar to state transition models, and both are difficult to deal with the interactions between components. It is necessary to develop a simulation model with all component sub-models running simultaneously, and their results communicating to each other. The model is mainly deterministic, but with starting conditions and certain values drawn from suitable probability distributions. The overall risk is simply given by the average value of some output parameters over a suitable number of runs of the simulation. The advantage of this technique is that the structure of the model can in principle be directly based on physical theory and experimental measurements.

As Frantzich mentioned [9], in chemical process industry, risk analysis can be separated in at least three levels: qualitative methods, semi-quantitative methods, and quantitative methods. Qualitative methods are used to identify the most hazardous events. In the chemical process industry, methods have been developed such as HAZOP, what-if and various checklists. Semi-quantitative methods are used to determine the relative hazards associated with unwanted events, which are equivalent to indexing methods, point scheme methods, or numerical grading. In these methods, the hazards are ranked according to a scoring system such as the Gretener system [23]. Quantitative methods are most extensive and labor intense methods. On this level, a distinction can be made between a deterministic analysis and probabilistic analysis. The deterministic analysis focuses on describing the hazards in terms of the consequences. The probabilistic approach determines the quantified risk based on both frequency and consequences.

These classifications of fire risk assessment or analysis are obtained from different points of view, and are interrelated. In the following part of this section, more details of semi-quantitative and quantitative fire risk analysis methods will be presented. In addition, event tree and fault tree methods are widely used in fire risk assessment so these methods are also briefly introduced.

### 2.1 Event Tree and Fault Tree Analysis

In fire risk assessment, event tree and fault tree analysis have been widely used to qualitatively or quantitatively analyze fire risk or safety of the whole fire protection system or a component. Even with the development of more and more advanced fire risk assessment models, this analysis method is still used to help perform some preliminary or in-depth work such as the selection of fire scenarios and the calculation of the reliability of fire protection components.

An event tree is a visual representation of all the events that can occur in a system. As the number of events increases, the picture fans out like the branches of a tree. All the events stem from the initiating event, which starts the sequence of events. Event trees can be used to analyze systems in which components involve sequential operations or transitions. In fire safety, event tree analysis is one way to build up a reasonable picture of the likelihood of fire scenarios using our knowledge of the mechanisms by which fire occurs, spreads, and is controlled [24]. The goal of an event tree is to determine the probability of a scenario based on the outcomes of each event in the chronological sequence of events leading up to the scenario.

A fault tree analysis is a deductive top-down methodology used to analyze the design or performance of a system or component. Similar to the event tree, it begins with a top event to analyze, followed by identifying all of the associated events in the system leading to the top event. Fault trees provide a convenient graphic representation of the combination of events resulting in the occurrence of the top event. Fault tree analyses are generally performed graphically using a logical structure of AND and OR gates. Sometimes certain events may need to occur together in order for that top event to occur. In this case, these events would be arranged under an AND gate, meaning that all of the events would need to occur to trigger the top event. If any of the lower level events alone will trigger the top event, these events would be grouped under an OR gate [25].

It can be seen from recent publications that event tree and fault tree methods are still widely used in fire risk analysis. For example, Watts used event tree analysis methods to develop appropriate fire scenarios to evaluate fire risk of cultural heritage based on locations, contents, and selected fire safety strategies. In SAFiRE (Simple Analysis Fire Risk Evaluation), both event tree and fault tree methods were used to analyze fire frequency [26]. In reference [27], an event tree was constructed for evaluation of the probability of fire department failure, while a fault tree for the probability of success of the fire department.

For both event tree and fault tree methods, commercial software is available to enable users to conveniently create complete event trees or fault trees and perform fast and accurate calculations.

## 2.2 Semi-Quantitative Methods

As mentioned above, semi-quantitative methods are used to determine the relative hazards associated with unwanted events, which are equivalent to indexing methods, point scheme methods, or numerical grading. In these methods, the hazards are ranked according to a scoring system such as the Gretener system.

As presented by Watts [1,20,21,28], a fire risk indexing or ranking, also called schedule may be defined as a systematic combination of pertinent fire protection factors. One basic assumption the indexing method is based on is that a relatively small number of factors account for most of the problems of fire protection. To systematically combine pertinent fire protection factors requires that the factors be measurable. Schedules are also distinct from narratives and checklists by their implicit inclusion of the concept of fire protection objectives. Both the identification of pertinent factors and the method of combination require consideration of an acceptable level of risk as the goal for achievement. Some representative examples of fire risk ranking are summarized in the following.

An insurance rating has been defined as an empirical standard for the measurement of relative quantity of the fire hazard. Schedule ratings take into consideration the various items contributing to the peril of fire with a view to determining which features either enhance or minimize the probability of loss. Credits and charges representing departures from standard conditions are incorporated in the schedules. Thus the schedule rate is typically the sum of all charges minus the sum of its credits, and constitutes a standard for the measurement of the fire risk.

The most commonly used insurance rating schedule in the U.S. is the ISO (Insurance Services Office) commercial fire rating schedule, which includes estimation of percentage charges, the basic building grade with the consideration of the related loss experience. The Gretener method is a different method developed in Europe, which considers the fire risk as the product of hazard probability and hazard severity [23]. In addition, the hazard is calculated as a ratio of potential hazard and protection measures. The Fire Safety Evaluation System (FSES) [29] is a schedule method developed at NIST to determine equivalencies to NFPA 101, Life Safety Code for certain institutional occupancies [30]. Dow's Fire and Explosion Index method was developed by Dow Chemical Company to provide a direct and logic approach for determining the probable risk exposure of a process plant and to suggest approaches to fire protection and loss prevention designs. Mond Fire, Explosion and Toxicity Index method was a further development by the Mond division of ICI, Ltd. based on the Dow's method to extend its potential to new project designs [31].

In addition to the fire indexing methods, some other methods, such as given by Dungan [10], may also be grouped into semi-quantitative methods, as briefly introduced below:

The first one is a methodology for fire-induced vulnerability evaluation, which is a screening tool developed for the nuclear power industry. This tool is a two-phase evaluation to assess the likelihood of a fire causing reactor core damage. The risk tolerance was established as a frequency of fire contributing to core damage. Phase I identifies safety significant fire areas by qualitatively identifying if any safe shutdown equipment is in the area or if a fire could cause a demand for safe shutdown equipment. The second phase for those not screened out is more quantitative. This includes an assessment of the fire frequency, availability and reliability of redundant safe shutdown equipment, and the performance of fire protection features.

The second example is on reliability-centered maintenance applied to inspection, testing and maintenance (ITM) for fire protection systems. Failure modes and effects analysis were applied to systematically identify failure modes, their causes and their effects on fire protection system performance. The failure modes for a component were derived from standard listings of failure modes by component type. The risk for each failure mode was characterized by qualitatively ranking the probability of failure on demand for the component failure mode and the resultant system degradation level. The rankings of the probability of failure on demand are high, medium, low and very low, which are the estimate of the likelihood of the component's failing in that particular mode. The system degradation levels are total, partial and minimal, which are the estimates of the severity level of the functional failure that results from a component failure mode. The system degradation and the rankings of the probability of failure on demand were used in the task selection and frequency assessment step to identify component failure modes that require ITM tasks and to determine the appropriate frequency for ITM tasks. The model was developed to allow the determination of the frequency with which ITM tasks need to be performed to achieve system and component reliability targets. The development of the model involved four steps, development of an event tree model, derivation of the mathematical expression for the event tree, prediction of failure rates for component failure modes, and calculation of system reliability.

