DRAFT INTERNATIONAL STANDARD ISO/DIS 16732

ISO/TC **92**/SC **4** Secretariat: **AFNOR**

Voting begins on:
2010-04-09

Voting terminates on:
2010-09-09

INTERNATIONAL ORGANIZATION FOR STANDARDIZATION • МЕЖДУНАРОДНАЯ ОРГАНИЗАЦИЯ ПО СТАНДАРТИЗАЦИИ • ORGANISATION INTERNATIONALE DE NORMALISATION

Fire safety engineering — Guidance on fire risk assessment

Ingénierie de la sécurité incendie — Lignes directrices pour l'évaluation du risque d'incendie

(Revision of ISO/TS 16732:2005)

ICS 13.220.01

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Foreword

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Attention is drawn to the possibility that some of the elements of this International Standard may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights.

ISO 16732 was prepared by Technical Committee ISO/TC 92, *Fire safety*, Subcommittee SC 4, *Fire safety engineering*.

Introduction

This draft standard is for use by fire safety practitioners who employ risk assessment based methods. Any fire safety practitioner can have reason to employ such methods. All fire safety decisions involve uncertainty. Probabilities are the mathematical representation of uncertainty, and risk assessment is the form of fire safety analysis that most extensively uses probabilities and so most extensively addresses all types of uncertainty.

Examples of types of such fire safety practitioners include fire safety engineers; authorities having jurisdiction, such as territorial authority officials; fire service personnel; code enforcers; code developers; insurers; fire safety managers; and risk managers. Users of this draft Standard are to be appropriately qualified and competent in the fields of fire safety engineering and risk assessment. It is particularly important that the user understand the limitations of application of any methodology that is used.

Risk assessment is preceded by two steps – establishment of a context, including the fire safety objectives to be met, the subjects of the fire risk assessment to be performed, and related facts or assumptions; and identification of the various hazards to be assessed.

The subjects of fire risk assessment include the design and control of any part of the built environment, such as buildings or other structures. Fire risk assessment of a design consists of analysis of the risks – frequency and severity of harm – that are predicted to result if the design is implemented, combined with an evaluation of the acceptability of those risks.

Fire risk assessment can be used to support any decisions about fire prevention or fire protection of new or existing built environments, such as buildings, where probabilistic aspects, such as fire ignition or the reliability of fire precautions, are important. Fire risk assessment also can be used to establish safety equivalent to a code, to assess the balance between the cost and the risk reduction benefit of a proposal, or to examine acceptable risk specifically for severe events. Fire risk assessment also can be used to provide general guidance or to support choices in the selection of scenarios and other elements of a deterministic analysis.

Fire risk assessment can be used as part of compliance with ISO 23932, and all the requirements of ISO 23932 apply to any application of this International Standard. For example, section 10.2 describes the use of qualitative or quantitative fire risk assessment in the selection of design fire scenarios and related elements of analysis. Section 6.2.8 of ISO 16732 addresses the use of fire risk assessment solely for the selection of design fire scenarios. Also, section 11.1.1 of ISO 23932 addresses fire risk assessment as one of the calculation methods that can be selected for a fire safety engineering analysis. All of ISO 16732 is relevant to this use of fire risk assessment.

Fire safety engineering — Guidance on fire risk assessment

1 Scope

This International Standard provides the conceptual basis for fire risk assessment by stating the principles underlying the quantification and interpretation of fire-related risk. These fire risk principles apply to all fire-related phenomena and all end-use configurations, which means these principles can be applied to all types of fire scenarios.

This International Standard is designed as a guide for future standards that provide formal procedures for the implementation of the risk assessment principles for specific applications, e.g., situations in which only certain types of fire scenarios are possible. Those future standards will complete the process of full standardization begun by this International Standard, which not only specifies the steps to be followed in fire risk assessment but also provides guidance for use in determining whether the specific approach used for quantification falls within an acceptable range.

Principles underlying the quantification of risk are presented in this International Standard in terms of the steps to be taken in conducting a fire risk assessment. These quantification steps are initially placed in the context of the overall management of fire risk and then explained within the context of fire safety engineering, according to ISO/TR 13387. The use of scenarios and the characterization of probability (or the closely related measure of frequency) and consequence are then described as steps in fire risk estimation, leading to the quantification of combined fire risk. Guidance is also provided on the use of the information generated, i.e., on the interpretation of fire risk. Finally, there is guidance on methods of uncertainty analysis, in which the uncertainty associated with the fire risk estimates is estimated and the implications of that uncertainty are interpreted and assessed.

This International Standard is not structured to conform with any national regulation or other requirement regarding the use of fire risk assessment or the type of analysis that is to be performed under the name of fire risk assessment.

2 Normative references

The following referenced documents are indispensable for the application of this International Standard. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO/TR 13387:1999, *Fire safety engineering*.

ISO 13943, *Fire safety – Vocabulary*.

ISO 16730, *Fire safety engineering — Assessment, verification and validation of calculation methods*.

ISO/TS 16733, *Fire safety engineering — Selection of design fire scenarios and design fires*.

ISO/TR 16738, *Fire-safety engineering — Technical information on methods for evaluating behaviour and movement of people*.

ISO 23932, *Fire safety engineering — General principles*.

3 Terms and definitions

Shown below are a number of definitions of terms and concepts that are relevant to fire risk assessment and are not already contained in ISO 13943. Shown in Annex A are additional definitions of terms and concepts that either describe specific fire risk analysis methods or can be relevant to fire risk assessment but are not used in this standard.

3.1
acceptance criterion
<fire risk assessment calculations> qualitative and quantitative criterion which forms an acceptable basis for assessing the safety of a built environment design, defined on particular fire risk measurement scales

See 3.9.

NOTE Adapted from ISO 13943:2008, definition 4.2.

3.2
consequence
outcome or outcomes of an event, expressed positively or negatively, quantitatively or qualitatively

3.3
design load
<fire risk assessment calculations> fire scenario with sufficient severity to provide an appropriate basis for assessing whether a design will produce unacceptably large consequences

NOTE 1 An acceptable design may result in unacceptably large consequences under a scenario more severe than the design load.

NOTE 2 In structural risk analysis, a “design load” is a mechanical load sufficiently large as to provide an appropriate basis of testing whether a design will fail.

NOTE 3 The severity of the design load is usually defined in terms of a single continuous scale of fire size or intensity.

3.4
engineering judgement
process exercised by a professional who is qualified by way of education, experience and recognised skills to complement, supplement, accept or reject elements of a quantitative analysis

3.5
event tree
depiction of temporal, causal sequences of events, built around a single initiating condition

NOTE 1 Adapted from ISO 13943:2008, definition 4.85.

NOTE 2 A fire scenario in an event tree is given by a time-sequence path from the initiating condition through a succession of intervening events to an end-event. Each fire scenario corresponds to a different branch of the event tree, and the branches collectively comprise or represent all fire scenarios. For an introduction to decision tree analysis, see Reference [1].

3.6
fault tree
depiction of the logical dependencies of events on one another, built around a critical resulting event, which usually has an unacceptable level of consequence and may be described as a failure

NOTE 1 Adapted from ISO 13943:2008, definition 4.95.

NOTE 2 A fire scenario in a fault tree is given by that critical resulting event and one of the alternative, fully specified logical sequences by which that critical resulting event can occur. For an introduction to decision tree analysis, see Reference [1].

3.7
fire hazard
condition with a potential for an undesirable consequence from fire

NOTE 1 Adapted from ISO 13943:2008, definition 4.112.

NOTE 2 Fire hazard can be a measure of consequence, using the term “potential” in a quantitative sense, or a physical object or condition with the potential to affect the frequencies or consequences of certain fire scenarios.

3.8
fire risk
(a) <scenario fire risk> combination of the probability of a fire and a quantified measure of its consequence
(b) <fire risk of design> combination of the frequencies and consequences of scenarios associated with the design

See 3.14.

NOTE 1 The (a) definition is adapted from ISO 13943:2008, definition 4.124.

NOTE 2 In definition 3.8(b), risk is typically expressed as risk per unit time, which is the reason that frequency is used instead of probability in the definition. Frequencies are normally calculated for fire scenario clusters (see 3.16), and consequences are normally calculated for representative fire scenarios (see 3.15).

3.9
fire risk, acceptable
<fire risk evaluation calculation> risk that satisfies defined acceptance criteria

See 3.1

3.10
fire risk assessment
<built environment fire risk calculation> well-defined procedure for estimation of fire risk for a built environment and evaluation of estimated fire risk in terms of well-defined acceptance criteria

3.11
fire-risk curve
graphical representation of fire risk

NOTE 1 Adapted from ISO 13943:2008, definition 4.125.

NOTE 2 Normally a log/log plot of cumulative probability versus cumulative consequence; when consequences are measured as fatalities, fire-risk curve is also called an fN-curve, where f refers to frequency and N refers to number of deaths.

3.12
fire risk evaluation
comparison of estimated risk, based on fire risk analysis, to acceptable risk, based on defined acceptance criteria

3.13
fire risk matrix
matrix display in which (a) rows or columns are defined by ranges of fire scenario cluster frequencies, (b) columns or rows are defined by ranges of fire scenario design loads, and (c) cell entries are specified acceptable consequences for the scenario clusters contained in the cell’s row and column

NOTE A fire risk matrix implicitly assumes that the design itself has no influence on the size or intensity of the fire challenging the building, but rather treats the fire scenario as an externally imposed load.

3.14
fire scenario

qualitative description of the course of a fire with time, identifying key events that characterise the fire and differentiate it from other possible fires

See 3.15 and 3.16.

NOTE 1 Adapted from ISO 13943:2008, definition 4.129.

NOTE 2 The fire scenario description typically includes the ignition and fire growth processes, the fully developed fire stage, the fire decay stage, and the environment and systems that will impact on the course of the fire. Unlike deterministic fire analysis, where fire scenarios are individually selected and used as design fire scenarios, in fire risk assessment, fire scenarios are used as representative fire scenarios within fire scenario clusters.

3.15
fire scenario, representative

specific fire scenario selected from a fire scenario cluster such that the consequence of the representative fire scenario can be used as a reasonable estimate of the average consequence of scenarios in the fire scenario cluster

See 3.14 and 3.16.

NOTE For additional information, see ISO/TR 13387-1, Section 8.2.1, a) to f).

3.16
fire scenario cluster

subset of fire scenarios, usually defined as part of a complete partitioning of the universe of possible fire scenarios

See 3.14 and 3.15.

NOTE 1 For additional information, see ISO/TR 13387-1, Section 8.2.1, a) to f).

NOTE 2 The subset is usually defined so that the calculation of fire risk as the sum over all fire scenario clusters of fire scenario cluster frequency multiplied by representative fire scenario consequence does not impose an undue calculation burden.

3.17
limit state

<fire risk assessment calculation> threshold or limiting value on a consequence scale that marks the line between acceptably large consequence and unacceptably large consequence

NOTE A limit state equates a condition of the built environment with just barely acceptable consequence, and so the term is usually used in the context of a time-sequence state description of the fire scenario. Such a description defines the scenario in terms of states, and that provides a basis for identifying states that are and are not limit states. In the context of structural engineering, a “limit state” defines a state beyond which the structure no longer satisfies the design performance requirements.

3.18
reliability

probability that a unit will perform a required function for given conditions and for a given period of time

NOTE Reliability applies to the performance of any building or product design feature whose performance can influence the course of fire development, thereby contributing to the specification of the fire scenario that occurs and the risk consequences associated with that scenario. It is also possible that the design feature performance is better described by a range of partial successes or partial failures. This requires a more general and flexible definition than the one given above.

3.19
risk, individual

measure of fire risk limited to consequences experienced by an individual and based on the individual's pattern of life

See 3.20

NOTE 1 Adapted from ISO 13943:2008, definition 4.195 for "individual accepted risk". There is nothing in the definition that implies or requires acceptance.

NOTE 2 For example, if the fire risk measure is frequency of an unwanted consequence, such as death, then individual risk would be an estimate, typically expressed as events per unit time, of the frequency of that unwanted consequence for a specific individual. The risk measure may be expressed as conditional on exposure to the hazard, such as being at a hazardous location. Individual risk is independent of the number of individuals affected. The individual referenced here can be a person but can also be a company, a site or building, or other single entity.

