

VILNIUS GEDIMINAS TECHNICAL UNIVERSITY

Jurgita ŠAKĖNAITĖ

COMBINED APPLICATION OF
MULTI-ATTRIBUTE SELECTION AND RISK
ANALYSIS TO THE ASSESSMENT OF
BUILDING FIRE SAFETY

DOCTORAL DISSERTATION

TECHNOLOGICAL SCIENCES,
CIVIL ENGINEERING (02T)



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VILNIAUS GEDIMINO TECHNIKOS UNIVERSITETAS

Jurgita ŠAKĖNAITĖ

DAUGIATIKSLĖS ANALIZĖS IR RIZIKOS
SKAIČIAVIMO DERINIMAS
VERTINANT PASTATŲ GAISRINĘ SAUGĄ

DAKTARO DISERTACIJA

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Abstract

The dissertation presents an approach to a building-related multi-attribute selection (multiple criteria decision making) which takes into account the fire safety of buildings. It is investigated how to incorporate fire risk measures into the standard scheme of such a decision making and found the way how to solve decision making problems in an unconventional situation when fire risk measures are expressed by random variables. The dissertation consists of introduction, three chapters, conclusions, lists of references and papers published by the author of the dissertation, as well as eight annexes.

Chapter 1 presents a review and evaluation of the published work on the multi-attribute selection, building fire risk assessment and fire risk indexing. The review addresses also evaluation of fire safety by means of two approaches: fire risk indexing and fire risk assessment. Pros and cons of either approach are analysed.

Chapter 2 proposes a formulation and solution of several problems of multi-attribute selection applied to making decisions which take into account the fire safety of buildings. Three selection problems are considered: selection of a cost-effective fire safety system, selection among several alternative buildings with regard to fire safety of each of them and choice between alternative fire protective measures with respect to fire risk. Decision matrices of these selection problems are formulated as deterministic ones and random ones. The former are used for a conventional multi-attribute selection and the latter are integrated in the process of a simulation-based uncertainty propagation which allows to solve the selection problem in an unconventional way.

Chapter 3 describes a combined application of multi-attribute selection and fire safety assessment to making decisions concerning medical facilities. An increased fire risk level in medical occupancies is identified and illustrated by fire incident data. Three examples of the multi-attribute selection with respect to fire safety are presented. The first example considers a selection of a fire safety system for a hospital building. The second example deals with a multi-attribute selection of a building for a nursing home. In these two examples, fire safety is quantified by means of fire risk indices. The third example describes a multi-attribute selection among several alternative designs of a floor in a hospital building. Fire safety is expressed through the risk to lives of patients and hospital personnel. The attribute considering this risk is quantified as time to untenable conditions in rooms of the building under analysis.

The main statements of the dissertation were published in six scientific articles: three articles – in the Thomson ISI Web of Science register, three articles – in other editions.

Reziumė

Disertacijoje pateikiamas originalus būdas atlikti daugiatikslę pastatų analizę, atsižvelgiant į pastatų gaisrinę saugą. Parodoma, kaip įtraukti kiekybinius gaisrinės saugos rodiklius į standartinę daugiatikslę analizę. Rasta, kaip spręsti šios daugiatikslės analizės uždavinius nestandartinėje situacijoje, kai gaisro rizikos rodikliai išreiškiami atsitiktiniais dydžiais. Disertaciją sudaro įvadas, trys skyriai, išvados, literatūros šaltiniai, autorės publikacijų sąrašas ir aštuoni priedai.

Pirmame skyriuje apžvelgiami mokslininkų atlikti tyrimai daugiatikslės analizės ir pastatų gaisro rizikos vertinimo srityse. Pateikti du pagrindiniai metodai, taikomi pastatų gaisrinei saugai vertinti, t. y. gaisro rizikos indeksų skaičiavimo ir formalaus gaisro rizikos vertinimo. Jie yra trumpai apžvelgiami, analizuojami jų privalumai bei trūkumai.