## 2.3 Quantitative Methods

In a quantitative fire risk assessment method, safety or risk can be evaluated either by comparing the proposed design with accepted solutions or with specified tolerable levels of risk. The former is a relative risk assessment method, in which the risk of the subject building is usually assessed and compared with the risk of a similar building designed in accordance with a prescriptive code. The later is a direct risk assessment method, in which the risk of the subject building is directly compared with an acceptable level of risk for such occupancy. Currently, the former approach is usually used because of the uncertainties involved in the assessment of the absolute value of the risk. In some other engineering fields such specified levels of risk are available. As for the later approach, the draft code of practice from the British Standards Institution (BSI) may be the only publication which has attempted to set acceptable levels of risk [5,9].

Frantzich [9] states a comparison of the design solution with acceptable solutions can be performed on three levels: simple handbook solution, i.e., using prescriptive regulations; calculation on sublevel, for example, evaluating escape time margin; evaluation on system level, i.e., performing a quantitative risk analysis (QRA). If safety is to be ensured by comparing a design with a specified level of risk, then two approaches are available: evaluation on system level, i.e., performing a QRA; using design values based on defined risk in deterministic equations.

The disadvantage of handbook solutions has been discussed earlier. The second approach is to make sublevel calculations such as occupant safety, in which the time for evacuation is compared with the available time for escape. The problem with this approach is that it only considers part of the whole safety design. The third approach is to make a full QRA, or to use design values in the calculations, which are based on a specified level of risk. The advantage of using QRA methods is that a large number of events are investigated. Furthermore, in the extended QRA method, inherent uncertainty in the variables is simultaneously considered. As for using design values derived from a specified level of risk, the problem is that such design values are not available.

The first step in QRA is usually related to defining and describing the system in terms of one or more scenarios. The system must also consider physical limitations, i.e., which physical area should be considered in the analysis. The second step is to identify hazards. Then, fire risk analysis is performed. In order to perform a fully quantitative risk analysis, the question regarding the extent of the analysis must be answered. The extended QRA can be seen as a standard QRA performed a large number of times. Each step in the repeating procedure considers the inherent uncertainty in the variables by using Monte Carlo sampling technique. The societal risk resulting from the extended QRA is expressed in terms of a family of risk profiles, showing a range of risk profiles. This method can provide the relevant confidence bounds.

Although there is a long way to go for fire risk assessment modeling, the development and implementation work of risk assessment models is still steadily advancing. This may be the only practical engineering way we can follow to fully implement and support performance-based fire codes.

## 3. COMPREHENSIVE FIRE RISK ASSESSMENT MODELS

In this section, a number of existing fire risk assessment models are introduced. Some of them are relatively mature with the models well documented and applied in real case studies. On the other hand, some of them are at the very beginning stage with only the framework of the model. The models to be described include CESARE-Risk developed in Australia, FiRECAM and FIERAsystem in Canada, CRISP in UK, and a QRA method developed at Lund University in Sweden.

### 3.1 CESARE-Risk

The CESARE-Risk model is a risk assessment model developed by the Center for Environmental and Risk Engineering in Australia to quantify the performance of a building fire safety system [7]. The development of this model is closely associated with the launching of the performance-based Building Code of Australia (BCA, 1996), which was the first set of performance-based regulations to be adopted gradually by each state and territory in Australia [17]. The BCA96 is based on a four level hierarchy; namely, objectives, functional statements, performance requirements, and deemed-to-satisfy provisions and verification methods. These verification methods can be used to prove that an alternative solution complies with the performance requirements.

Along with the code, a document with fire engineering guidelines was developed by the Fire Code Reform Center Limited to describe procedures and methodologies for a performance-based approach to the design of the building fire safety system [7]. The guideline document identifies the quantitative performance parameters that should be used to demonstrate compliance with the objectives. The Fire Engineering Guidelines contain three levels of design. Levels 1 and 2 make use of single or multiple scenarios that are considered in isolation. Design level 3 uses multiple scenarios that are combined using the probability of their occurrence; that is, a risk assessment approach, which enables cost-effective designs to be identified. The CESARE-Risk model has been developed as such a risk assessment tool to be used by consulting engineers and building officials to help identify cost-effective design solutions for buildings.

The CESARE-Risk model is based on the recognition that the modeling of fire growth and spread of fire in a building and its interaction with occupant egress can be split into two components. The first component consists of establishing an event tree to describe the conditions of the building. Given the occurrence of each scenario, deterministic models are used to calculate the fire environment, occupant response and evacuation, and then the expected number of deaths. The expected risk-to-life for occupants in a given fire scenario is then determined by the life loss associated with that scenario multiplied by the probability of the scenario occurring. The over-all expected risk-to-life from fires in a building is the sum of the expected life risks of all the scenarios over the expected life of the building. Similarly, the total fire cost expectation is the sum of all the investment in fire safety systems plus the expected property loss from fires in the building over the expected life of the building. The separation of life risks and protection costs is intended to avoid the difficulty of assigning a monetary value to human life and allows the comparison of risks and costs separately [32-34].

The following sections give more details of CESARE-Risk.

#### 3.1.1 Probabilistic Approach

In CESARE-Risk, an event tree is set up to describe the conditions of the building. However, if considering all of the factors affecting fire safety of a building, the number of scenarios will be effectively infinite. To go around this problem, the CESARE-Risk model only considers the most important factors, which could significantly affect the number of lives lost. These important factors have been grouped into six categories: building condition, fire starts, building content, occupant profile, occupant condition, and fire brigade. Currently, three types of fires are considered, smoldering, flaming non-flashover and flaming flashover.

One difficult point is that fire is essentially a stochastic process. The failure of a barrier will not be known until the fire is simulated, while in turn, the failure of the barrier may have an effect on the fire growth. For smoldering fires and flaming non-flashover fires, it is assumed that there will be no fire spread from the room of fire origin; therefore the event tree for the fire scenario is static. However, for flaming flashover fires, the event tree for the fire scenarios can change because of fire spread. The initial fire scenarios for flaming/flashover fires are the same as for smoldering fires and flaming non-flashover fires, in which only the conditions of whether doors being open are considered and no conditions on barrier failures are considered. However, in the case of barrier failure, some additional scenarios are considered. In CESARE-Risk, a time-dependent barrier failure model is used to predict the probability and time of barrier failure [35]. In an attempt to reflect the inherent nature of the stochastic process, a dynamic structure is then used to represent the event tree for fire scenarios; that is, the event tree changes with the failure of barriers and/or fire spread.

Zhao and Beck [36] describe the procedure used to establish the dynamic structure of fire scenarios for a generic residential building. To incorporate the distributional effect of independent variables, such as fuel load, on the severity of the fire, the CESARE-Risk uses a three-realization method for the apartment of fire origin. In this method, the values chosen for each random variable correspond to $\mu$, $\mu \pm 1.2\sigma$, where $\mu$ and $\sigma$ are respectively the mean and the standard deviation of the random variable. It was found that the three-realization approximation drastically reduced the error associated with the single realization to manageable proportions. The fire severity random variable was determined a priori using a Monte Carlo simulation by considering distributions for each of the input parameters. In addition, in the human behavior model, CESARE-Risk uses an expected response approach to calculate the number of deaths. The advantage of this approach is that the number of human behaviour scenarios is always one irrespective of the number of cues considered.

### 3.1.2 Fire Growth and Smoke Spread Models

The CESARE-Risk model uses the NRCC fire growth model, based on its merits of simplicity, efficiency and robustness [37]. Predictions from the NRCC fire growth model; have been compared with experimental results obtained for various fire conditions; namely, smoldering, flaming and flashover. Modifications to the NRCC model have been undertaken to achieve closer agreement between the predicted and the measured results.

The center developed a model of smoke spread in large residential buildings called CESARE-SMOKE model using the zone concept and network approach [38]. The CESARE-SMOKE model is coupled with the NRCC fire growth model to predict smoke movement to each enclosure in a building.