3.20
risk, societal

measure of fire risk combining consequences experienced by every affected individual

See 3.19.

NOTE 1 Adapted from ISO 13943:2008, definition 4.298 for "societal accepted risk". There is nothing in the definition that implies or requires acceptance.

NOTE 2 The individual referenced here can be a person but can also be a company, a site or building, or other single entity. Combining consequences to all affected parties will also affect the overall frequency of an incident. It will equal the sum of the individual risks of all affected individuals but can be expressed as a rate relative to the number of affected or exposed individuals, in which case it will be in a form directly comparable to the component individual risk measures.

NOTE 3 In societal risk, some consequences experienced by one individual may cancel consequences experienced by another individual. For example, business interruption losses experienced by one company can be exactly offset by increased business income for a competitor not affected by fire.

3.21
risk acceptance

decision to accept an estimated level of risk, based on either compliance with acceptance criteria or an explicit decision to modify those criteria

3.22
risk aversion

given two choices for which the product of frequency and consequence are identical, preference for the choice with the lower consequence

NOTE Risk aversion is one of several risk perception phenomena that can be considered during the risk evaluation phase of a fire risk assessment.

3.23
risk communication

exchange or sharing of information about risk between decision-maker and other individuals, groups or organisations who may affect, be affected by, or perceive themselves to be affected by the risk

3.24
risk management

processes, procedures, and supporting culture for ongoing achievement of desired risk criteria

NOTE 1 Risk management is a combination of risk assessment, risk treatment, risk acceptance, and risk communication.

3.25
risk treatment
(a) process of selection and implementation of risk modification measures, normally used to refer to changes other than changes to design
(b) risk modification measure

NOTE Risk modification measures that are not changes to design include changes to fire safety management procedures.

3.26
sensitivity
measure of degree to which a small perturbation of a system will create a large change in system status

NOTE Sensitivity analysis is useful in setting priorities for uncertainty analysis by focusing attention on variables and parameters having greatest impact on the results and so on variations most likely to change the conclusion of the analysis.

3.27
uncertainty
quantification of systematic and random error in data, variables, parameters, or mathematical relationships; or of failure to include a relevant element

See 3.28.

3.28
uncertainty, propagation of
mathematical analysis of uncertainty of calculated risk as a function of uncertainty in variables, parameters, data, and mathematical relationships used in the calculation

See 3.27.

3.29
variability
quantification of probability distribution function for variable, parameter, or condition

4 Applicability of fire risk assessment

4.1 Circumstances where fire risk assessment is useful

Fire risk assessment is useful in circumstances where it is important to give due consideration to scenarios with low frequency but high consequence. The following examples of such circumstances are not intended to be exhaustive:

a) large numbers of vulnerable people, whose vulnerability results from sleeping, disability, age, impairment, or unfamiliarity;

b) initiating fires with very high fire growth rates; or

c) transitory high fuel loads, particularly in vulnerable areas such as escape paths.

Fire risk assessment is also useful in circumstances where spatial measures of fire size, commonly used in deterministic fire hazard assessments, are insufficient as measures of event severity. The following examples of such circumstances are not intended to be exhaustive:

a) properties involving very high value in small spaces;

b) vulnerable property, such as the contents of clean rooms;

c) contents whose importance is not reflected by its physical size or direct cost, such as the cables controlling safety equipment in a nuclear power facility;

d) properties where the principal form of harm to property is not direct damage, such as properties with high potential for environmental damage, high costs for business interruption, or high potential for lost image and goodwill if a major fire were to occur; or

e) properties that have undergone changes in use, alterations, or renovations.

4.2 Circumstances where fire risk assessment is essential

Fire risk assessment is essential where deterministic fire safety engineering cannot adequately address the fire scenarios of concern. This tends to occur when deterministic treatment of a small number of fire scenarios cannot adequately capture the total fire risk of the property.

Fire risk assessment is essential where reliability is critical, because reliability is inherently probabilistic. For example, fire risk assessment is required if it is necessary to assess the defence in depth of a design that relies heavily on a single fire safety system.

Fire risk assessment is essential where the variability of input parameters has a significant impact on the results. Fire risk assessment is needed where there are significant variations in variables like the number of people, their characteristics, or fire growth rates, and deterministic analysis shows that credible combinations of the variables are not acceptably safe.

Fire risk assessment is essential where a wide range of fire scenarios is deemed to be necessary. Fire risk assessment is needed when a large number of distinct fire scenarios pose sufficiently different challenges to the property and its fire safety goals as to preclude the use of any one scenario to represent others.

5 Overview of fire risk management

Risk management includes risk assessment but also typically includes risk treatment, risk acceptance, and risk communication. Risk acceptance marks the conclusion of risk assessment. If risk is not accepted, another risk assessment is necessary, and risk treatment is an option after each risk assessment. Risk communication is conducted after risk acceptance. (See Figure 1.) Fire risk assessment can also be used to assess alternative designs, prior to selecting a specific design or making changes to that design to achieve compliance with the acceptance criteria.

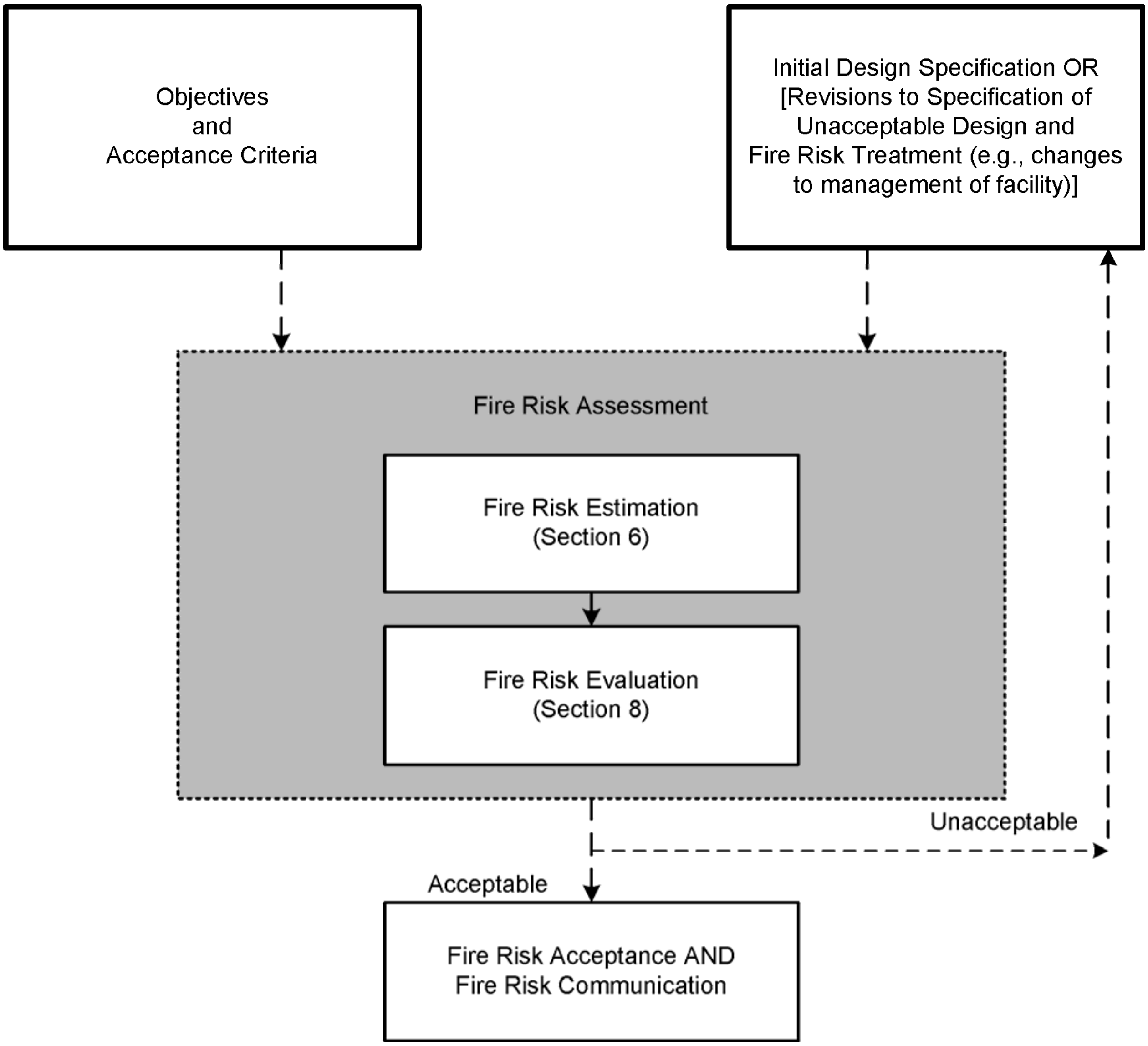


Figure 1 — Fire Risk Management Flow Chart

Fire risk assessment begins with objectives and a proposed design specification for the structure or other part of the built environment to be assessed. The risk associated with the design specification is estimated and then evaluated. Risk evaluation consists of comparison of the estimated risk for the design to the acceptance criteria. If the estimated risk is found to be unacceptable, it is necessary to make changes – either change the design specification or treat the risk or both – and then reassess. If the evaluation is acceptable, it can still be desirable to treat the residual risk, but it will definitely be necessary to formally accept the risk and to communicate the risk to stakeholders.

The stakeholders can decide to accept a risk that the evaluation had found to be unacceptable, and such a change is implicitly a change in the fire safety objectives.

6 Steps in fire risk estimation

6.1 Overview of fire risk estimation

Figure 2 describes the sequence of steps involved in fire risk estimation as it is conducted when the scenario structure is explicit and when frequencies and consequences are explicitly calculated in quantitative form. Later sections describe the use of risk curves, risk matrices and other techniques for which the flow chart is not fully applicable in detail.

Fire risk estimation begins with the establishment of a context. The context provides a number of quantitative assumptions, which are required with the objectives and the design specifications to perform the estimation calculations.