Antrame disertacijos skyriuje formuluojama ir sprendžiama keletas daugiatikslės analizės problemų, priimant sprendimus, susijusius su pastatų gaisrine sauga. Šiame skyriuje yra svarstomos trys pasirinkimo problemos: racionalios gaisrinės saugos sistemos parinkimas iš kelių galimų, pasirinkimas iš keleto pastatų, atsižvelgiant į jų gaisrinę saugą, ir gaisrinės saugos sistemos parinkimas, vertinant gaisro riziką. Šių problemų sprendimų matricos yra formuluojamos tiek kaip deterministinės, tiek kaip atsitiktinės. Analizės uždaviniai su deterministinėmis sprendimų matricomis sprendžiami tradiciniais metodais, uždaviniai su atsitiktine sprendimų matrica sprendžiami disertacijoje pasiūlytu nauju metodu, kuris paremtas stochastiniu modeliavimu.

Trečiame disertacijos skyriuje tyrimų rezultatai taikomi medicinos įstaigų pastatams. Nustatyta, kad jiems yra būdinga didelė gaisro rizika. Sprendžiami trys daugiatikslės analizės uždaviniai, kuriuose atsižvelgiama į gaisrinę saugą. Pirmasis uždavinys nagrinėja gaisrinės saugos sistemos parinkimą ligoninei iš kelių galimų. Antruoju uždaviniu sprendžiama, kaip parinkti pastatą slaugos namams iš trijų alternatyvių pastatų. Pirmajame ir antrajame uždaviniuose pastato gaisrinė sauga kiekybiškai išreiškiama gaisro rizikos indeksais. Trečiasis uždavinys yra rekonstruojamos ligoninės architektūrinio sprendimo parinkimas. Gaisrinę saugą atspindintis daugiatikslės analizės rodiklis šiame uždavinyje yra išreiškiamas per evakuacijos laiką ir per laiką iki nepakeliamų sąlygų susidarymo galimos evakuacijos keliuose. Sprendžiant trečiąjį uždavinį, taikytas kompiuterinis gaisro ir evakuacijos procesų imitavimas.

Darbo rezultatai publikuoti šešiuose mokslo leidiniuose: trys – recenzuojamuose mokslo žurnaluose, įtrauktuose į *Thomson ISI Web of Science* duomenų bazę; trys – kituose leidiniuose.

Notation

Symbols

Latin

A	– area
a	– symbol for the year as a unit of time (for Latin <i>annus</i>)
$A_k(\cdot)$	– component of the FRAME fire risk index
$\bar{A}_i(t_s)$	– an average (mission) availability
a^*	– the best alternative
a_i	– alternative i
$B(\cdot)$	– binomial distribution
$B(x_i)$	– the anticipated benefit derived from the existence of the alternative a_i
$Be(\cdot)$	– beta distribution
c_{ij}	– value of the attribute j related to alternative I
$\bar{c}_{ij}$	– element of the normalised decision making matrix
$\hat{c}_{ij}$	– element of the matrix of estimates
$\tilde{c}_{ij}$	– element of the stochastic decision making matrix