### 3.1.3 Human Behavior Model

The aim of the CESARE-Human Behavior Model is to estimate the number of persons in different locations in an apartment building at different times during a fire incident. The model consists of the response submodel that deals with behavior up to the time when evacuation begins by occupants leaving an apartment and the evacuation submodel that deals with the movement of people in a building. The Human Behavior Model, in conjunction with the Fire Growth and Smoke Spread Models, is used to estimate the cumulative time-dependent exposure of occupants to toxic and thermal effects.

The evacuation submodel is a dynamic network model that is used to estimate the spatial distribution of the expected number of occupants as a function of time. It is assumed that, once occupants leave an apartment, they seek to exit the building. However, this movement strategy can be altered by smoke conditions, which can force occupants to seek alternative exit routes. If these exits are not available, then occupants are assumed to attempt to return to their apartment.

Since occupants can have different response parameters such as probabilities, response durations and movement speeds, several occupant group categories were defined using demographic data of the Australian population. Also in recognition of the importance of the effect of age, drugs and alcohol use, and mobility-related handicaps on fire fatalities, further occupant groups were defined. The conditions of occupants are defined to be stationary, ambulatory, incapacitation or fatality.

The calculation of occupant incapacitation and fatality is based on the temporal accumulation of toxic and thermal effects associated with each occupant. For simplicity, it is assumed that the effects of toxic gases and heat are mutually exclusive; i.e., death can be caused by either toxic gases or heat, but not both.

### 3.1.4 Fire Brigade Model

To quantify the effects of fire brigades, the Australian Fire Authorities Council has developed a Fire Brigade Intervention Model (FBIM). The FBIM, which can be characterized as an event tree, is used to estimate the time of arrival of the fire brigade at the enclosure of fire origin, as a function of the time of notification and operational procedures, resource availability and capability. In addition, actions such as fire control and extinguishment and search and rescue are also modeled as a function of the fire conditions, the number and distribution of occupants trapped and incapacitated, fire brigade operational procedures, and resource availability and capability.

### 3.1.5 Barrier Performance

To estimate the time-dependent performance of barriers under real fire conditions, a CESARE-Fire Barrier model has been developed to predict the time and probability of failure. Deterministic time-dependent submodels for fire severity, thermo-structural response and failure criteria, are used to predict the time of failure of a barrier to a realistic fire and load condition scenario. A Monte Carlo simulation is used to conduct multiple numerical simulation experiments to determine, for each experiment, whether failure of the barrier occurs. This information is then used to estimate the cumulative probability of the time to failure.

## 3.2 FiRECAM

The National Research Council of Canada (NRCC) in collaboration with Public Works and Government Services Canada have developed a computer program called FiRECAM (Fire Risk Evaluation and Cost Assessment Model), which can be used to identify cost-effective fire safety designs of apartment and office buildings that provide the intended safety level that meets the requirements of the National Building Code of Canada [8,39].

The basic concept of FiRECAM was originated from Beck's work in Australia. For each fire scenario, FiRECAM calculates the expected number of deaths and fire losses. These values are then combined at the end with the probabilities of occurrence for the fire scenarios to obtain the following two decision-making parameters: expected risk to life (ERL), defined as the expected number of deaths over the design life of a building, divided by the population of the building and the design life of the building; fire cost expectation (FCE), defined as the expected total fire cost, which is the sum of capital costs of the passive and active fire protection systems, maintenance cost of the active fire protection systems, expected losses as a result of all probable fire spread in the building, divided by the cost of the building and its contents.

FiRECAM consists of a number of submodels that simulate the dynamic interaction of fire growth, smoke spread, occupant response and fire department intervention. Each of these models calculates a different set of simulations for fire growth, occupant behaviour, fire department response, and fire hazards. As other computer models, FiRECAM uses certain input parameters to describe the characteristics of various fire safety designs. A parametric study was carried out and the sensitivity of these parameters on the predicted risks was found to be reasonable [40]. More details of these submodels are given in the following sections.

### 3.2.1 Probabilistic Approach

As mentioned above, FiRECAM assesses the fire safety performance of a fire safety design in terms of two decision-making parameters, ERL and FCE. FiRECAM uses six design fires in the compartment of fire origin, and the subsequent fire and smoke spread, to evaluate life risks and protection costs for apartment and office buildings. The six design fires, representing the wide spectrum of possible fire types, are a combination of three fire types and two status of the door of the compartment of fire origin. The three fire types are smouldering fire, flaming non-flashover fire, and flashover fire. The door of the compartment of fire origin can be opened or closed.

The probability of occurrence of each design fire, given that a fire has occurred, is based on statistical data. For example, in Canada, statistics show that 24% of all office fires reach flashover and become fully developed fires, 54% are flaming fires that do not reach flashover and the remaining 22% are smouldering fires that do not reach the flaming stage [41]. If sprinklers are installed, the model assumes that some of the flashover and non-flashover fires, depending on the reliability and effectiveness of the sprinkler system, are rendered non-lethal.

FiRECAM evaluates the cumulative effect of all probable fire scenarios that could occur in the building during the life of the building. For example, in an office building, a fire scenario could be one resulting from one design fire in any one of the floors in the building. The number of fire scenarios, therefore, is the product of the number of design fires and the number of floors in the building. In the case of an apartment building, the scenarios with occupants awake and occupants asleep are treated separately.

### 3.2.2 Building and Risk Evaluation Model

Building and Risk Evaluation Model is an optional model that can be run to evaluate the fire characteristics of a building, especially if the building is not a typical building where normal fire statistics can be applied. Based on the types and quantity of combustibles in the building and the separation of the combustibles from potential ignition sources and the maintenance of fire suppression systems (if they are installed), the model calculates the factors that can be used to correct the statistical values of the probability of fire starts, probability of various design fires that may develop, and the reliability of the fire suppression systems. These factors are used later in the Design Fire Model to correct the normal statistical values.

### 3.2.3 Fire Growth and Smoke Movement Models

The fire growth model predicts the development of the six design fires in the compartment of fire origin. Details of the fire growth model for apartment buildings were described in Takeda et al. [37]. The model is a one-zone model, which calculates the burning rate, room temperature and the production and concentration of toxic gases as a function of time. With these calculations, the model determines the time of occurrence of five important events: time of fire cue, time of smoke detector activation, time of heat detector or sprinkler activation, time of fire flashover, and time of fire burnout. The model also calculates the mass flow rate, the temperature and the concentrations of CO and $CO_2$ in the hot gases leaving the fire compartment, which will be used in the Smoke Movement Model to calculate the spread of smoke throughout the building as a function of time. In addition, fire growth is computed based on the combustion of a representative fuel, polyurethane foam for residential buildings and wood cribs for office buildings.

The smoke movement model calculates the spread of smoke and toxic gases to different parts of the building as a function of time. Details of this model are described in Hadjisophocleous et al. [42]. The model also calculates the critical time that the stairs become untenable. This is the time that the remaining occupants, who have not evacuated the building, cannot use the stairs to evacuate and are considered trapped in the building. This model also calculates the smoke hazard (probability of incapacitation due to toxic gases) at every location in the building at the time of arrival of the fire department. If there is no fire department response, this model calculates the smoke hazard at the time of burnout in the compartment of fire origin. The smoke hazard is based on the dosage and temperature of the toxic gases that the occupants are exposed to.

### 3.2.4 Boundary Element Failure and Fire Spread Models

The Boundary Element Failure Model calculates the probability of failure of the boundary elements (such as walls, floors and doors) in the building when exposed to a design flashover fire that could occur in the building. The characteristics of the design flashover fire are obtained from the Fire Growth Model. The failure probability values are used later in the Fire Spread Model to calculate the probability of fire spread from the compartment of fire origin to every location in the building. This model is based on the normalized heat load concept. It compares the heat attack in the fire resistance-rating test on the boundary element with the heat attack in a real fire to estimate the probability of failure of the element. The heat attack in real fires is computed based on the fire load, the area of the compartment and the ventilation openings.