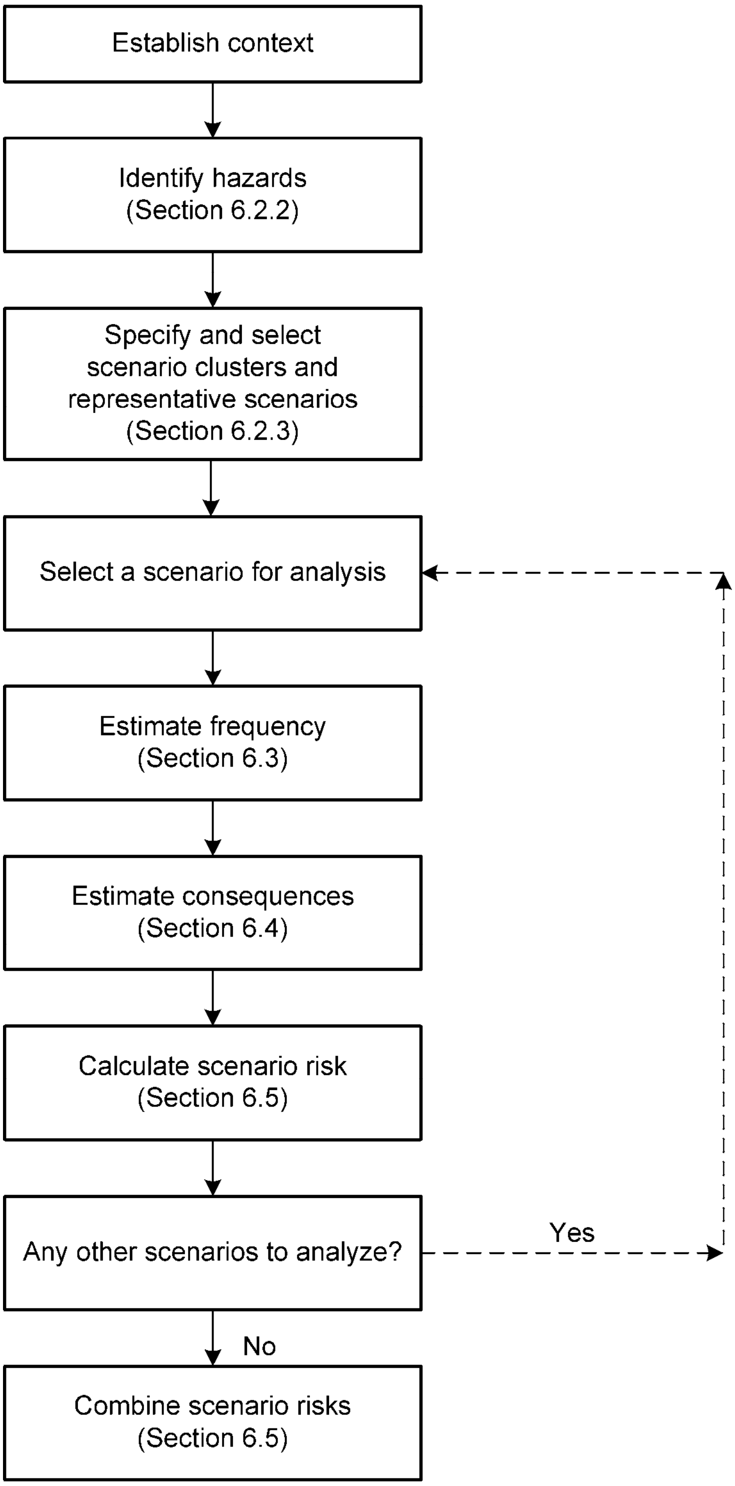


Figure 2 — Fire risk estimation flow chart

The next step is identification of hazards, which are then used as the basis for specification and selection of the scenario clusters and associated representative fire scenarios that will form the basis for the estimation. One scenario cluster and representative scenario pair is then selected for analysis, and the frequency of that scenario cluster and consequence for that scenario are estimated. This procedure is repeated until all the selected scenarios and scenario clusters have been analyzed. The combined fire risk for the design is then calculated as the fire risk for all scenarios combined.

An abbreviated fire risk calculation can be used to select a small number of scenarios for a deterministic evaluation. (See Section 6.2.4 and ISO/TS 16733.) If this is the application, then the final step is not combining the scenario fire risks but selecting the scenarios with the highest scenario fire risks (or perceived fire risks, if for example risk aversion is explicitly considered). That alternative final step is not shown on Figure 2 because it is not a step in fire risk estimation.

6.2 Use of scenarios in fire risk assessment

6.2.1 Overview of specification and selection of scenarios

The number of distinguishable fire scenarios is too large to permit analysis of each one. Therefore, any fire risk assessment must develop a scenario structure of manageable size but must also make the case that the estimate of fire risk based on these scenarios is a reasonable estimate of the total fire risk. The principal techniques to achieve these goals are identification of hazards, combining of scenarios into clusters and exclusion of scenarios with negligible risk.

6.2.2 Identification of hazards

Identify all conditions with potential for undesirable consequences. Develop this list of hazards into a description of the universe of possible fire scenarios. The conditions creating the hazard can be used as part of the specification of the associated fire scenarios. (Additional guidance for this step is contained in ISO/TS 16733, Section 6.2.4, Step 3 – Potential fire hazards).

Each fire scenario comprises a qualitative description of the course of a fire with time, identifying key events that characterize the fire and differentiate it from other possible fires. It typically defines the ignition and fire growth process, the fully developed stage, and the decay stage, together with the building environment and any fire protection systems whose presence or absence and performance if present provide part of the basis for calculating fire growth. (Additional guidance for this step is contained in ISO/TS 16733, Section 6.2.3, Step 2 – Type of fire).

Location should be specified not only in terms of the room or space of fire origin but also in terms of location within that space. The positioning of a fire in the middle of a room versus in a corner of a room can greatly influence subsequent fire development. Areas of origin should not be limited to rooms but should address means of egress, concealed spaces, and exterior surfaces. Positioning relative to the locations of automatic fire detection or suppression equipment should also be included in the location specification because of the likely effects on fire development. (Additional guidance for this step is contained in ISO/TS 16733, Section 6.2.2, Step 1 – Location of fire).

Variable conditions of the building and its occupants should be considered as elements in scenario definition. These conditions include the composition, location, and quantity of nearby combustibles that will determine early fire development, as well as the locations, basic capabilities (e.g., handicapped), and transitory capabilities (e.g., impaired by drugs or alcohol) of occupants.

Variable statuses of fire protection features of the building should be considered as elements in scenario definition for fire risk assessment. These statuses include the status of doors and windows as open or closed and the status of automatic detection or suppression equipment as operational or not operational.

6.2.3 Combining scenarios into scenario clusters

The characterisation of scenarios performed in section 6.2.2 should now be refined into a concise, parametric description of the universe of possible scenarios. For example, one could identify five types of rooms or areas (e.g., normally occupied rooms, normally unoccupied rooms, means of egress, concealed spaces, exterior locations) or three ranges for the rate of increase in fire severity (e.g., linear growth, corresponding to smouldering, and two ranges for the alpha parameter in a t-squared fire representation, corresponding to flaming and fast flaming). By selecting a type or range from each parameter, the user defines a specific scenario cluster, which combines more fully specified scenarios (e.g., each of the specific points of origin in each of the rooms that fit a particular room type). Each scenario cluster is represented by a single representative fire scenario whose consequence will be used to characterize the average consequence for all scenarios in the cluster.

6.2.4 Exclusion of scenarios with negligible risk

The set of fire scenario clusters, each with its associated representative fire scenario, is the first representation of the scenario structure. At this point, the user can reduce the size and complexity of the scenario structure by excluding scenario clusters that are known to have such low risk that their exclusion, individually or collectively, will not significantly affect the calculation of the risk measure. Such exclusions shall be explicitly justified. Either high frequency or high consequence can produce a significantly large fire risk for a scenario cluster.

As part of considering scenario clusters and representative fire scenarios for inclusion or exclusion, consider the uncertainty regarding their frequencies and consequences. If the uncertainty is such that a scenario cluster could be eligible for inclusion, then an appropriately conservative selection procedure will include those scenario clusters. If the selection is done before any uncertainty information has been developed, then consider that there is often more uncertainty involved in estimating the frequency of a scenario cluster than in estimating the consequence of its representative fire scenario. Therefore, a conservative selection procedure will include more rare-event scenario clusters. Note the distinction here between a conservative selection procedure as contrasted with conservative estimates of frequency and consequences. A conservative selection procedure can improve the accuracy of the risk estimates, while conservative estimates will introduce unknown biases and not improve accuracy.

6.2.5 Demonstrating that the scenario structure is appropriate and sufficient

Provide a mapping of the universe of potential scenarios into scenario clusters either selected for analysis or specifically excluded, as specified in sections 6.2.3 and 6.2.4. This will establish that all scenarios have been considered and that their treatments were explicitly chosen.

If two or more candidate designs are to be compared to each other rather than to externally defined acceptability criteria, then scenario clusters can be excluded even if they involve significant risk, if the two designs can be expected to have similar or identical risk in those scenarios, where “similar” means that the expected difference in risk for the scenarios proposed for exclusion is substantially less than the expected difference in risk for the scenarios proposed for explicit analysis. Set these expectations on the basis of engineering judgement. Because consensus engineering judgment can reflect a shared misperception of the true risk, these kinds of exclusions should be few in number.

In any scenario structure, it is difficult to strike an appropriate balance between high-frequency, low-consequence scenarios and low-frequency, high-consequence scenarios. Yet, both are important.

6.2.6 Fire risk assessment without explicit scenario structures

Some fire risk assessment methods do not use an explicit scenario structure. Examples include analysis using risk curves or risk matrices. Even if an explicit scenario structure is not used, it is necessary to provide evidence that the underlying or implicit scenario structure is appropriate and sufficient. Examine the procedure for implicit assumptions regarding the specification, inclusion or exclusion, and relative likelihood of underlying scenarios. Then use engineering judgment to identify and document sources of bias in those assumptions, and propose changes to the analysis to compensate for those biases in the interpretation.

6.2.7 Behavioural scenarios

For purposes of analysis, it will normally be necessary to specify not only fire scenarios but also behavioural scenarios, in which the number, characteristics and behaviours of occupants related to fire, including egress, are specified. Additional guidance on behavioural variables is provided in ISO/TR 16738 and in ISO/TS 16733, Section 6.2.6, Step 5 – People response.

6.2.8 Fire risk assessment for selecting design fire scenarios for deterministic analysis

When the selection of design fire scenarios for deterministic analysis is the purpose, it is possible to abbreviate the estimation process, for example, using engineering judgment, readily available data, and order-of-magnitude values for estimation of frequencies and consequences. In this approach, the mapping of all potential scenarios into scenario clusters is normally highly abbreviated and is typically not done explicitly. The name given to the scenario cluster is normally based on the obvious choice for representative fire scenario.

More detailed guidance on this use of fire risk assessment is provided in ISO/TS 16733.

6.3 Characterization of frequency and probability

As shown in Figure 2, a frequency must be estimated for each fire scenario cluster included in the final scenario structure in compliance with sections 6.2.1 to 6.2.7. Section 6.3.1 describes alternative general methods of frequency estimation, and Sections 6.3.2 and 6.3.3 provide specific guidance for estimation of frequencies of ignition and probabilities of system status, respectively. (Additional guidance is provided in ISO/TS 16733, Section 6.3.2, Step 7 – Consideration of probability).

6.3.1 Methods of estimation of probabilities and frequencies

The probabilities and frequencies discussed here are initiating event frequencies and status probabilities, including reliability measures. Some risk analysis methods, such as state-transition models, require additional probabilities. For detailed, broadly applicable guidance on estimation of needed probabilities, see Reference [2].

Probability and frequency values can be obtained from any or all of three approaches: (1) direct estimation from data; (2) inference from a model that relates the probabilities and frequencies of interest to other probabilities and frequencies, such as relating the frequency of fire ignition to frequencies of equipment component failure, relevant human error, proximity of readily ignited materials, and the like; and (3) engineering judgment.

Note that while frequencies and probabilities are themselves expressions of uncertainty, there is also uncertainty attached to the estimates of these frequencies and probabilities. This uncertainty is part of the uncertainty to be examined in the uncertainty analysis phase.

In estimating probabilities and frequencies, there are certain common errors or biases, and the following steps are designed to reduce or avoid these errors and biases:

— Be aware that individuals often under-estimate low frequencies and probabilities and over-estimate high frequencies and probabilities. Seek to compensate for this common tendency when eliciting judgment estimates. Do not seek to compensate by deliberately over-estimating the high consequences associated with low frequencies or deliberately under-estimating the low consequences associated with high frequencies.

— Do not assume that conditions and events are statistically independent. Look for common-cause events, correlated high-risk occupant characteristics, and other situations where the combined probability will be higher than the product of the component probabilities. For example, practices that make ignition more likely are typically associated with practices that reduce the performance or reliability of active and passive fire protection systems and features, resulting in non-operational detectors and sprinklers, penetrations in walls, doors blocked open, or other degradations of fire safety systems and features.

- Use fire incident data in estimating ignition frequencies. It is not unusual for engineering judgment to over-estimate the relative likelihood of scenarios involving the special hazards and conditions of a property while under-estimating or ignoring common scenarios such as heating-equipment or electrical-system fires.

- When selecting databases, place at least as much emphasis on data representativeness as on data quality. It is not unusual for engineers to rely on databases with the highest quality and thoroughness of fire investigation in each incident. Such databases lead to misleading results in probability and frequency estimation, because they include only a small fraction of the fires that occur and are biased toward fires with high death tolls, thereby missing the smaller fires where most deaths actually occur and many of the largest fires in terms of property damage.

- Redundancy of fire safety systems and features is neither necessary nor sufficient for high overall reliability. Estimates of reliability should not use redundancy as a dependable indicator of high reliability.

- Do not use a frequency estimate of zero for fires that have never occurred or have never been documented in the databases used for analysis. Instead, use a larger scenario cluster for which a meaningful frequency can be calculated or consider the use of extreme value statistical methods to estimate a non-zero frequency for an event that is known not to have yet occurred.