$\mathbf{C}$	– initial decision making matrix
$\overline{\mathbf{C}}$	– normalised (dimensionless) decision making matrix
$\hat{\mathbf{C}}$	– matrix of estimates
$\tilde{\mathbf{C}}$	– random decision making matrix
$C_{ini}(\mathbf{x}_i)$	– the initial cost of a_i
$C_m(\mathbf{x}_i)$	– the cost of maintenance of a_i
$C_{fk_i}(\mathbf{x}_i)$	– the expected cost of failure according to the failure mode k_i
$C_{fl}(\mathbf{x}_i)$	– failure costs
$D_k(\cdot)$	– component of the FRAME fire risk index
E_{0i}	– initiating event
$F(\cdot)$	– component of the FRAME fire risk index
f_r	– frequency
$G(\cdot)$	– gamma distribution
I_D	– Dow's fire and explosion (F&EI) index
I_{FRAME}	– the fire risk assessment method for engineering (FRAME) index
I_{FSSES}	– fire safety evaluation system (FSSES) index
I_G	– Gretener's index
I_H	– hierarchical approach (HA) index
$I(\mathbf{x}_i)$	– fire risk index related to alternative i
K_K	– criterion of the multi-attribute selection
$L(\cdot)$	– lognormal distribution
L_{ir}	– random likelihood
l_{ir}	– likelihood
l_{0i}	– likelihood of fire initiation
m''_{∞}	– burning rate of unlimited pool
$N(\cdot)$	– normal distribution
$N(\cdot)$	– component of the FRAME fire risk index
n_{crew}	– crew size
n_f	– the number of potential fires
n_{si}	– the number of states of a_i , in which a partial or total loss of availability poses the corresponding failure costs $C_{fl}(\mathbf{x}_i)$
n_T	– the number of trapped occupants

o_{ir}	– outcome (consequences) related to scenario r
$P(\cdot)$	– Poisson distribution
$P_k(\cdot)$	– probability, component of the FRAME fire risk index
$S(\cdot)$	– component of the FRAME fire risk index
s_{ir}	– vector of severities related to alternative i and fire scenario r
$S_k(\mathbf{x}_{li})$	– the variable expressing the k th aspect of the fire safety in building
$p_f(x_i)$	– the failure probability of non-reparable objects
P_{fe}	– fire extinguishment effectiveness
$p_{fk_i}(\mathbf{x}_i)$	– the probability that a_i will fail according to the mode k_i
p_k	– branching probability
P_{re}	– rescue effectiveness
$\bar{q}_o$	– average heat release rate
$\dot{q}_o(t)$	– heat release rate at the time t
$\bar{q}_o(t)$	– the average value of the heat release rate at the time t
$R_k(\mathbf{x}_{2i})$	– is the variable used to measure fire risk related to the k th fire safety aspect of the building a_i
T	– random time
t_d	– dispatch time
t_f	– firefighting time
t_{FO}	– the flashover time
t_{int}	– intervention time
t_n	– notification time
t_p	– preparation time
t_r	– the response time
t_t	– travel time
$U_{tot}(\mathbf{x}_i)$	– the total (life-cycle) utilities
$U(\mathbf{x}_i)$	– utility
w_j	– weight of attribute j
$\mathbf{w}$	– vector of weights
$\mathbf{x}_i$	– vector characterising the alternative i
Greek	
Δh_c	– complete heat of combustion
δ	– confidence factor in the Hodges-Lehman's criterion

ξ	– random variable
ρ	– density
σ	– standard deviation
λ	– the weighting factor in the Hurwicz's criterion; parameter of the Poisson distribution
μ	– mean value
ϕ	– parameter of the binomial distribution
χ	– combustion efficiency coefficient

Abbreviations

AHP	– analytic hierarchy process
ANP	– analytic network process
ARAS-G	– additional ratio assessment with grey numbers
CAFAST	– consolidated model of fire growth and smoke transport
COPRAS-G	– a method of multiple criteria complex proportional evaluation with grey numbers
DM	– decision making
DO	– delivery opening
ED	– elevator door
ER	– escape route
F&EI	– Dow's fire and explosion index
FRA	– fire risk assessment
FD	– fire department
FEMA	– federal emergency management agency
FRAME	– fire risk assessment method for engineering
FRMC	– Factory Manual Research Corporation
FSES	– fire safety evaluation system
FTA	– fault tree analysis
HA	– hierarchical approach
HRR	– heat release rate
IAEA	– International Atomic Energy Agency
MAUT	– multi-attribute utility theory
MCDM	– multi-criteria decision making