The Fire Spread Model calculates the probability of fire spread to every location in the building based on the probability of failure of the boundary elements and fire fighting effectiveness. The model is non-time-dependent where the probability of fire spread to every location in a building is assumed to occur at the time of fire burnout in the compartment of fire origin.

### 3.2.5 Occupant Response and Evacuation Models

Details of this model can be found in Proulx and Hadjisophocleous [43]. The Occupant Response model calculates the probability of occupant response at different locations in the building. This model uses the concepts of fire states and time frames. Fire states are the times of occurrence of important events during the development of a fire. There are five different fire states: fire cue; smoke detector activation; heat detector and sprinkler activation; flashover; and burnout. The probability of response is calculated based on warnings received from: fire cues, local alarms, central alarms, voice alarms, warnings from others, and warnings from fire fighters.

The Evacuation Model is a time-dependent, deterministic model that calculates the egress of the occupants from the building. Based on the probability of response at the time frames computed by the Occupant Response Model and the critical time in the stairs computed by the Smoke Movement Model, the model calculates the number of occupants who can evacuate the building, and those who are considered trapped in the building. The model computes the movement of occupants through the stairs and out of the building. The flow of occupants through the stairs is computed using empirically derived occupant flow equations. Occupants who are unable to exit the building remain trapped inside the building and they are subjected to the probabilities of death at their location. The number of occupants who are trapped in the building is reduced by the effectiveness of the rescue efforts of the fire department.

### 3.2.6 Fire Department Action and Response Models

The Fire Department Response Model is an optional model that evaluates the fire department response characteristics to a building where normal fire department response statistics cannot be applied. This model considers the characteristics of the fire department and the distance to the building to calculate the response time to the building. The computed response time is used later in the Fire Department Action Model instead of the normal statistical value.

The Fire Department Action Model calculates the effectiveness of fire fighting and rescue efforts, based on the time of arrival of the fire department, the time of flashover computed by the Fire Growth Model, and the fire fighting resources that have arrived at the scene. The rescue effectiveness value is used later in the Evacuation Model to reduce the number of occupants who are trapped in the building and the fire fighting effectiveness in the Fire Spread Model to reduce the probability of fire spread. The time of arrival is also used later in the Smoke Movement Model to evaluate the smoke hazard conditions to the occupants at the time of arrival of the fire department. The expected time of action (intervention time) is computed by adding the notification time, the travel time, the response time and the set-up time.

#### 3.2.7 Economic and Cost Models

The Economic Model calculates the building construction cost and the capital and maintenance costs of the fire protection systems. It also calculates the replacement costs of building contents and the restoration costs of building elements as a result of smoke, fire and water damage. These costs are used later in the Property Loss Model to calculate the expected fire losses for each fire scenario, and in the Fire Cost Expectation Model to calculate the total fire cost expectation.

The Property Loss Model calculates the replacement costs of building contents and restoration costs of building elements for the fire scenario being considered, based on smoke spread values computed by the Smoke Movement Model, fire spread probabilities obtained from the Fire Spread Model, and replacement and restoration unit costs calculated by the Economic Model.

The Fire Cost Expectation Model calculates the total fire cost expectation (FCE) by using the capital and maintenance costs for the fire protection systems obtained from the Economic Model, the expected fire losses for each fire scenario obtained from the Property Loss Model, and the probability of occurrence of each scenario obtained from the Design Fire Model. For a particular fire scenario, a probable cost of damage due to fire is calculated by multiplying the losses from fire damage with the probability of occurrence of that scenario. This value is added to the cost of protection systems and the annual costs associated with the building and protection system design, and normalized by the cost of the building structure and contents to obtain the Fire Cost Expectation.

#### 3.2.8 Life Hazard Models

The Expected Number of Deaths Model calculates the probability of life loss in every location in the building, based on smoke hazard values obtained from the Smoke Movement Model and fire spread values obtained from the Fire Spread Model. In this model, the probability of life loss is reduced if there is a refuge area nearby, such as a balcony, which the occupants can use to avoid the hazard. The model then calculates the expected number of deaths for the fire scenario being considered, based on the residual population obtained from the Evacuation Model and the life loss probability values. The expected number of deaths is used in the Expected Risk to Life Model to calculate the total expected risk to life.

The Expected Risk to Life Model calculates the overall expected risk to life (ERL) by using expected number of deaths in the building for each fire scenario obtained from the Expected Number of Deaths Model, and fire rates and probability of occurrence of each scenario obtained from the Design Fire Model.

### 3.3 FIERAsystem Model

FIERAsystem (Fire Evaluation and Risk Assessment system) is a new computer model being developed at NRCC to evaluate fire protection systems in industrial buildings, with a primary focus on warehouses and aircraft hangars [44].

FIERAsystem has been designed as a tool that can be used to do performance-based fire protection engineering design. FIERAsystem provides several calculation options, which allow the user to use standard engineering correlations, run individual submodels, conduct a hazard analysis, or conduct a risk analysis. The standard engineering correlations are a collection of relatively simple equations and models that can be used to quickly perform simple fire protection engineering calculations, including procedures for calculations in the general areas of fire development, plume dynamics, smoke movement, egress, fire severity and ignition of adjacent objects. In FIERAsystem, a calculation can also be performed to evaluate a single part of the fire protection system by running only a single submodel, such as the detection model. In addition, a complete hazard or risk analysis can be conducted using the models supplied with FIERAsystem.

The following section will present the main submodels included in FIERAsystem, while the related probabilistic approach is omitted because it is similar to that used in FiRECAM, which has been introduced in the previous section.

#### 3.3.1 Fire Development and Smoke Movement Models

Models are currently available in FIERAsystem for the following fire scenarios: liquid pool fires, storage rack fires, and t-squared fires. Each of the Fire Development Models calculates the quantities characterizing the fire (heat release rate, temperature and thermal radiation heat fluxes) as functions of time. Currently, the equations used are standard engineering correlations, such as those found in the SFPE Handbook of Fire Protection Engineering [45].

The thermal radiation heat fluxes from the pool fire to a point located 1 m from the ground at various distances are calculated using the solid flame model of Mudan and Croce [46]. A height of 1 m was chosen so as to be representative of the mid-height of a person. At each time step, the heat flux from the pool fire is calculated at the outside of each of a number of rings located from the center of the room to the boundary of the compartment. These heat fluxes are used by the life hazard model to calculate the probability of death from exposure to high heat fluxes [47].

FIERAsmoke is a two-zone model for calculating smoke production and spread through the compartments in a building. For each of the two zones, differential equations based on mass, energy and species conservation are solved, subject to boundary and initial conditions based on user input. These equations consider the combustion process, vent flows, plume entrainment, and conduction, convection and radiation heat transfer. The output of this submodel provides information on the temperature and thickness of smoke layers and species concentrations throughout the building. Thermal radiation heat fluxes from the smoke layer in each compartment are also calculated by the model. More details on this model can be found in Fu and Hadjisophocleous [48].

#### 3.3.2 Fire Detection and Suppression Effectiveness Models

Activation times of heat detectors, smoke detectors and sprinkler heads are determined using the Fire Detection Model. Standard engineering correlations are used to predict the temperatures and velocities at different locations within the fire plume, ceiling jet and smoke layer. This information is then used to calculate the temperatures of all detection elements in the space with time. The time-dependent temperature of each detection element (or rate of temperature increase, for rate of rise detectors) is then used to determine the activation time of each heat detector and sprinkler head in the space. Information on the smoke layer is used to predict the activation time of smoke detectors in the space [49].