6.3.1.1 Probability and frequency estimation directly from data

Probabilities and frequencies estimated from data typically are estimated as ratios, each of which is calculated from a numerator of an estimated number of relevant events and a denominator giving the extent of exposure or opportunities for events to occur. Denominator measures for frequencies include time units (e.g., events per year), people (e.g., fires per thousand persons located in a property), valued property (e.g., fires divided by total value of all buildings and contents), spatial entities (e.g., fires per thousand buildings of a type), or other entity (e.g., fires per thousand companies operating buildings of this type). Denominator measures for probabilities include numbers of events (e.g., number of times a fire large enough to activate an operational sprinkler occurs in an area protected by a sprinkler).

Databases for numerators or denominators may be sample-based (permitting a statistically sound basis for estimating the size of the total group, or universe, from which the sample was drawn) or census-type (providing an essentially complete tally of the total group of interest).

6.3.1.2 Probability and frequency estimation using models

A major advantage of using a model is that, unlike the other two methods of estimation, a model typically provides not only the estimates needed to analyse a design but also an understanding of the relationship between changes in the design and changes in the resulting frequencies and probabilities, which will be needed if the fire risk assessment of the initial design does not produce an acceptable estimate of associated risk.

Use of a model does not remove the need for experiential or subjective data but does change the type of data needed. Instead of requiring data to support direct estimation of frequencies or probabilities from data, typically through ratio calculations, a model-based estimate requires data to support estimates of the variables used by the model. For these model variables, data may be more or less difficult to obtain. It may be necessary to trade off the advantages of the model, in terms of sophistication and fundamental grounding, against the uncertainty associated with the data inputs required by the model, as compared with the uncertainty associated with data if used directly.

The simplest type of model for probability estimation is Bayesian analysis, which calculates needed probabilities from other probabilities that may be more easily measured. Bayesian analysis is a mathematical technique for reverse-analyzing conditional probabilities, so that a body of evidence (e.g., a set of observations) can be combined with known probability distributions giving the probability of the evidence given an assumed probability distribution for a parameter of interest to yield a best estimate of the probability distribution for the parameter most consistent with the evidence

Bayes' Law, the basis for Bayesian analysis, is a generalization of the statement that the conditional probability of y given x is equal to the joint probability of x and y, divided by the conditional probability of x given y. In Bayesian analysis, non-observational information, such as the best estimates of experts, can be converted to an equivalent number of observations and used in combination with observational data, in order to produce probability and frequency estimates that are not simply sampling frequencies.

For an introduction to Bayesian analysis, see Reference [3].

Monte Carlo sampling is not an alternative source of probability and frequency estimates but is a numerical method for executing the fire risk calculation from a defined set of probability distributions. The latter are used as a basis for selecting a sample of specific scenarios, with implicitly equivalent probability weightings, so that the average consequence for such a sample is a best estimate of the probability-weighted consequence for the entire universe of scenarios. For detailed guidance on Monte Carlo sampling and variance reduction, see References [4] and [5].

6.3.1.3 Probability and frequency estimation using engineering judgment

Engineering judgment can be made more systematic and consistent from one engineer to another through the use of Delphi methods or other explicit procedures for reducing bias and improving the quality of estimates. For a description of the Delphi method, see Reference [6]. For a comparison of the Delphi method to other procedures, see Reference [7].

Engineering judgment can be done for point values or for ranges. The latter will be subject to less disagreement between estimators and will be sufficient for use in a risk matrix or other qualitative fire risk assessment procedure. For guidance on elicitation of engineering judgment-based estimates, see Reference [8].

6.3.2 Initiating event frequencies

Loss experience used as data for calculation of the numerators of frequencies may be specific to the building being studied, all buildings of a type sharing a common location or owner, or any larger aggregation of properties up to national or international databases. Each of these choices has advantages and disadvantages, in terms of demonstrated relevance, level of detail available, data accessibility, and magnitude of the database to support precise estimates.

Frequencies can be estimated through calculation from estimated frequencies of some but not all of the characteristics of a full scenario. For example, the frequency of a fire due to sparks from a piece of equipment beginning in a factory's production area could be estimated from probabilities that factory fires, when they occur, will be due to sparks combined with frequencies of fires beginning in a factory's production area. In such calculations, it is essential that assumptions of statistical independence not be made without substantiation. Independence needs to be demonstrated, not just assumed.

The most serious example of violation of independence in initiating events is in common cause event fires, such as an earthquake that simultaneously contributes to multiple fire ignitions and breaks the sprinkler piping. Each fire and the damage to sprinkler piping are rare events, but the frequency of the combination event is not equal to the low value given by treating the unconditional probability of each characteristic, given that fire occurs, as a valid estimate of the conditional probability that a fire will have that characteristic, given that it has the other characteristics. Such a calculation will inappropriately compound the unlikelihood of the multi-characteristic event, because the earthquake is a common cause. If an earthquake occurs, which is itself unlikely, then all the other characteristics become likely.

6.3.3 Status probabilities and reliability

Every fire safety feature or system will have alternative possible statuses when ignition occurs, such as detector connected or not connected to power source, sprinkler valve open or closed, and door open or closed. Any status condition that can affect the frequency or consequence of a scenario must be addressed, which requires estimation of a probability for that status.

Other conditions also have status probabilities. The number, locations and conditions of occupants all have associated status probabilities important to the handling of behavioural scenarios. The amounts, locations and burning properties of frequently-moved contents all have associated status probabilities important to the estimation of fire growth and the availability of paths for occupant movement.

Status probabilities refer to conditions at time of ignition. Reliability normally refers to probabilities of events after ignition, such as detector or sprinkler did or did not activate and structural element did or did not continue to bear its load without unacceptable deformation. Reliability probabilities are probabilities of success or failure, where “failure” refers to not performing a required function, in whole or in part and need not refer solely to a failure to activate. For the load-bearing elements of structures, “failure” is most often used to describe collapse. For active fire protection systems, “failure” can be used only when activation does not occur or can also be used when the result of activation is not acceptable or is not in accordance with design specifications.

These are examples of probabilities that are not ignition frequencies but are also required for fire risk estimation. Behavioural scenarios will also require frequencies and probabilities.

6.4 Characterization of consequence

As shown in Figure 2, consequence must be estimated for each representative fire scenario included in the final scenario structure in compliance with sections 6.2.1 to 6.2.7. Sections 6.4.1 through 6.4.3 describe alternative methods of consequence estimation, using loss experience; models; or engineering judgment, respectively. (Additional guidance is provided in ISO/TS 16733, Section 6.3.2, Step 8 – Consideration of consequences).

In estimating consequences, there are certain common errors or biases to be wary of, including:

- When selecting a representative fire scenario, be careful not to assume that the fire scenarios in the scenario cluster are dominated by the lowest or highest severity scenarios. It is not unusual for estimates to be simplified, so that a scenario cluster with a wide variety of scenarios is regarded stereotypically in terms of its most or least severe scenarios. As an example of erring in the direction of too much severity, the average consequence of an arson fire is statistically only slightly greater than the average consequence of an unintentional fire. It is a mistake to assume that a typical arson fire involves multiple points of origin, the use of accelerants, or actions to deliberately impair the operation of fire safety systems or features. As an example of erring in the direction of too little severity, some stovetop or chimney fires spread to and destroy entire buildings even though most remain very small and are quickly and easily extinguished with only minor damage.

- It is difficult to estimate consequences through engineering judgment for scenarios involving partial effectiveness of any fire safety system, feature, or program. Full effectiveness and complete ineffectiveness, which is typically the same as absence of the system, feature, or program, are simpler, easier to visualize, easier to model, and so easier to estimate through judgment. Partial effectiveness often includes a wide variety of different types and degrees of degradation of performance, and the user may not have enough experience to select a specific form of partial effectiveness for estimation purposes.

6.4.1 Consequence estimation from loss experience

When loss experience is used, it can be loss experience specific to the structure (or other part of the built environment) being studied (if it already exists and its design is intended to modify it, as in a building renovation, because clearly, anything new has no loss history), all structures of a common type sharing a common location or owner, or any larger aggregation of structures of a common type, up to national or international databases. Each of these choices has advantages and disadvantages, in terms of demonstrated relevance, level of detail available, data accessibility, and magnitude of database to support precise estimates.

6.4.2 Consequence estimation from models

See the first two paragraphs of section 6.3.1.2 for general guidance on the use of models in risk-related estimation.

Do not assume that a more detailed model leads to more accurate final risk estimates. A more detailed model typically requires much more input data, and some types of data, such as field observation data, is subject to greater uncertainty when estimated in greater detail, because a limited number of real cases is spread more thinly over a larger set of needed estimates. Also, the detail available from a typical deterministic fire model is far greater than the detail available to support the estimation of associated frequencies and probabilities. These two sources of greater data uncertainty can lead to the same uncertainty in the combined estimates as would be achieved with a simpler model.

6.4.3 Consequence estimation from engineering judgment

See section 6.3.1.3 for general guidance on more systematic methods to elicit and use engineering judgments for risk-related estimation.

6.5 Calculation of scenario fire risk and combined fire risk

6.5.1 Mathematical formulations of fire risk

Based on the form of the objectives and acceptance criteria, select an appropriate definition of fire risk. Any such definition will fit the general mathematical formulation of a combination of the frequencies and consequences of all scenarios associated with a design:

> Risk = ∑ f (frequency, consequence of a given scenario), for all scenarios (conforming to one of the definitions of risk in ISO/TR 13387).

The two most frequently used specific mathematical formulations are:

> Risk = ∑ (frequency x consequence of a given scenario), for all scenarios (conforming to one of the definitions of risk in ISO/TR 13387 as also contained in ISO 13943).
>
> Risk = Combined frequency of all scenarios where the consequences exceed the specified safety threshold (conforming to one of the definitions of risk in ISO/TR 13387).

The first of the two formulations above defines scenario fire risk as the expected value, i.e., product of frequency and consequence, and defines the combined fire risk estimate as the sum of the scenario fire risks.

The second of the two formulations above defines scenario fire risk as the frequency of scenarios whose consequences are unacceptable, therefore as the frequency of the scenario times 1 if the consequences are unacceptable and 0 if the consequences are acceptable.

6.5.2 Event trees, fault trees, and alternative definitions of fire risk

Use event trees and fault trees as efficient formats for calculating fire risk according to any of the risk definitions shown in Section 6.5.1.

Event trees provide a basis for estimating scenario cluster frequencies using a tree structure with both logical and temporal sequencing. Additional guidance is contained in ISO/TS 16733, Section 6.3.1, Step 6 – Event tree. Fault trees normally use only logical sequencing, while event trees normally emphasize temporal sequencing. If consequence estimation is done using fire models that track developments over time, then there is a parallel construction to the event tree format and the consequence estimation format. This favors the use of event trees. When the second definition of risk from 6.5.1 is used – combined frequency of consequences exceeding a specified threshold – then consequence estimation can be less elaborate and either event trees or fault trees can be used to develop needed scenario cluster frequencies.

6.5.3 Risk defined by the design load or limit state

When a safety threshold is used, an associated measure useful for design purposes is the design load, in which one of the scales defining the fire scenarios is set at the value just sufficient to exceed the specified safety threshold. This is sometimes referred to as the limit state just sufficient to cause failure. Such a measure will focus attention on consequence and not so much on frequency.

6.5.4 Other aspects of risk calculation

If estimation by engineering judgment is used for both frequency and consequence, it is not necessary to estimate them separately. Instead, a risk measure implicitly combining the two can be estimated directly. An explicit procedure, with or without calculation, may be used to provide greater consistency of subjective estimation between users, either for estimation of frequency or consequence values or for direct estimation of a risk measure.

Measures of risk can be expressed as dimensionless, nonparametric statistics, such as ranking values. These are qualitative risk measures, as contrasted with quantitative risk measures for which the rules of ratio-scale numbers apply. Semi-quantitative risk measures use dimensionless, nonparametric statistics derived from categories that are themselves defined by numerical ranges of ratio-scale variables.