NFIRS	– National Fire Incident Reporting System
NFPA	– National Fire Protection Association
NTNU	– Norwegian University of Science and Technology
PRA	– probabilistic risk assessment
SD	– stochastic dominance
SFPE	– Society of Fire Protection Engineers
SMAA	– stochastic multi-criteria acceptability analysis
SRA	– safety related attribute
QRA	– quantitative risk assessment
THERP	– technique for human error rate prediction
TOPSIS	– technique for order preference by similarity to an ideal solution

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Introduction

Formulation of the problem

Fire safety is an important component of building safety and is indispensable for a successful exploitation of the building. The prevention of fires is a complex task, which must be solved by taking into account economic, technological, psychological and social considerations. Building-related decisions, which are concerned with fire safety and other aspects of building design and exploitation, could be facilitated by applying the methodology of multi-criteria decision making (MCDM). The building-related MCDM problems must be supplemented with attributes which numerically express the level of fire safety as well as attributes which characterise fire protection measures. These attributes must be included into the decision making matrix of MCDM. As a solution of safety related problems often requires a probabilistic modelling of uncertainties, an MCDM method must be developed to solve selection problems with a decision making matrix, the components of which are random variables.

Topicality of the problem

The fires in built property are still a serious problem. They happen in buildings despite all preventive efforts and some of them take a heavy toll. The modern fire protection measures are expensive and not necessarily highly reliable. The general safety culture, which directly influences the success of fire prevention, is far from perfect in many countries. The building-related decision making still lacks to a great degree a complex and integrated approach which could take into account conflicting factors related to fire safety in one way or another. There is a lack of mathematical models which allow to solve problems of fire safety in one complex with other building design and exploitation problems which are not necessarily related to building safety.

Research object

The object of research is fire safety of buildings considered from the standpoint of fire risk management. In mathematical terms, the research object is an integration of risk assessment models and mathematical models used for multi-attribute selection.

The aim of the work

The aim of the work was a combination of fire safety assessment and MCDM by supplementing the decision making matrix of MCDM with attributes expressing the level of fire safety and fire risk.

Tasks of the work

1. To find out numerical indicators of building fire safety or risk which can serve as attributes of a building-related MCDM.
2. To formulate and solve most likely to-be-met-in-practice building-related MCDM problems which take into account fire safety and can be dealt with presently available MCDM methods.
3. To integrate results of a formal fire risk assessment produced by the quantitative risk analysis (QRA) into MCDM.

4. To develop an MCDM method allowing to solve the selection problem with a decision making matrix, all or some elements of which are random variables.

Methodology of research

The methodology of research was an analysis of presently available methods used in the fields of fire safety, QRA and MCDM. The methodological core of research was analysis of the aforementioned methods with an aim to combine them in one decision making model. Stochastic simulation was applied to a solution of MCDM problems with random decision matrices. A computer-aided fire simulation model, known as the two-zone model was applied for specifying attribute values of a building-related MCDM problem.

Scientific novelty

The main scientific novelty consists in combining methods of MCDM and fire safety assessment. The combining aims to improve decision making concerning various aspects of construction and safe exploitation of buildings. This requires to introduce novel elements into MCDM. To solve MCDM problems with respect to fire safety, the following new methodological developments are suggested:

1. An integration of fire risk indices into MCDM problems which consider a selection among several buildings, fire safety systems in an individual building, alternative architectural solutions of the building under design.
2. An incorporation of elements of a fire risk profile into the decision making matrix of an MCDM problem. The risk profile is a comprehensive measure of fire safety and MCDM problems involving estimates of fire risk can consider the fire safety problem in a very detailed manner.
3. A solution of MCDM problems with the decision matrices, all or some elements of which are random variables, accomplished via a simulation-based propagation of uncertainties expressed by probability distributions of these variables. Such matrices can be composed from elements of risk profile which are uncertain in the epistemic sense. This uncertainty is quantified by probability distribution specified by means of QRA.