The Suppression Effectiveness Model calculates the effect of automatic suppression systems on fires in the building. The model requires the user to input a suppression effectiveness value from 0 to 1.0, which quantifies the ability of the automatic suppression devices to extinguish the fire scenarios being considered. This value is then used to modify the fire heat release rate, diameter, thermal radiation heat fluxes, and plume temperature.

#### 3.3.3 Building Element Failure

Times to failure for the structural elements and barriers in the building are estimated using the Building Element Failure Model. Presently, the program can do calculations for steel beams and columns, concrete slabs, wooden beams and columns, and wood frame walls and floors. Calculations are performed based on standard fire protection engineering correlations, or use numerical techniques, such as finite difference heat transfer models, for some structural elements. The output of these models consists of the predicted time of failure of the structural element or barrier and, in some cases, the yield stress and modulus of elasticity at elevated temperatures. The predicted failure times of the building elements are used by the fire spread model to calculate spread of fire from the compartment of fire origin to other compartments in the building.

#### 3.3.4 Fire Department Response and Effectiveness

The Fire Department Response Model is used to determine the expected fire department response and intervention times, which are calculated using the times estimated for notification, dispatch and preparation, travel and set-up. These calculations are based on factors such as the fire scenarios selected by the user and activation times for the detectors in the building. The presence of fire alarms in the building (and if these are connected directly to the fire department), occupant response to fire cues or other warning signals, the location of the building relative to the fire department, and preplanning, are also considered in the calculations.

Once fire department activities begin, the effectiveness of these activities is estimated by the Fire Department Effectiveness Model according to information on the fire development at the time suppression commences and the resources (e.g., equipment, water and human resources) available to the fire department. Factors such as the nature of the department (e.g. professional, volunteer or a combination of both), and fire fighters' experience and training are also considered in this calculation.

#### 3.3.5 Occupant Response and Evacuation

The Occupant Response and Evacuation Models are used to track the movement of occupants in the building during the selected fire scenarios, based on the occupant characteristics entered by the user. Calculations take into account the processes of perception (occupants become aware of fire by means of direct perception of fire cues, warning by alarm or others, etc.), interpretation (occupants make decision to respond), and action (e.g. occupants call fire department, pull alarm, begin to evacuate, etc.). Once the occupants respond to the fire, the submodel then calculates their movement, taking into account their locations, characteristics, fire development and smoke movement [50].

#### 3.3.6 Life Hazard and Expected Number of Deaths Models

The FIERAsystem Life Hazard Model calculates the time-dependent probability of death for occupants in a compartment due to the effects of being exposed to high heat fluxes and hot and/or toxic gases. The Life Hazard Model uses input from other FIERAsystem models that describe the heat fluxes (Fire Development and Smoke Movement Models) in the compartment, and the temperature and chemical composition of hot gases (Smoke Movement Model) [51].

The time-dependent probability of death from exposure to high thermal radiation heat fluxes at a given location in the compartment is calculated using the sum of the heat fluxes from the fire (calculated by the Fire Development models) and from the hot smoke layer (calculated by the Smoke Movement Model). The revised vulnerability model of Tsao and Perry [52] is used to calculate the probability of death from the heat flux data.

The probability of death due to breathing toxic gases is calculated using the same techniques originally developed for FiRECAM™.

The FIERAsystem Life Hazard model also considers the probability of death due to breathing or being exposed to hot gases, where a person would become incapacitated because of heat stroke, skin burns and/or respiratory tract burns.

The total probability of death, at a given location in the compartment is calculated using the union of the individual probabilities of death from being exposed to high thermal radiation heat fluxes, and breathing hot or toxic gases.

The Expected Number of Deaths Model calculates the number of occupants expected to die in each compartment with time as a result of exposure to toxic and hot gases and thermal radiation. This calculation is based on the residual population in each compartment computed by the evacuation model and the probability of death in that compartment computed by the Life Hazard model. At each time step, the expected number of deaths is computed by multiplying the probability of death at that time with the residual live population at that time. The total number of deaths for each fire scenario is then used by the Expected Risk-to-Life model, together with the probability of each scenario, to calculate the Expected Risk to Life (ERL).

#### 3.3.7 Economic and Downtime Models

The Economic model calculates the following costs and losses: capital cost of building construction, capital cost of building contents, capital cost of fire protection systems, annual cost of fire protection systems maintenance and associated activities, cost of building and contents damage during a fire. Damages to the building and contents are estimated for each fire scenario using information from the Fire Development and Smoke Movement submodels and the sensitivities of the building and contents to the presence of smoke, heat and water, which are user inputs. These damage estimates are then used along with the cost information to estimate the value of the property loss for each fire scenario. Combined with the probability of each scenario FIERAsystem calculates the Fire Cost Expectation (FCE).

The Downtime Model calculates the amount of time that operations in a building will be shut down after a fire based on the information on the expected downtime for various levels of fire damage. This information is then compared with estimates of damages to the building and contents for the fire scenarios selected by the user based on information from the Fire Development and Smoke Movement submodels and the sensitivities of the building and contents. Based on this comparison, an expected downtime for operations in the building is calculated.

### 3.4 CRISP Model

CRISP (Computation of Risk Indices by Simulation Procedures) is a tool developed at Fire Research Station to assess fire risk based on simulation models and Monte Carlo methods. This model includes mechanisms representing physical and chemical process of fire development as well as the behavior of people trying to escape from the fire. Statistical techniques based on Monte Carlo methods are used to handle random parameters. The sub-models representing physical objects include rooms, doors, windows, detectors, items of furniture, hot smoke layers and people. The stochastic aspects include starting conditions such as whether windows and doors are open or closed, the number, type and location of people in the building, the location of the fire and the type of the burning item. Typically, the output of the studies is in the form of a distribution representing fire loss or the number of casualties. Using this model, it is possible to examine the risk to the occupants under a wide range of circumstances. A new version of the model is being developed to improve the simulation of fire growth and smoke movement as well as human behavior [6,22].

### 3.4.1 Probabilistic Approach

The stochastic aspects fall into two categories – random processes and random initial conditions. In principle any parameter could be taken as a random variable depending on the degree of the uncertainty of the value and the sensitivity of the overall result to the value. This model is intended to deal with fires in domestic houses of two to three stories. All the fires of buildings of this category are further divided according to the season of the year, time of the day, room of fire origin, and type of the item first ignited. For each replication of the simulation, the fire scenario is determined by the Monte Carlo rejection method based on the four parameters. The family type and actual smoke detection locations for each replication is also chosen by the rejection method. Once all the input conditions have been defined, the model then predicts how the scenario develops with time, until the fire is put out or all the occupants have escaped or are dead. The simulation is repeated many times and the distribution of the number of casualties versus frequency is built up. The mean number of casualties defines the overall risk given that a fire has started. The scenario selection by the rejection method automatically ensures that the most common scenarios are given greater weight (i.e., simulated more often). Usually, a large number of replications are needed to estimate the mean with a high accuracy. A number of variance reduction techniques may be applied to reduce the required number of replications.

### 3.4.2 Deterministic Models

The basic concept of object-oriented program is that a system may be treated as a collection of objects, which may interact in a number of ways. CRISP II is a zone model, in which each zone is represented by one object. The object classes in CRISP II are: items of furniture, hot gas layers, cold gas layers, vents, walls, rooms, smoke detectors, fire brigade and occupants. These objects are briefly described in the following.