Both frequency and consequence can be characterized using categories, either categories based on ranges of underlying numerical values or categories directly defined. If both frequency and consequence are so characterized, the summary characterization of fire risk outcomes can be constructed as a risk matrix, using the category characterizations of frequency and consequence to define rows and columns. Each matrix cell represents a fire risk measure that need not be explicitly calculated. In such a case, rules must be specified to determine whether any matrix cell falls above or below a threshold of acceptable risk.

For design purposes, it can be useful to construct a risk matrix in a different manner. If scenarios can be characterized by a single scale of external hazard severity (e.g., earthquake intensity or energy in a lightning strike), then categories can be derived from that scale to provide the rows of a risk matrix for which the columns are categories corresponding to ranges of frequency of occurrence for a defined range of hazard severity. Matrix cell entries can be specified as consequence, which will be a function of hazard severity and the performance of the design. Acceptable risk can be defined as a threshold on consequence, cell by cell, without the need to construct a formal risk estimate. Note that this approach implicitly assumes that hazard frequency is independent of design. For fire hazards, this assumption requires close scrutiny and evaluation.

The results of fire risk estimation can also be presented in the form of a risk curve. Such a curve, plotted with frequency versus consequence axes, smoothly connects points representing individual estimates of the frequency and consequence associated with specifically analysed fire scenarios. Once a fire risk curve has been established for a specified design and with specified assumptions, changes in the design can be translated into a new risk curve through the risk estimation process. The relative proximity of alternative risk curves to the origin of the graph (i.e., the zero-frequency, zero-consequence position) is a measure of the relative risk of alternative designs.

7 Uncertainty, sensitivity, precision, and bias

Uncertainty refers to any potential differences between the computed risk measure and the underlying true risk that the computed measure is intended to represent. Precision refers to the statistical magnitude of such deviations, based implicitly on the standard deviation of a probability distribution of error around the computed risk measure. Bias refers to any lack of symmetry in the distribution of deviations.

Sensitivity analyses do not quantify uncertainty but are an initial step toward such quantification. Sensitivity analyses examine the propagation of uncertainty, by measuring the magnitude of change in the computed risk measure produced by a change in the value of one of the variable or parameters involved in the computation. If a sensitivity analysis can be combined with information on the likely magnitudes of errors in the component values, then a full calculation of random uncertainty is possible.

Uncertainty is not limited to statistical variation but also occurs as a result of gaps or errors in the knowledge underlying the procedure for computing the risk measure. If a particular phenomenon is missing from the calculation, such as pre-movement time from an evacuation time calculation or turbulence from a calculation of fire development and effects, then this will be a source of uncertainty, typically biased uncertainty, in the risk measure calculation.

Additional guidance on techniques of uncertainty analysis relevant to fire safety engineering models is contained in ISO 16730.

7.1 Elements of uncertainty analysis

Fire risk assessment can be affected by deficiencies of relevant data or of scientific understanding of some relevant fire phenomena. In many instances, uncertainty analysis can be used to express the magnitude and address the importance of such deficiencies.

In fire risk assessment, uncertainty analysis involves quantifiable uncertainty for the frequency and consequence estimates. Uncertainty can also be quantified for the risk evaluation criteria. More difficult to quantify are errors associated with missing phenomena or misapplication of data or calculation methods.

Quantification of uncertainty in frequency and consequence estimates begins with quantification of uncertainty in source data.

Quantification of uncertainty in laboratory measurements can normally rely upon known calibration data and precision values for the laboratory equipment. A better quantification is possible if multiple experiments are conducted for every measurement of interest. Then, a probability distribution of the experimental results can be used to represent that portion of the uncertainty.

Quantification of uncertainty in field data, such as statistics on reported fire experience, can be achieved by using the variation in values from year to year or from place to place. Each fire is not a data point for estimation of the number of fires per year, but each year’s experience in each community can be a data point. If the data is converted to a probability or frequency, such as an ignition frequency or a reliability probability, then one uses the variability in field data to fit parameters on a probability distribution for the probability or frequency parameter.

Quantification of uncertainty in subjective estimates or subjectively derived parameters is possible if the estimates have been systematically solicited in a process with multiple participants. Then, the variability in individual estimates provides a basis for quantification of uncertainty.

None of these methods is useful to quantify the role of systematic bias in uncertainty. For example, if the fire experience data of one country is used to estimate ignition frequencies in another country, there are likely to be systematic differences. Subjective estimates of these differences can be elicited, and uncertainty quantified for them based on variation in those subjective estimates.

Once these uncertainty distributions have been developed for all identified parameters in the fire risk calculation, it is necessary to calculate the effect of these different forms of uncertainty on the final risk estimates. Because the initial risk calculation can involve calculations of frequency and consequence for a large number of fire scenarios, it is possible that many of the uncertainty variations of one scenario will correspond to other scenarios that are already due to be calculated. This fact can reduce the calculation burden. Alternatively, one can use Monte Carlo or other sampling methods to calculate the estimated uncertainty-based frequencies and probability distributions for the fire risk estimates.

In conducting the uncertainty analysis, it is important to examine the basic risk estimation procedure for any parameters, or assumptions that can be expressed as parameters, that are not normally regarded as variables. Any such parameters involve uncertainty. Even the speed of light and the gravitational force constant have uncertainty in their measurements, although the uncertainties are now so small as to be safely ignored. For a fire modelling example, if fire growth is represented by a t-squared curve, there is uncertainty involved not only in the parameter (alpha) that is the coefficient of time-squared fire growth but also in the value (two) of the exponent in the representation. It is not practical to conduct uncertainty analysis on every parameter, but it is important to consider every one and to systematically identify those uncertainties that have the potential to be sufficiently large to change not only the estimate of risk but also the decisions to be based on those estimates.

7.2 Validation and peer review

The purpose of uncertainty analysis is to provide validation of the fire risk estimation. As noted, many of the data estimates can involve the use of subjective engineering judgment, in the absence of observational bases. For this reason, peer review can be useful when quantitative methods of validation are not possible. The level of peer review deemed appropriate can range from peer review by another engineer from the company leading the project to peer review by an engineer from another company. The value of a review by someone from another company is greater if the estimated performance of the design is highly sensitive to precise probability estimates or to elements of design with which there is little or no field experience available. This can be the case if the design differs from a traditional prescriptive design with respect to multiple design elements, if the building design is complicated and innovative, if improved performance of one design element is used to justify reduced performance of multiple design elements, or if the maximum scenario consequence is more severe than with a traditional prescriptive design.

Separately from these peer reviews, regulatory authorities in some jurisdictions require a third party independent review for approval, as described in more detail in Section 13.3 of ISO 23932.

8 Fire risk evaluation

Figure 2 indicates that after uncertainty analysis of estimated risk, the resulting estimates must be evaluated through comparison to defined acceptance criteria. Risk evaluation compares the estimated risk against predetermined criteria that may be explicit, such as standards or target risk levels, or implicit, such as comparison to the estimated risk for an alternative design or a reference design compliant with existing prescriptive requirements. Additional guidance is contained in ISO/TS 16733, Section 6.3.4, Step 9 – Risk ranking, and Section 6.3.5, Step 10 – Final selection and documentation.

8.1 Individual and societal risk

Acceptance criteria may be defined in terms of individual or societal risk. An example of a measure of individual risk is the annual frequency of a specified person suffering a specific type of harm such as loss of life as the result of a particular type of incident. An example of a corresponding measure of societal risk is the annual frequency that a specified minimum number of persons will suffer that type of harm as the result of that type of incident. Individual and societal risks are rarely the same. Individual risk focuses on who is harmed and also has no special concern with the total number of fatalities. Society is typically more averse to multiple deaths than a simple sum of the individual risks of the multiple victims would imply.

8.2 Risk acceptance criteria

Risk acceptance criteria are an expression of society’s or a decision-maker’s values, and as such, they are not yet ready and may never be appropriate for international normalisation. However, it is possible to provide a format and structure for selecting criteria.

8.2.1 Baseline from defined recent experience

The normal first step in setting risk acceptance criteria from defined recent experience is the use of documented loss experience for a specified type of loss and a specified population to be used as a point of reference. For example, a point of reference for the estimated risk of a proposed new building is the risk experience of similar buildings constructed and used in the same ways during the past five to ten years.

8.2.2 Establishing criteria based on baseline

The normal second step in setting risk acceptance criteria is to set the criteria as some fraction of the baseline. If the baseline is set in terms of existing risks, for example, then the criterion for new risks could be set equal to the baseline, viewed as acceptable to society because society has allowed it to occur, or lower than the baseline, taking the view that newer techniques of risk reduction are more affordable if implemented in a new design than in an existing design.

If the criterion is set in terms of acceptable risk for each specific scenario, then the risk assessment must address the implications for combined risk from all scenarios. For example, a criterion set an order of magnitude lower than the baseline for each scenario will mean a combined risk higher than the baseline if there are more than ten scenarios.

It is common practice to set a lower criterion for a new risk than for an existing risk. It is common practice to set a lower criterion for an involuntary risk than for a voluntary risk, but there can be disagreement as to the voluntary or involuntary nature of a risk. It is not unusual to set different criteria for risk due to natural causes and for other risks. It is not unusual to set a higher criterion for a risk whose effects are delayed. Other characteristics of a risk can also be the basis for differentiation of risk acceptance criteria.

8.2.3 Acceptable frequency and revised criteria for multiple-death events

If an annual acceptable risk level has been defined, then the implied acceptable annual frequency for a fire involving more than one death would be equal to the acceptable annual risk divided by the number of deaths involved in the event. However, society is normally more risk-averse than this proportional formula would imply. An acceptable annual frequency reflecting risk aversion will be lower than the implied acceptable annual frequency.

This risk aversion can be reflected by setting the acceptable annual frequency for such an event as the acceptable annual risk divided by a power function (such as the square) or exponential function of the number of deaths involved in the event. More generally, it is possible to define an acceptance curve on a graph of annual frequency versus consequence.

8.2.4 Acceptance based on ALARP

A further refinement of risk acceptance criteria is the establishment of three risk-acceptance regions on a display of frequency versus consequence – acceptable risk (the left-most region), risk that is As Low As Reasonably Practicable (ALARP) (the middle region), and unacceptable risk (the right-most region). Through the use of logarithmic axes, the lines separating the regions can be defined as implied exponential curves.

When estimated risk falls in the ALARP region, it is not clear whether the risk is acceptable or not. This can lead to more discussion or a more detailed analysis of technical feasibility and cost. If the proposal is not technically feasible, then the proposal could be rejected. Also, a proposal to further reduce risk would be rejected if the costs were deemed to be disproportional, and a proposal to further reduce cost would be rejected if the increase in risk were deemed to be disproportional.

8.3 Safety factors and safety margins

Safety factors and safety margins are multiplicative and additive terms, respectively, which are applied to the measure of risk to permit interpretation of the risk information to compensate for the uncertainty in that measure.

If a safety factor is used, then the ratio of the acceptable risk to the estimated risk for the design should equal or exceed the safety factor. If a safety margin is used, then the value of the acceptable risk minus the estimated risk for the design should equal or exceed the safety margin.

Because of uncertainty considerations, there is a probability distribution for the risk of the design around the point estimate of the design's risk. The safety factor or safety margin is equivalent to selecting a point on this probability distribution of uncertainty. For example, if the uncertainty distribution is normally distributed around the point estimate of the estimated risk and the safety margin is equivalent to 1.64 times the standard deviation of that uncertainty distribution, then there is a 95 % probability that a design satisfying that safety margin relative to the acceptable risk will in fact have a risk that is lower than the acceptable risk.

The uncertainty distribution around the estimated design risk should ideally be calculated from an analysis of the uncertainties associated with each variable involved in the risk calculation. Such calculations can be easier to interpret using safety factors rather than safety margins. More often, the uncertainty analysis is more qualitative and does not provide a sufficient basis for choosing between safety factors and safety margins.

For reasons of practicality, the choice between safety factor and safety margin can be based instead on the type of final risk measure.

If risk is estimated as a frequency (of unacceptable events), then a risk estimate will be described in terms of an order of magnitude (such as events per million exposure years). With very small numbers, a safety margin is inconvenient to use and can lead to a conclusion that the only acceptable risk is less than zero. A safety factor is more realistic and is equivalent to a safety margin applied to the logarithm of the risk estimate.