Practical significance of the work results

The achieved research results can be used for the decisions concerning fire safety of built property. These decisions may involve alternative solutions (alternatives) of fire protection measures, comparison of buildings with different fire safety levels, the choice among construction products with different properties of performance in fire. The need to choose among alternatives may be faced by various interested parties: fire safety regulators (authorities on national level), insurers, architects (building designers), and manufacturers of fire protection measures, property owners and buyers. The problem of choice will often involve the need to consider simultaneously several characteristics (attributes) of alternatives, and those related to fire safety. Such a choice can be formalised as a problem of MCDM.

The statements presented for the defence

1. Fire safety of existing and future buildings must be taken into account in building-related MCDM. This requires to express fire safety quantitatively.
2. Methods of MCDM can be combined with the assessment of fire safety, because fire safety can be expressed by numerical measures and these can be applied as attributes in MCDM problems.
3. Results of fire safety assessment can be expressed either by fixed (deterministic) indices or by components of risk profile which are uncertain in the epistemic sense and are computed by means of QRA. Indices can be included MCDM problems solved by means of conventional MCDM methods. An inclusion of uncertain components of the fire risk profile will yield a random decision making matrix. A special MCDM method must be developed to solve an MCDM problem expressed by such a matrix.
4. An MCDM problem with a random decision making matrix can be solved by applying a simulation-based uncertainty propagation. For this purpose, algorithm of a conventional (deterministic) MCDM method must be integrated into a Monte Carlo loop and the problem of MCDM solved repeatedly in the simulation run, each time for a different decision making matrix generated by means of simulation. The MCDM alternative with the highest frequency of selection as the best one can be chosen as a final result of MCDM.

Approval of the results

The main statements of the dissertation were published in six scientific articles: three articles – in the Thomson ISI Web of Science register (Vaidogas and Šakėnaitė 2010b; Vaidogas and Šakėnaitė 2011a, 2011b), three articles – in other editions (Šakėnaitė 2009, 2010; Šakėnaitė and Vaidogas 2010a).

The main statements of the dissertation were discussed during three national scientific conferences:

- one – in the 10th International Conference on Modern building materials, structures and techniques, held in Vilnius, 2010;
- two – in the Conference of Lithuanian Young Scientists “Lithuania without science – Lithuania without Future”, held in Vilnius, 2009–2010.

Dissertation structure

The dissertation consists of an introduction, three numbered chapters, conclusions, list of references and author’s publications and eight annexes. The structure of the dissertation is presented in Fig. 1.

The volume of the dissertation is 136 pages, excluding annexes. The dissertation includes 46 numbered formulas, 39 pictures and 32 tables. The list of references consists of 171 items.