The behavior of a burning item has three main stages: the conversion of fuel to the pyrolyzed state, the conversion of pyrolyzed fuel to fire products, and the transport of fire products to the hot layer together with air entrained by the plume. The empirical equations used to calculate fuel pyrolysis rate, species production rates, heat release rate, plume entrainment rate are presented in reference [22]. A hot layer includes carbon dioxide, carbon monoxide, oxygen, fuel gas, heat and smoke, transferred by the plume of any fire burning in the room. Mass may also flow between hot layers in adjoining layers via vents. Heat of hot layers may be lost through heat transfer. Mass flow through a vent (door/window) is calculated by integrating the Bernoulli equation over the entire area of the vent. Flow rates are only calculated for hot gases, while the flow of cold is assumed to be such that the total volume of gas in each room remains constant. Glass of closed windows may break if the temperature difference between the two sides exceeds about 90 °C. Heat from the hot layer is simply absorbed by walls assuming an infinite specific heat capacity.

The tenability level of a room reflects the degree of undesirability of an occupant remaining in the room. It takes integer values from 0 to 5. Factors affecting the tenability level are the radiation level, depth of the cold layer, the temperature and obscuration of the smoke, and the difficulty in breathing. If the optical density of the smoke exceeds a threshold, it is assumed that the detector sounds an alarm. Once the fire brigade is summoned, they will take a variable time to arrive and set up. After this time, any person still in the building is assumably to be rescued. As for occupants, physiological reaction is first considered for their behavior. The uptake of various toxic compounds is expressed in terms of fractional effective dose (FED), defined for carbon monoxide, oxygen deficiency, carbon dioxide, and convective heat. When some thresholds of FED are exceeded, unconsciousness will occur. People also have a number of sensory perceptions to be aware of the fire or smoke conditions. Once alerted to the fire, the people may take various actions. Each action requires movement to a specified room, followed by a time delay until the action is completed. The first stage of initiating a new action requires a destination to be decided. To make this process easier, people are assumably allowed to access information they should not have. The next stage requires a route to be determined. The algorithm choosing the route will pick one route with the lowest possible degree of difficulty (DOD). Routes with the same DOD from a room will be chosen in the order of their utility ranking. The route choosing occurs instantaneously. At each time step, the person must decide whether to continue following the route or choose some alternative action. At present, the decision process is purely deterministic, depending on the person's type, local room conditions and previous action.

A case study is presented in reference [53]. This study investigates whether the provision of smoke alarms in a building would remove the need for staircase protection. Occupants are classified into three types: leader, led and dependent. The behavioral rules for the dependents do not allow them to escape unaided. It is shown the relative risk of any member of the family dying is significantly increased when dependents comprise more than half of the family present.

## 3.5 Lund QRA Method

Lund University has developed two fire risk assessment approaches, standard Lund QRA (Quantitative Risk Assessment), and extended QRA. The standard QRA is most frequently used in describing risk in the process industries and in infrastructure applications. It has also been applied in the area of fire safety engineering, but as part of a more comprehensive risk assessment of a system, for example, safety in railway tunnels. Standard QRA does not explicitly include any uncertainty analysis. To study the influence of uncertainties in branch probabilities or variables, an extended QRA must be performed. The advantage of using QRA methods is that a large number of events are investigated. Furthermore, in the extended QRA method, inherent uncertainty in the variables is simultaneously considered [9,15,54].

The assessment results for societal risk are usually expressed in terms of an FN (Frequency-Number of deaths) curve or a risk profile in a log-log diagram. The FN curve from a standard QRA can be used to compare different design solutions or to determine whether or not the design complies with tolerable risk levels. The tolerable risk can be defined as a limit line in the FN diagram, usually together with a gray zone in which the risk is tolerable but should preferably be decreased. Another measure to present results for societal risk is to condense the information in the risk profile into one number, the average societal risk. The average risk makes it possible to compare different design alternatives in a simple way. The average risk is basically the sum of the probabilities and consequences in all sub-scenarios.

### 3.5.1 Probabilistic Approach

The probabilistic part of Lund's QRA is based on an event tree description of the scenarios. In this way, the problem can be analyzed in a structured manner. The standard QRA is based on a large number of deterministic sub-scenario outcome estimates, but the method is still considered probabilistic. Treating a large number of sub-scenarios and the associated individual probabilities leads to a probabilistic measure of the risk. In the standard QRA, the consequences and probabilities of the scenarios can be examined individually or together as a system, depending on the objective of the analysis.

Each final outcome in the event tree has its own set of answers, called the Kaplan and Garrick triplet, composed of three variables ($S_i$, $P_i$, $C_i$). The term $S_i$ is the event description, and $P_i$ and $C_i$ describe the probability and consequences of the sub-scenario. The idea of triplets can also be used for situations where variables are subject to uncertainty. Small event trees can be evaluated by hand calculations, but if the event tree is large, commercial software is recommended. Both individual risk and societal risk can be calculated using this method. The assessment results for societal risk are usually expressed in terms of an FN curve or a risk profile in a log-log diagram. The profile displays the information contained in the probabilities $P_i$ and the consequences $C_i$ for all scenarios, fire locations and hazard targets.

### 3.5.2 Deterministic Approach

Fire risk to life for each scenario in Lund's QRA is quantified by calculating the safety margin, i.e., time to reach untenable conditions minus the time for evacuation for each of the scenarios in the event tree. In more detail, the safety margin G is calculated as follows:

$$G = M_s S - D - R - E$$

$M_s$ is the model uncertainty, and S, D, R, E are times to reach critical conditions in the room, time to detect the fire, time for occupants to respond and behave, and time to move out of the room, respectively. Using regression method, the authors obtained the expressions of S and D with respect to fire growth rate and room height and area. R is taken as a random variable. E is calculated using a simple equation with respect to the number of occupants per square meter, floor area, and door width.

Frantzich presented an example regarding the fire risk assessment of a hospital ward [9]. This ward has 22 patients and between 2 and 4 staff members. An event tree with 48 sub-scenarios is established. The probability $P_i$ for each branch is obtained as the product of the branch probabilities, chosen according to subjective judgment, leading to the final outcome. Severity $C_i$ is obtained from the safety margin equation mentioned above for each sub-scenario. Then FN curves are obtained. In addition, the average societal risk is derived from this analysis, providing a simpler measure of risk. The extended QRA is also used to calculate the uncertainties in $P_i$ and $C_i$. The process can be seen as a standard QRA performing a large number of times. Each step in the repeating procedure considers the inherent uncertainty in the variables by using Monte Carlo sampling technique. The societal risk resulting from the extended QRA is expressed in terms of a family of risk profiles, showing no unique risk profile but a range. This method can provide the relevant confidence bounds.

Nystedt gave another case study about a fictive hospital using Lund QRA method [55]. The aim of the study was to quantify the fire risks for a number of trial design solutions when building new hospitals. Expert judgment was used to determine which scenarios would be analyzed quantitatively: the nursing room fire caused by smoking in bed, staff room fire caused by electrical failure in a coffee machine, and the cafeteria fire caused by fire in the deep fryer. Then three trial design solutions with different fire protection measures were evaluated in the analysis. Event trees were also created to include a number of events. A large number of scenarios were derived from the event trees. The two-zone model FAST was used to calculate the elapsed time before critical times are reached. Based on the assessment, the most cost effective design was selected from the three trial design solutions.

### 3.6 Brief Introduction to Carleton University Fire Risk Model

Under the sponsorship of NSERC (Natural Science and Engineering Research Council of Canada), and Forintek Research Corporation, a new computer fire risk model is under development at Carleton University to evaluate fire safety design for four-storey timber-framed commercial buildings. In this model, both risk to life and expected cost will be evaluated based on possible scenarios and the related probabilities. There are two major parts of the model, system model and other submodels. The system model deals with the system methodology and the basic structure of the assessment model, basic functions of each submodel, relationship of all the submodels, as well as data input and output of the whole model. Other submodels include Fire Growth, Smoke Movement, Boundary Failure, Fire Spread, Smoke and Fire Detection, Occupant Response and Evacuation, Fire Department Response and Action, and Economic Loss [56].