If risk is estimated as an expected value (such as deaths per year or monetary loss per year), then the risk values will tend to fall in a range where a safety margin is appropriate.

Because safety factors and safety margins are intended to be used to assess risk acceptability in the presence of uncertainty, the appropriateness and adequacy of the safety factors and safety margins will depend on the adequacy of the uncertainty analysis. A safety factor or safety margin that is well designed to address natural variability (such as variations in travel speed by different occupants escaping a building) cannot be assumed to be adequate to address missing variables (such as pre-movement time).

A partial safety factor is an uncertainty-based adjustment in a specification or characteristic of a fire scenario. The "safety concept approach" is a variation of the use of fire risk assessment to identify a short list of fire scenarios for deterministic analysis. First, fire risk assessment is used to identify a list of fire scenario clusters and to identify a representative fire scenario from each. Then, partial safety factors are applied to the defining characteristics of each representative fire scenario so that assessment based on the modified fire scenarios will incorporate the relevant uncertainties. It is then unnecessary to conduct additional uncertainty analysis on the final calculated scenario consequences or scenario risks.

Annex A
(informative)

Example - Office Building

Introduction to the Example

This is an example of the application of ISO 16732, prepared in the format of ISO 16732. It includes only those sections of ISO 16732 that describe steps in the fire risk assessment procedure. It preserves the numbering of sections in ISO 16732 and so omits numbered sections for which there is no text or information for this example.

This example is intended to illustrate the implementation of the steps of fire risk assessment, as defined in ISO 16732. Some steps are well illustrated by the example, and others are not well illustrated. The text of this section indicates where the example is strongest.

Risk assessment is preceded by two steps – establishment of a context, including the fire safety objectives to be met, the subjects of the fire risk assessment to be performed and related facts or assumptions; and identification of the various hazards to be assessed.

A.1 Scope

The scope section is not reproduced here; it is not part of the calculations.

A.2 Normative references

The normative references section is not reproduced here; it is not part of the calculations.

A.3 Terms and definitions

This section is not reproduced here; it is not part of the calculations.

A.4 Applicability of fire risk assessment

This example was conducted to support a policy analysis of alternative national courses of action for fire safety for a class of properties. This situation qualified under several of the circumstances cited in section 4 of the International Standard. A wide range of scenarios was deemed to be necessary. There were multiple fire safety goals which made it inappropriate to use a short list of scenarios to represent all scenarios. The objectives were stated in risk terms such as expected annual losses.

A.5 Overview of fire risk management

This section, including Figure 1, is not reproduced here; it is not part of the calculations.

A.6 Steps in fire risk estimation

A.6.1 Overview of fire risk estimation

Figure 2 describes the sequence of steps involved in fire risk estimation.

Fire risk estimation begins with the establishment of a context. The context provides a number of quantitative assumptions, which are required with the objectives and the design specifications to perform the estimation calculations.

A.6.1.1 Objectives

The main objectives and requirements of the building owner are:

1) to provide the occupants with a level of fire safety that meets the building code requirements;

2) to provide a safe area for occupants with disabilities;

3) to minimize the potential for fire and smoke damage so as to minimize business losses to tenants, and

4) to minimize the cost of fire protection and expected fire losses.

In the case study[1], the objectives were defined as (a) equivalent life-safety performance to that provided by a reference, code-compliant design, and (b) equivalent or better net cost over monetary benefits as compared to the reference design. Equivalence is to be established through engineering analysis using a fire risk estimation modeling package developed by the analysts for use on cases like this one.

A.6.1.2 Design Specifications

Several alternative designs were considered, differing in the use or non-use of automatic sprinkler protection, the use of different fire resistance ratings, and the use or non-use of a refuge area.

1) Option 1, the reference option, is the code-compliant option: with a fire resistance rating (FRR) of 2 h, sprinkler protection (with an assumed 95 % reliability), without a refuge area, and with a central alarm with voice communication, as described in the NBCC requirements[2].

2) Option 2 is the same as Option 1 but with a slightly lower FRR of 90 min. This option is used to check the reduction in protection cost and the corresponding increase in risk.

3) Option 3 is the same as Option 2 but with a refuge area to help reduce risk.

4) Option 4 is the same as Option 2 but with a 99 % reliability of the sprinkler system to help reduce risk.

5) Option 5 is the same as Option 2 but without sprinkler protection to check the risk without sprinklers.

Table A.1 — Fire protection design options considered[1]

Design Option	Fire Resistance Rating (min)	Refuge Area	Sprinklers (% Reliability)
1 (Reference)	120	No	95
2	90	No	95
3	90	Yes	95
4	90	No	99
5	90	No	No

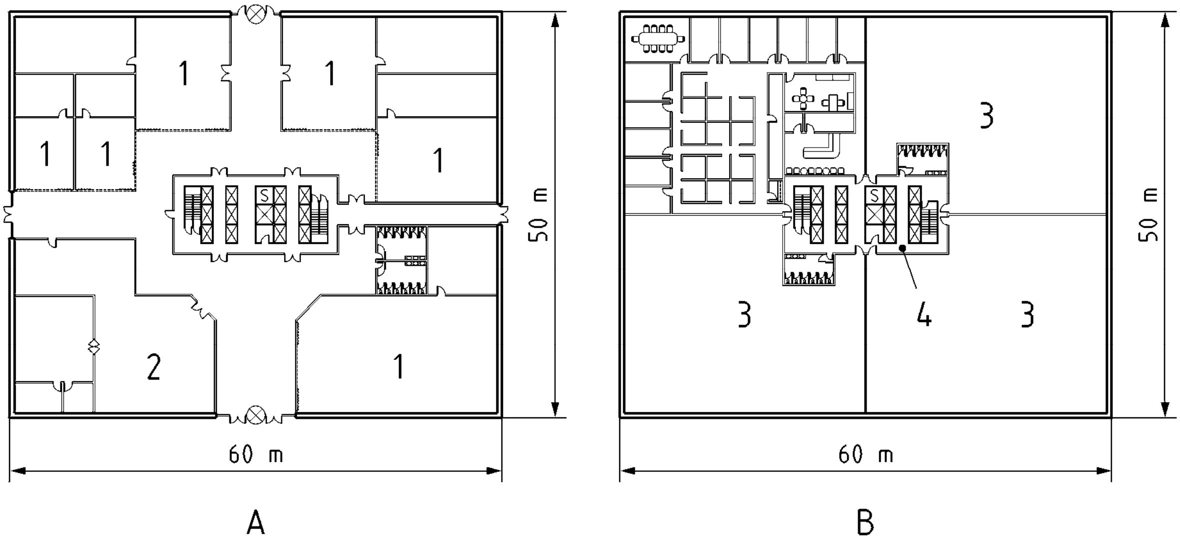
The building is a 40-storey, steel-framed, office building 60 m long by 50 m wide. The layout of the floors is shown in Figure A.1. The centre core contains the elevator, stair and service shafts, which provides:

1) a profitable use of the perimeter and window area of the building for office space;

2) a simple floor layout that can be easily compartmented and fire separated; and

3) a refuge area that may act as a temporary safe place for occupants with disabilities and those who cannot evacuate during an emergency.

The ground floor has a restaurant, various retail stores, a lobby area at the main entrance, and three side exits with one connected directly to the stairs via a protected corridor. Floors 2 to 40 are divided into four spaces, suitable for use by professional companies (e.g., law offices). Each space can have two means of egress to the centre core area.



Key

1	Store
2	Restaurant
3	Office space
4	Refuge area
A	Grand floof
B	Floors 2 to 40

Figure A.1 — Floor plans[1]

Since the building is an office building, the occupants are mainly office workers with the exception of some working in the restaurant and in the retail stores. The occupants on the upper floors with impaired mobility are assumed, in case of a fire emergency, to be helped by co-workers or to wait in the refuge area for rescue by the firefighters when they arrive on scene. The number of occupants per floor is assumed to be 300 (one occupant per 9.3 m^2 usable space, as per NBCC[2]). The refuge area in Figure A.1 can accommodate 300 people. The total number of occupants in the building is 12,000.

A.6.2 Use of scenarios in fire risk assessment

A.6.2.1 Overview of specification and selection of scenarios

This step is just an introduction and does not need to be implemented as a step. The following steps define how the scenarios are selected in this study.

A.6.2.2 Identification of hazards

In this example, the scenario structure was established from the top down by partitioning the set of possible fires, rather than from the bottom up, as is anticipated in a process that begins with hazard identification. In this example, fire incident statistics were used to identify the range of typical fire hazards in an office building. Because the example did not involve analysis of a particular building but was an analysis of policy alternatives for a class of buildings (office buildings), there was no need to examine whether the building under consideration is different from a typical building in terms of hazards (e.g., fuel load or combustibles, and heat sources[4]).

This step could also require a sensitivity analysis to determine the hazards that have the most impact on the probability of failure. This was not done for this example as the statistics used to define the probability of fire start were based on typical fire hazards in office buildings.

A.6.2.3 Combining scenarios into scenario clusters

This example began with a concise, parametric description of the universe of possible scenarios.

The scenario structure defines three distinct types of fires:

1) smouldering fires, where only smoke is generated;

2) non-flashover flaming fires, where a small amount of heat and smoke is generated; and

3) flashover fires, where significant amounts of heat and smoke are generated with a potential for fire spread to other parts of the building.

The definition of the type of fire is based on the severity of the fire when it was observed and recorded by the firefighters upon their arrival at the scene of the fire. Of course small fires can develop into fully developed fires (another name for flashover fires) if they are given enough time and the right conditions. However, the fire conditions at the time of fire department arrival are the ones used. They represent the fire conditions that the occupants are exposed to prior to fire department extinguishment and rescue operations.

The three fire types are extended into six scenario clusters by adding consideration of the status (open or closed) of the door to the room of fire origin.

The modeling package used in the example includes a set of standard design fires. The initiating conditions of the fire and the status of the door from the first involved compartment are taken from the scenario cluster specifications. Other parameters are taken from the description of the subject property, which in this example was a 40-storey office building with specified room sizes and other dimensions, as well as standard fuel loads in the rooms and occupant loads and locations in the building. Some of these standard assumptions for an office building are taken from values set in the national building code. For some parameters – such as the location of the ignition point – the case study documentation does not clearly indicate how the parameters were determined. Details on such parameters can be found in the fire growth model.

The representative fire scenarios for the scenario clusters are therefore taken from the library of available design fires based on the best match to the defined characteristics of the subject property.

A.6.2.4 Exclusion of scenarios with negligible risk

In this example, the use of fire statistics to identify fire scenarios and to assemble the scenarios into scenario clusters made it unnecessary to exclude any scenarios based on negligible risk.

A.6.2.5 Demonstrating that the scenario structure is appropriate and sufficient

In the example, the scenario structure was comprehensive by definition, in that all types of fires were included in the scenario clusters. Questions could still remain regarding the representativeness of representative scenarios chosen for each scenario cluster, with respect to any conditions not defined by the subject property's specifications, the scenario cluster specifications, or the national building code's standard assumptions for engineering analysis. The location of the ignition point is an example of a condition not defined by any of those sources. The case study did not perform any analysis to demonstrate representativeness of its choices for those conditions.

Many other scenario characteristics, including the timeline of fire growth and spread of fire products, are derived from the modeling package operating on the externally defined initiating conditions. Therefore, the representativeness of those characteristics of the scenarios would depend in large part on the evidence for the validity of the models. That is discussed later.

This approach is not well designed to capture extreme events such as the fire that led to the collapse of the World Trade Center towers in New York City in 2001. This type of scenario should be treated separately from the more typical scenarios considered here. For analysis of alternative policies for a class of buildings, the analysis of extreme events can be conducted in a side analysis, but no such analysis was conducted in this example.

A.6.2.6 Fire risk assessment without explicit scenario structures

This section is not relevant in this example.

A.6.2.7 Behavioural scenarios

As noted above, this example used only one behavioural scenario, in which the initial conditions (e.g., number and location of occupants) were derived from assumptions tailored to the subject property or from standard assumptions in the national building code. All other behavioural scenario conditions were derived from the modeling package operating on those initial conditions.