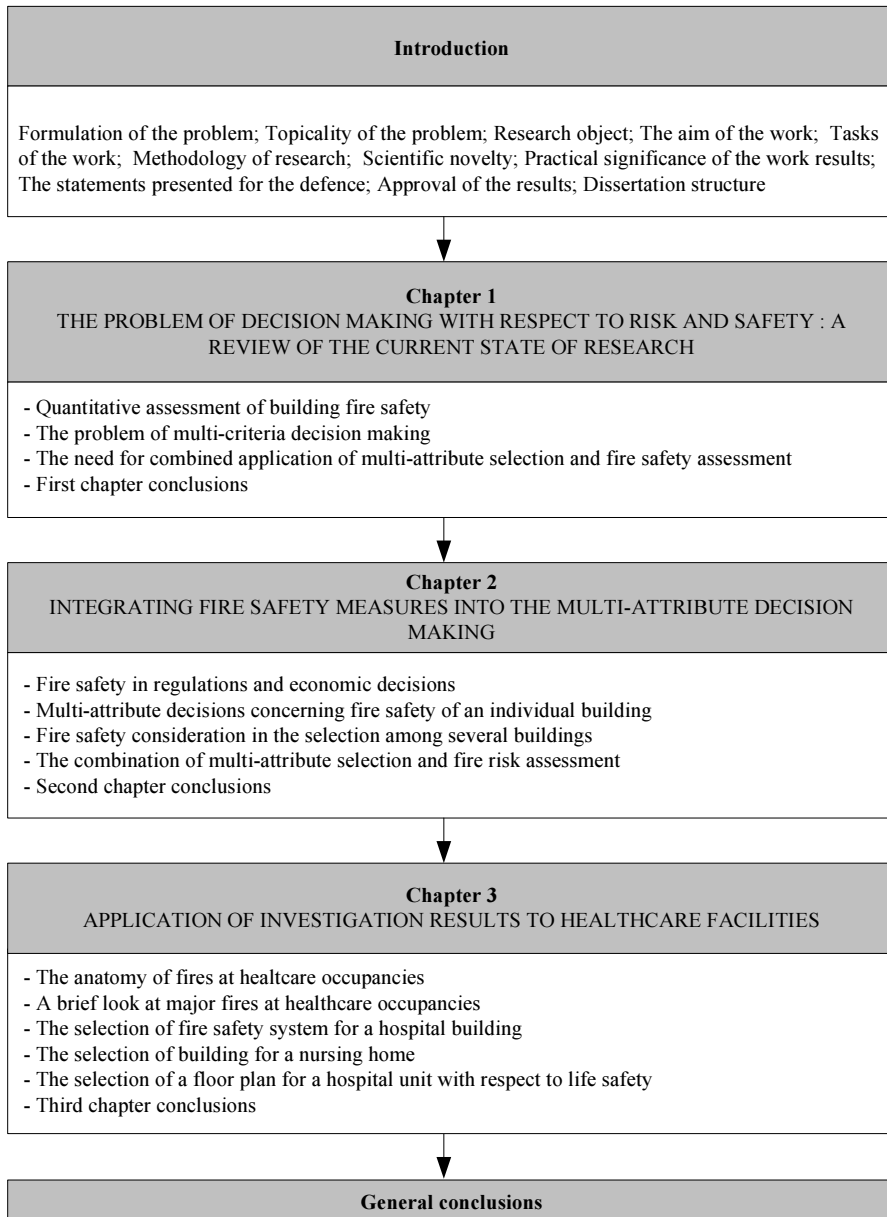


Fig. 1. The structure of the dissertation

The problem of decision making with respect to risk and safety: a review of the current state of research

The first chapter presents a review and evaluation of the published work on the multi-attribute selection, building fire risk assessment and fire risk indexing. The review covers general aspects of the multi-attribute selection, an application of this methodology to reliability and safety problems and modelling uncertainties which can be present in selection problems. The review addresses also evaluation of fire safety by means of two approaches: fire risk indexing and fire risk assessment. Pros and cons of either approach are analysed. The necessity to include fire risk indices and fire risk profile into multi-attribute selection related to built property is stated. The review was partially presented in the papers published by Šakėnaitė (2010) and Šakėnaitė and Vaidogas (2010a).

1.1. Quantitative assessment of building fire safety

1.1.1. Fire safety assessment by fire risk indexing

Description of the approach

Fire risk indexing is considered to be a link between fire science and fire safety (SFPE 2002). Indexing is a practical approach alternative to a detailed risk assessment, which is often an expensive and labour-intensive process. Indexing can provide a cost-effective means of risk evaluation.

Fire risk indices are heuristic models of fire safety assessment. They allow a simple scoring of fire hazard and rating buildings according to individual indices. Fire risk indexing uses professional judgment and past experience for assigning values to selected variables representing both positive and negative features of fire safety. The selected variables and values assigned to them are then transformed into a single value, which is compared to other similar assessments or to a standard.

A risk index is defined as a single number measure of the risk associated with a building. Thus, insurance rates are fire risk indices, as are the outputs of other similar schedules or scoring methods. Fire risk indexing, then, is the process of modelling and scoring hazard and exposure attributes to produce a rapid and simple estimate of fire risk. The concept has gained widespread acceptance as a cost-effective prioritization and screening tool for fire risk assessment programs. It is a useful and powerful approach that can provide valuable information on the risks associated with fire.