The system model sets up a predetermined set of procedures to coordinate all the submodels. Finally, the two decision-making parameters, Expected Risk to Life and Fire Cost Expectation will be obtained. The system model is so designed that the whole model should be as flexible as possible. This is partly achieved by making the system model open to certain external submodels. For example, this model is to be designed to be able to use CFAST [57] to predict fire growth and smoke movement. This will increase the generality and flexibility of the whole model. In addition, a new life hazard model, which is part of the system model, has recently been developed.

The results of the fire growth and smoke movement model (e.g. CFAST), together with fire spread model, are used to calculate the tenability level of each compartment. The parameters indicating the tenability level include temperature, species concentrations and depth of the smoke layer, radiation flux to its boundary surfaces, and smoke obscuration of each compartment. The fire spread model is used to calculate the time at which the barrier will fail and thus fire spreads to other compartments when flashover fire occurs. A computer model WALL2D developed at Forintek is used to calculate the performance of timber-frame walls to a fire attack [58]. The fire and smoke detection model checks temperatures and species concentrations in each compartment to determine whether the activation conditions are satisfied so that the activation time can be predicted. Other models being developed are the occupant response a fire department response and action model.

## 4. DISCUSSION

As countries worldwide move towards performance-based codes, the need for quantitative risk assessment methods to evaluate whether building fire safety designs comply with the objectives of these codes increases. Quantitative risk assessment usually involves two basic components, identification of scenarios and their likelihood, and quantification of the consequences of these scenarios. Currently, different models treat the two basic issues using different methods. Some use a single "worst credible" scenario as the basis upon which the risk assessment is performed; some use a small number of representative scenarios to represent the whole set of fire scenarios to conduct fire risk assessment, while employing relatively complex physical models; some use a large number of scenarios and Monte Carlo method to assess fire risk, while employing relatively simple physical models. As Bukowski [5] pointed out that, this difference in the development of quantitative fire risk assessment methods raises an interesting question: Is the fire risk affected more by the distribution of possible conditions of the scenarios or by the physical and chemical processes present in the fire itself?

Another problem pointed out by Bukowski in current methods is in generating fire scenarios required by current fire risk assessment models. Only in a few countries, fire incident data are collected that can be used to describe detailed scenarios and their likelihood of occurrence. Thus some risk methods use scenario descriptions and ignition frequency estimates obtained from experts. However, in this approach, data will be skewed by the perception of the expert and lack of representativeness in sampling.

Meacham [3] also made some important comments on some existing risk assessment models. First, in the models based on the risk-cost assessment method, including CESARE-Risk, FiRECAM, and FIERA, certain conservative assumptions and approximations have been made due to the complexity and the lack of sufficient understanding of fire phenomena and human behavior. As a result, these models should not be used for absolute assessments of fire risk and loss, while they are considered to be reliable when used for comparative assessments and for the selection of a cost-effective fire safety system solution. Second, as for the CRISP model, its scope have been limited to two-story residential occupancies, and have been used to evaluate such tradeoffs as fire detection installation versus the need for additional passive fire protection, and caution has been urged relative to the model's use in more complex buildings. Finally, he pointed out challenges and limitations to the use of LUND QRA method, including difficulties in developing appropriate analytical expressions and uncertainty factors.

As computers become faster and faster, some of the assumptions and simplifications made in the earlier versions of various risk assessment models cannot be justified. For this, some of these models have been improved considerably from their earlier versions. For example, the latest versions of CESARE-risk include the distribution of some independent variables using the three-realization approximation. In addition, the models developed for specific occupancies are only applicable to those buildings and cannot be easily extended to other ones. This is mainly due to the implicit assumptions and simplifications made within the computer code.

Another important issue relates to the acceptance of the fire risk assessment methodologies for fire safety designs. For a variety of reasons, acceptance of risk analysis by the fire community is not progressing at a rate that will make fire risk analysis a popular design tool necessary for fire protection designs in a performance based code environment in the near future. Some of the reasons include the lack of education and technology transfer to educate designers and code officials on the use and usefulness of these methods, as well as the lack of proper validation of the models. As, however, more and more professionals begin to recognize the usefulness of risk assessment in a performance-based code environment, it will lead to the acceptance and wider use of this powerful technique.

## REFERENCES


1. J.M. Watts and J.R. Hall, "Introduction to fire risk analysis", SFPE Handbook of Fire Protection Engineering, National Fire Protection Association, Quincy, MA, pp. 5−1 (2002).
2. Society for Risk Analysis, Glossary of risk analysis terms, http://www.sra.org/glossary.htm (2000).
3. B.J. Meacham, "Building fire risk analysis", SFPE Handbook of Fire Protection Engineering, National Fire Protection Association, Quincy, MA, pp. 5−153 (2002).
4. B.J. Meacham, "Addressing risk and uncertainty in performance-based fire protection engineering", Fire Protection Engineering, Vol. 10, pp. 16-25 (2001).
5. R.W. Bukowski, Risk and performance standards, NISTIR 6030, National Institute of Standards and Technology, Gaithersburg, MD 20899-0001, USA (1996).
6. W.G.B. Philips, "Simulation models for fire risk assessment", Fire Safety Journal, Vol. 23, No. 2, pp. 159-169 (1994).
7. V. Beck, "Performance-based fire engineering design and its application in Australia", Proceedings of the Fifth International Symposium on Fire Safety Science, Melbourne, Australia, pp. 23 (1997).
8. D. Yung and V.R. Beck, "Building fire safety risk analysis", SFPE Handbook of Fire Protection Engineering, National Fire Protection Association, Quincy, MA, pp. 5−95 (1995).
9. Frantzich, Håkan, "Risk analysis and fire safety engineering", Fire Safety Journal, Vol. 31, No. 4, pp. 313-329 (1998).
10. K.W. Dungan, "Practical applications of risk-based methodologies", Fire Protection Engineering, Vol. 10, pp. 4-15 (2001).
11. W. Armim, "Accommodating perceptions of risk in performance-based building fire safety code development", Fire Safety Journal, Vol. 34, No. 3, pp. 297-309 (2000).
12. W. Armin, "The importance of risk perceptions in building and fire safety codes", Fire Protection Engineering, Vol. 10, pp. 27-33 (2001).
13. B.J. Meacham, "International experience in the development and use of performance-based fire safety design methods: evolution, current situation and thoughts for the future", Proceedings of 6$^{th}$ International Symposium on Fire Safety Science, International Association for Fire Safety Science, Bethesda, MD, USA (1999).
14. J.R. Mehaffey, "Performance-based design for fire resistance in wood-frame buildings", Proceedings of Interflam '99, pp. 293 (1999).