It should be mentioned that the models relating to occupant response and evacuation use four categories of occupants: senior and children, occupants with special needs, able-body female occupants, and able-body male occupants. A travel speed is assigned for each category. The locations of the occupants and the types of warnings (cues) they receive are also taken into consideration.

A.6.2.7 Fire risk assessment for selecting design fire scenarios for deterministic analysis

This section is not relevant in this example.

A.6.3 Characterization of probability

The probability of occurrence of each of the three types of fire is based on statistical data gathered by fire departments in Canadian provinces and territories. In Canada, statistics[3] show that the probability of fire starts in office buildings is 7.68×10^{-6} per m^2. Of these fires, 24 % 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.

There is a procedure in the modeling package that permits the probability of fire start to be modified when it is judged that the building under consideration is different from a typical building in terms of fuel load or combustibles, and heat sources[4]. The probabilities for some other parameters is obtained from engineering judgement (e.g., probability of the door to the compartment of fire origin being open). Still other probabilities, such as probability of fire spread, probability of fire department notification and intervention, probability of fire fighting effectiveness, and probability of rescue effectiveness, are derived from a combination of available relevant statistics, engineering judgement, and prediction by the modeling package. For example, the probabilities of glass breakage and barrier failure (see Figure A.2) are determined in an entirely deterministic manner from the model's prediction of developing fire size and effects.

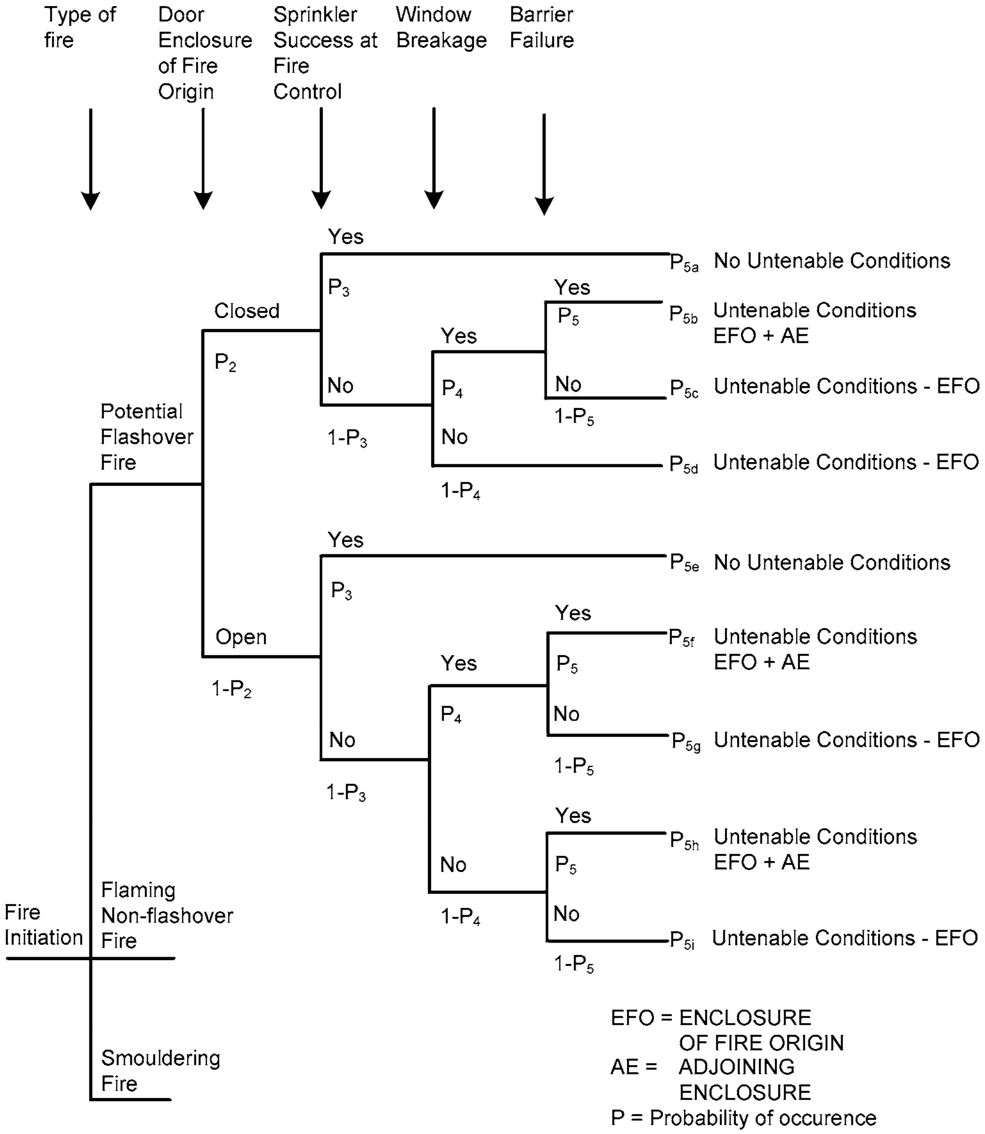


Figure A.2 — Typical fire scenario structure based on an event tree formulation

Engineering judgment can be made more systematic and consistent from one engineer to another through the use of Delphi methods or other explicit procedures for reducing bias and improving the quality of estimates. [For a description of the Delphi method, see, for example, N. Dalkey and O. Helmer, “An experimental application of the Delphi method to the use of experts,” Management Science, Vol. 9 (1963), pp. 458-467. For a comparison of the Delphi method to other procedures, see, for example, F. Woudenberg, “An evaluation of Delphi,” Technological Forecasting and Social Change, Vol. 40 (1991), pp. 131-150].

Engineering judgment can be done for point values or for ranges. The latter will be subject to less disagreement between estimators and will be sufficient for use in a risk matrix or other qualitative fire risk assessment procedure. [For guidance on elicitation of engineering judgment-based estimates, see, for example, A. Kidd, ed., Knowledge Elicitation for Expert Systems: A Practical Handbook, Plenum Press, New York, 1987].

As an aid to probability estimation by engineering judgment in cases where relevant data is nearly or completely non-existent, a risk matrix may be used in which all probability estimates are channeled into a small number of well-distributed values. For example, a five-value protocol with values separated by an order of magnitude would use 0.5 %, 5 %, 50 %, 95 %, and 99.5 % as values. A five-value protocol with values separated by half an order of magnitude would use 5 %, 16 %, 50 %, 84 %, 95 %.

The engineering judgments used in this example were developed less formally and without the benefit of these methods.

A.6.4 Characterization of consequence

There are a number of ways to characterize consequences. Each way has advantages and disadvantages. In the present example, the consequences were quantified using deterministic models.

A.6.4.1 Consequence estimation from loss experience

This section is not relevant in this example.

A.6.4.2 Consequence estimation from models

A.6.4.2.1 Fire growth

In the example, the fire growth model is a zone model using a single zone for a compartment. It predicts the development of the six design fires, mentioned above, in the compartment of fire origin using representative fuels, such as polyurethane slabs for residential furniture and wood cribs for office furniture[5]. The model 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:

1) time of fire cue (that can be detected by human senses);

2) time of smoke detector activation;

3) time of heat detector or sprinkler activation;

4) time of flashover; and

5) 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.

A.6.4.2.2 Smoke movement beyond the initial compartment

Based on the building characteristics and internal air movement due to temperature differences between the inside and outside of a building, smoke movement in the building is calculated as a function of time. The smoke movement model[6] also calculates the critical time in the stairwells. This time is defined as the time that the build-up of smoke at a level that the occupants cannot use the stairwells to egress. The trapped occupants are then exposed to the build-up of smoke and toxic gases in the building until the fire department arrives at the fire scene to rescue them. Life hazards to the occupants are assessed by the total dose of toxic gases that the occupants have inhaled into their body up to the time of the fire department's arrival.

A.6.4.2.3 Occupant response and evacuation

Depending on where the occupants are located, they receive the various warning signals at different times. As a result, occupants at different locations would respond at different times. The occupants are assumed to respond when a fire could be detected by fire cues (state 1), smoke or heat detectors (states 2 and 3). The response of occupants in an emergency situation follows a process called perception, interpretation and action (PIA)[7]. The clearer the signals are that there is an impending danger, the more likely and more quickly the occupants would go through the PIA process and respond.

The fire signals can be from any of the following:

1) fire cues detectable by human sensors;

2) warnings from other occupants;

3) warnings from firefighters;

4) alarm from local detectors;

5) central alarm; and

6) central alarm with voice communication.

The probability of interpreting the above signals as fire signals depends on what the signal is; i.e., higher probability for direct perception of a fire and lower in the case of a central alarm bell. The probability of taking action to evacuate depends on the interpretation of the fire signals; i.e., higher probability for a more definite interpretation and lower for a less definite interpretation that there is impending danger. In addition, the model assumes that the probability of receiving alarms from local detectors or central alarms depends on the reliability of detectors and alarms. The probability could be close to 1 when the detectors and alarms are properly installed and maintained, or close to 0 otherwise.

Once an occupant has decided to respond, the evacuation can be calculated by following the movement of the occupant from the original location, through corridors, stairwells and eventually out of the building. The occupants would be trapped on their floors if the stairwells become untenable because of the build-up of smoke. This method allows the user to calculate whether the occupants can successfully evacuate a building.

A.6.4.2.4 Deaths as a consequence

Based on outputs from the smoke movement and occupant response and evacuation models, life hazards to the occupants are assessed by the total dose of toxic gases that the occupants have inhaled into their body up to the time of the fire department's arrival[8]. The occupants would be trapped on their floors if the stairwells become untenable because of the build-up of smoke. When this happened, the trapped occupants are then exposed to the build-up of smoke and toxic gases in the building until the fire department arrives at the fire scene to rescue them, otherwise they would be considered dead.

A.6.4.2.5 Property damage as a consequence

Based on outputs from the smoke movement model and fire spread model, the costs of heat, smoke, and water damage for a building structure and its contents are estimated, for the fire scenario being considered. The damage estimates are based on statistical averages of monetary damages for recent fires in the same kind of property.

A.6.4.3 Consequence estimation from engineering judgment

This section is not relevant in this example.

A.6.5 Calculation of scenario fire risk and combined fire risk

In the example, scenario fire risk is calculated as probability times consequence for each of two measures of consequence, life loss and property damage. Combined fire risk is then calculated as the sum of scenario fire risk for life loss and for property damage. The former is used as a decision-making parameters called expected risk to life (ERL).The latter is combined with cost for the design relative to cost for the reference code-compliant design to produce a second decision-making parameter called fire cost expectation (FCE).

ERL is the expected number of deaths per year as a result of fire in the subject building. FCE is the expected total fire cost, which includes the capital cost for passive and active fire protection systems, the maintenance and inspection costs for the active fire protection systems, and the expected losses resulting from fire in subject building.

The separation of life risks and protection costs eliminates the difficulty of assigning a monetary value to human life and allows for a separate comparison of risks and costs. The ERL value can be used to determine whether a fire safety design meets the performance code requirements, or whether it provides a level of safety that is equivalent to that of a code-compliant design in a prescriptive code, whereas the FCE value can be used to identify cost-effective designs.