15. S.E. Magnusson, "Risk assessment", Proceedings of the Fifth International Symposium on Fire Safety Science, Melbourne, Australia, pp. 41 (1997).
16. The Building Regulations, Department of the Environment, London, England (1985).
17. Australian Building Codes Board, Performance-Based Building Code of Australia, Canberra, Australia (1996).
18. S.E. Magnusson, H. Frantzich, B. Karlsson and S. Särdqvist, "Determination of safety factors in design based on performance", Proceedings of the 4th International Symposium on Fire Safety Science, Ottawa, Canada, pp. 937 (1994).
19. H. Frantzich, S.E. Magnusson, B. Holmquist and J.Ryden, "Derivation of partial safety factors for fire safety evaluation using the reliability index β method", Proceedings of the Fifth International Symposium on Fire Safety Science, Melbourne, Australia, pp. 667 (1997).
20. J.M. Watts, "Fire risk assessment schedules", The SFPE handbook of fire protection engineering. Quincy, MA: National Fire Protection Association, pp. 4–89 (1988).
21. J.M. Watts, "Fire risk ranking", The SFPE handbook of fire protection engineering, Quincy, MA: National Fire Protection Association, pp. 5–12 (1995).
22. J.N. Fraser-Mitchell, "An object-oriented simulation (CRISP II) for fire risk assessment", Proceedings of the 4th International Symposium on Fire Science, pp. 793, Ottawa, Canada (1994).
23. J. Kaiser, Experience of Gretener method. Fire Safety Journal, Vol. 2, No. 3, pp. 213-222 (1980).
24. J.M. Watts and E.R. Rosenbaum, "Fire risk assessment for cultural heritage", Interflam 2001, 9th International Fire Science and Engineering Conference, Edinburgh, September 2001, pp. 203 (2001).
25. N.G. Berlin, "Probability models in fire protection engineering", SFPE Handbook of Fire Protection Engineering, 1st edition, National Fire Protection Association, Quincy, MA, p. 4–43 (1988).
26. D. Charters, J. Paveley and F.B. Steffensen, "Quantified fire risk assessment in the design of a major multi-occupancy building", Interflam 2001, 9th International Fire Science and Engineering Conference, Edinburgh, September 2001, pp. 213 (2001).
27. K. Tillander and O. Keski-Rahkonen, "Determination of success probability of fire department intervention for a building fire", International Conference on Engineered Fire Protection Design, San Francisco, June 2001, pp. 163 (2001).
28. J.M. Watts, Fire risk indexing, SFPE Handbook of Fire Protection Engineering, National Fire Protection Association, Quincy, MA, p. 5–125 (2002).
29. H.E. Nelson and A.J. Shibe, A system for fire safety evaluation of health care facilities, NBSIR 78-1555, Centre for Fire Research, National Bureau of Standards, Washington, DC (1980).
30. NFPA 101 A, Guide on alternative approaches to life safety, National Fire Protection Association, Quincy, MA, USA (1995).
31. The Mond Index, 2nd edition, Imperial Chemical Industries (ICI) PLC, Explosion Hazards Section, Technical Department, Winnington, UK (1985).
32. V.R. Beck, "A cost-effective decision-making model for building fire safety and protection", Fire Safety Journal, Vol. 12, No. 2, 121-138 (1987).
33. V.R. Beck, Cost-effective fire safety and protection design requirements for Canadian apartment buildings, Contract report for the National Research Council Canada, Footscray Institute of Technology, Melbourne, Australia, May (1988).
34. V.R. Beck and D. Yung, "The development of a risk-cost assessment model for the evaluation of fire safety in buildings", Proceedings of the 4th International Symposium on Fire Safety Science, Ottawa, Canada, pp. 817 (1994).
35. P. Clancy, "Sensitivity study of variables affecting time-of failure of wood framed walls in fire", Proceedings of the International Wood Engineering Conference, New Orleans, Louisiana, October 1996, pp. 263.
36. L. Zhao and V. Beck, "The definition of scenarios for the CESARE-Risk model", Proceedings of the Fifth International Symposium on Fire Safety Science, Melbourne, Australia, pp. 655 (1997).
37. H. Takeda and D. Yung, "Simplified fire growth models for risk-cost assessment in apartment buildings", Journal of Fire Protection Engineering, Vol. 4, No. 2, pp. 53-66 (1992).
38. Y. He and V. Beck, "Smoke spread in multi-story buildings", Proceedings of the First International Conference on Fire Science and Engineering AsiaFlam-95, Hong Kong, pp. 507, March (1995).
39. D. Yung, G.V. Hadjisophocleous and G. Proulx, "Modelling concepts for the risk-cost assessment model FiRECAM and its application to a Canadian government office building", Proceedings of the Fifth International Symposium on Fire Safety Science, Melbourne, Australia, pp. 619 (1997).
40. G.V. Hadjisophocleous and D. Yung, "Parametric study of the NRCC fire risk-cost assessment model for apartment and office buildings", Proceedings of the 4th International Symposium on Fire Safety Science, Ottawa, Canada, pp. 829 (1994).
41. J. Gaskin and D. Yung, Canadian and U.S.A. fire statistics for use in the risk-cost assessment model, IRC Internal report no. 637, National Research Council Canada, Ottawa, Canada, January (1993).
42. G.V. Hadjisophocleous and D. Yung, "A model for calculating the probabilities of smoke hazard from fires in multi-story buildings", Journal of Fire Protection Engineering, Vol. 4, No. 2, pp. 67-80 (1992).

43. G. Proulx and G.V. Hadjisophocleous, "Occupant response model: A sub-model for the NRCC risk-cost assessment", Proceedings of the 4th International Symposium on Fire Safety Science, Ottawa, Canada, pp. 841 (1994).

44. G.V. Hadjisophocleous, N. Bénichou, D.A. Torvi and I. Reid, "Evaluating compliance of performance-based designs with fire safety objectives", Proceedings of the 3rd International Conference on Performance-Based Codes and Fire Safety Design Methods, Lund, Sweden, pp. 307 (2000).

45. SFPE Handbook of Fire Protection Engineering, 2nd edition, National Fire Protection Association, Quincy, MA (1995).

46. K.S. Mudan and P.A. Croce, "Fire hazard calculations for large open hydrocarbon pool fires", SFPE Handbook of Fire Protection Engineering, 2nd edition, National Fire Protection Association, Quincy, MA, pp. 3−197 (1995).

47. D.A. Torvi, G.V. Hadjisophocleous and J. Hum, "A new method for estimating the effects of thermal radiation from fires on building occupants", Proceedings of the ASME 2000 International Mechanical Engineering Congress and Exposition, Orlando, FL (2000).

48. Z. Fu and G.V. Hadjisophocleous, "A two-zone fire growth and smoke movement model for multi-compartment buildings", Fire Safety Journal, Vol. 34, No. 3, pp. 257-285 (2000).

49. B. Yager and G.V. Hadjisophocleous, FIERAsystem theory report: Detection model, IRC Internal report no. 794, Institute for Research in Construction, National Research Council Canada, Ottawa, ON (2000).

50. G. Proulx, "Evacuation time and movement in apartment buildings", Fire Safety Journal, Vol. 24, No. 3, pp. 229-246 (1995).

51. D.A. Torvi, D.W. Raboud and G.V. Hadjisophocleous, FIERAsystem theory report: Life hazard model, IRC Internal report no. 781, Institute for Research in Construction, National Research Council of Canada, Ottawa, ON (1999).

52. C.K. Tsao and W.W. Perry, Modifications to the vulnerability model: A simulation system for assessing damage resulting from marine spills (VM4), Report CG-D-38-79, U.S. Coast Guard Office of Research and Development, Washington, DC (1979).

53. J. Fraser-Mitchell, "Risk assessment of factors related to fire protection in dwellings", Proceedings of the Fifth International Symposium on Fire Safety Science, Melbourne, Australia, pp. 631 (1997).

54. Frantzich, Håkan, Uncertainty and risk analysis in fire safety engineering, Lund University Report tvbb-1016, Institute of Technology, Department of Fire Safety Engineering, Sweden (1998).

55. F. Nystedt, "A quantified fire risk design method", Fire Protection Engineering, Vol. 10, pp. 41-45 (2001).

56. G.V. Hadjisophocleous and Z. Fu, "A fire risk computer model for commercial timber frame buildings", Submitted to the International Conference on Building Fire Safety Conference to be held in Brisbane from 20-21 November (2003).

57. W.W. Jones and G.P. Forney, "Improvement in predicting smoke movement in compartment structures", Fire Safety Journal, Vol. 21, No. 4, pp. 269-297 (1993).

58. H. Takeda and J.R. Mehaffey, "WALL2D: A model for predicting heat transfer through wood-stud walls exposed to fire", Fire and Materials, Vol. 22, pp. 133-140 (1998).