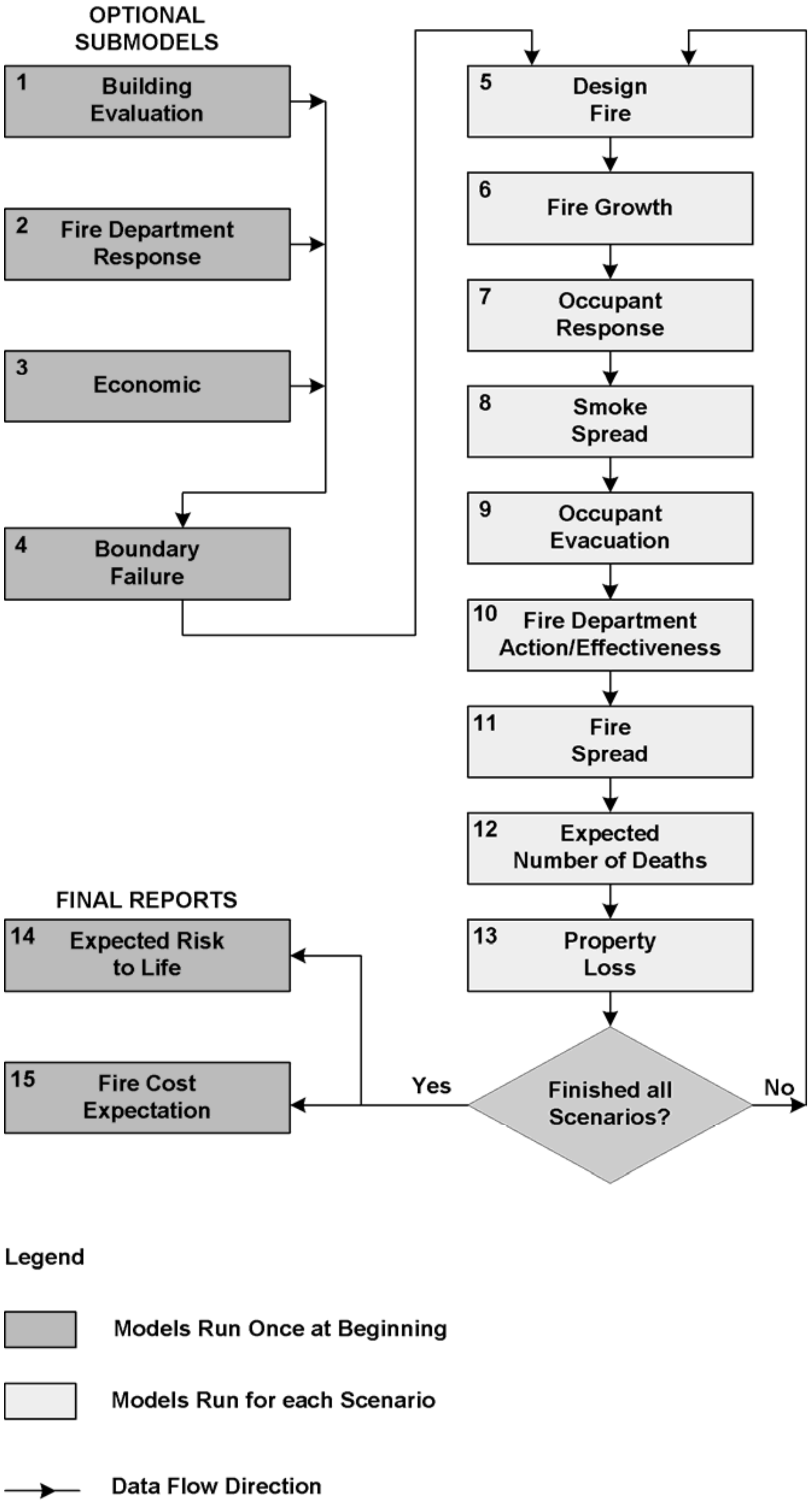


Figure A.3 — Modeling package flowchart[9]

Figure A.3 provides an overview of the models included in the modeling package. The package includes two optional sub-models (Building and Risk Evaluation and Fire Department Response) that can be run if the building fire characteristics and fire department response are not considered typical. The Boundary Element Failure and Economic sub-models are run only once to obtain the failure probability values of boundary elements and the capital and maintenance costs of fire protection systems. The other ten sub-models are run repeatedly in a loop to obtain the expected risk to life values and the expected fire losses from all probable fire scenarios.

A.7 Uncertainty, sensitivity, precision, and bias

The example did not include a formal analysis of uncertainty or sensitivity.

The models employed use conservative engineering assumptions, which can result in over-prediction of life loss and property loss. This is not so much a problem for risk measure that is estimated risk to life relative to the code-compliant reference design, because the biases work the same way on both calculations. For fire cost expectation, however, the potentially conservative over-prediction of property damage will not be offset by comparable over-prediction of the costs of a design. Therefore, some cost-effective designs can appear less cost-effective or even not cost-effective.

A.8 Fire risk evaluation

A.8.1 Individual and societal risk

This example dealt exclusively with societal risk in that it was focused on the implications of alternative policies for risk in an entire class of buildings.

A.8.2 Risk acceptance criteria

In this example, the risk acceptance criteria were derived based on calculation of the risk associated with the baseline. The baseline or reference case was the building code compliant case, and the other cases were measured against this reference.

A.8.2.1 Baseline from defined recent experience

This section is not relevant in this example.

A.8.2.2 Establishing criteria based on baseline

A.8.2.2.1 Building code prescriptive requirements[1)]

Because fire risk evaluation is conducted through comparison for equivalency between estimated risk and cost for an alternative design and estimated risk and cost for a reference code-compliant design, it is appropriate to summarize the building features required for code compliance.

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1) The National Building Code of Canada was used in this study.

The prescriptive requirements of the national building code used are still part of this code, and alternative design solutions and equivalency are permitted provided that any alternative design can be demonstrated to provide the same safety level as implied by the prescriptive requirements. This existing legal framework coincides with the fire risk assessment approach used here, in which the baseline was defined by the prescriptive requirements and the implied risk provided the criteria for acceptable risk. For the 40-storey building being considered in this case study, the relevant prescriptive requirements are:

1) **Fire Separation**: The building is required to be of non-combustible construction with major structural elements having a fire resistance rating (FRR) of not less than 2 h. On each floor, the FRR of partition compartment walls can range from 15 min (between office suites) to 2 h (from restaurant to retail store). Every door in a fire separation is required to be fire-rated and equipped with a self-closing device, designed to return the door to the closed position after each use.

2) **Exits**: Two exit stairs are required, and must be located so that the travel distance to at least one is not more than 40 m. This requirement is met in the layout of this building.

3) **Detectors and Alarms**: The building is required to have a fire alarm system and a voice communication system. Manual pull stations are required near principal entrances and exits. Smoke detectors are required in stairshafts. Fire detectors are required in storage areas and elevator shafts.

4) **Automatic Sprinklers**: Sprinkler protection is required for this building.

5) **Stairwell Pressurization**: Pressurization is required for stairwells serving anything below ground level. Stairwells serving above ground level are naturally vented and they are not required to be pressurized.

6) **Limiting Distance**: The building is located at a distance to the property line that satisfies the requirements of the NBCC in order to minimize the potential for fire spread to adjacent buildings.

A.8.2.2.2 Results of Fire Risk Evaluation

The results are shown in Figure A.4 and Figure A.5.

In Figure A.4, the ERL of each option is compared to the reference option, which has a relative ERL of 1 (normalized against itself).

In Figure A.5, the FCE of each option is shown, which includes the capital costs of passive and active fire protection systems, the worth of the annual maintenance cost of the active fire protection system and the worth of annual fire losses (building restoration cost) as a result of damage the fire and smoke.

For Option 2, the results show that this option has the same relative ERL of 1.0 (the actual numerical value is at 1.04), but has a lower FCE. This is expected because a slightly lower fire resistance rating (FRR) would increase the risk slightly due to fire spread and a correspondingly lower fire protection cost (with a slight increase in fire losses).

Option 3 is shown to have a lower relative ERL of 0.5 and a lower FCE, when compared to the Reference Option. This is possible since the refuge area protects a large number of trapped occupants who may not be able to evacuate for some of the design scenarios. The FCE is lower because of the lower FRR. The active protection cost is slightly higher (not very visible in figure) because of the use of a smoke control system, but the property loss is lower because smoke control reduces smoke damage.

Option 4 is shown to have a slightly lower relative ERL of 0.9 and a lower FCE, when compared to the Reference Option. Sprinkler protection has a significant impact on flashover fires, limited impact on non-flashover fires and no impact on smouldering fires. The reduction in risk is mainly due to the reduction in the probability of flashover fires.

Option 5 is the one without sprinkler protection. As expected, both the relative ERL and the fire losses increase significantly, although the active protection cost is reduced.

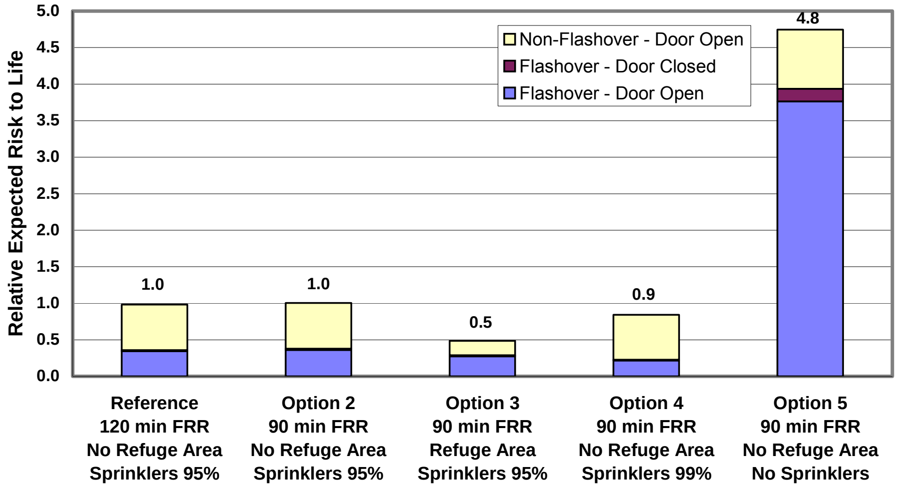

Figure A.4 — Relative expected risk to life for the five design options shown in Table [1]

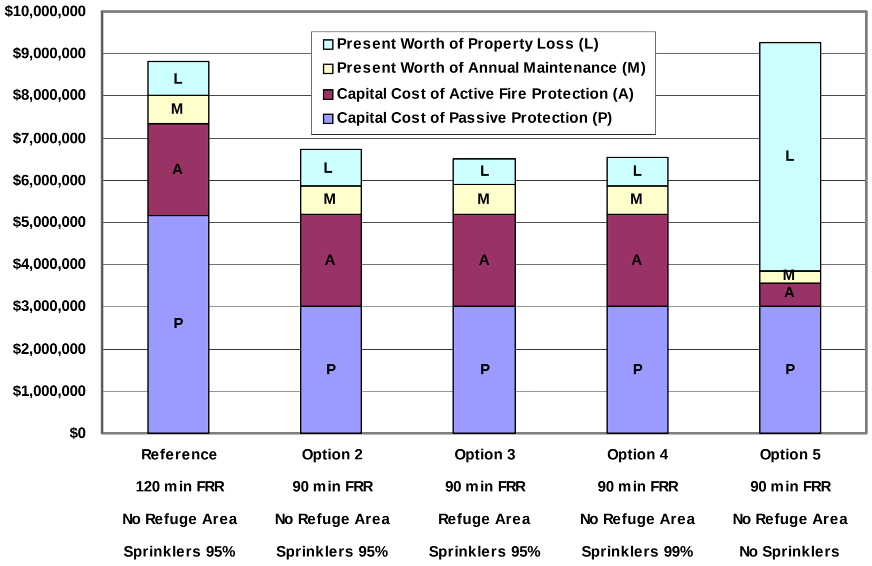

Figure A.5 — Fire cost expectation for the five design options shown in Table [1].

Looking at the results of Figure A.4 and Figure A.5, they show two cost-effective options. The first is Option 3, which uses a refuge area where smoke control was used to protect the occupants. This option has a relative ERL of 0.5 when compared to the Reference option, and an FCE of approximately $6.5 million, which is much lower than the $8.8 million for the Reference option. The second option is Option 4, which uses a higher reliability sprinkler system, where higher maintenance is implied. This option has a relative ERL of 0.9 and an FCE of approximately $6.5 million.

Both of these options have lower expected fire losses, which should minimize business down time. Option 3 would be considered the better of the two because it provides safety for occupants with disabilities and has an overall lower ERL.

A.8.2.3 Acceptable frequency and revised criteria for multiple-death events

This section is not relevant in this example.

A.8.2.4 Acceptance based on ALARP

This section is not relevant in this example.

Reference for Annex A

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[5] ISO/CD 16731, "*Fire safety engineering – Data needed for fire safety engineering*".

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