The importance of fire risk indexing has been widely recognized. A working group of educators and researchers addressed the issue of fire risk indexing at the National Academy of Sciences 1987 “Workshop on Analytical Methods for Designing Buildings for Fire Safety” (Building Research Board 1988). They concluded there is a need for three-part system of fire safety comprised of (1) codes; (2) the methods of fire risk indexing, referred to as numerical grading systems; and (3) the means of supplying inputs to that system derived, as far as feasible, from basic principles of decision science. The working group went on to state the rationale for its conclusion.

It is difficult to describe a typical fire risk index method. The practical necessity of trying to assess multifaceted fire risks with limited resources has led to the creation of several of fire risk indexing. Representative examples of fire risk indexing were selected from the literature and are summarized in Table 1.1. They provide some idea of the types of variations involved with modelling and quantifying fire risk.

Widely-used fire risk indices

Five widely used fire risk indices mentioned in the literature on fire safety assessment are summarised in Table 1.1. The common feature of the methods used to calculation of these indices is that:

- all of them apply a predefined list of variables (attributes) to specify the input;
- the calculation of fire risk indices yields a single number which represents the magnitude of risk; however, this value is neither frequency nor consequence severity;
- the calculated fire risk indices can be compared with some tolerable or target values which are the different for each index.

Input variables used for calculation with Gretener's as well as FSES and hierarchical methods as a listed in Tables A.1 and A.2 given in Annex A. The variables represent partially physical characteristics and partially abstract values used for calculation of the Gretener's index. In the case of FSES method, and hierarchical approach normalized values of attributes are applied (Table A.1, Annex A). They values depend on specific feature of the building being assessed. For example, if the variable x_i represents the presence and type of fire alarm, it can take on values 0, 2, 3, 4, 5; the lowest value 0 stand for the absence of any alarm system, whereas highest the value 5 means a total coverage of the entire building floor area by the alarm system (SPFE 2002). It is obvious that assigning one of these values to x_i is rather an outcome of agreement than a result of same measurement for observation.

Table A.2 of Annex A shows the parameter of the FSES and values of their general fire safety scores. The twelve fire safety parameters are listed in the left-hand column. The third and fourth columns specify the minimum and maximum values for each parameter, extracted from Table 7-1 of NFPA 101A (1998).

The indices calculated by means of the methods listed in Table 1.1 can be compared to some tolerable values, say, the value 1.3 in case of Gretener's method. Although these values are some answer to the well-known question „how safe is safe enough”, both indices and tolerable values are a result of agreement among specialists and not some statistically or economically substantiated characteristics of fire safety.

In addition, methods used for the calculation of fire risk indices use a considerable amount of information, mainly, for specifying input data. In this sense, fire risk indices are similar to formal methods of risk assessment. The latter use the considerable amount subjective information, mainly in the Bayesian framework.

Table 1.1. The widely used fire risk indices

Index	Mathematical expression of the index	Reference
Gretener's index $I_G^{(1)}$	$I_G = \frac{P(\mathbf{x}_{1i}, \mathbf{x}_{2i}, \mathbf{x}_{3i}) A(\mathbf{x}_{1i}, \mathbf{x}_{2i}, \mathbf{x}_{3i})}{N(\mathbf{x}_{3i}) S(\mathbf{x}_{2i}) F(\mathbf{x}_{2i})} \leq 1.3$	Kaiser (1979)
FRAME index $I_{FRAME,k}$	$I_{FRAME,k} = \frac{P_k(\mathbf{x}_{1i}, \mathbf{x}_{2i}, \mathbf{x}_{3i})}{A_k(\mathbf{x}_{1i}, \mathbf{x}_{2i}, \mathbf{x}_{3i}) D_k(\mathbf{x}_{2i}, \mathbf{x}_{3i})} \leq 1.0$ ($k = 1, 2, 3$)	FRAME (2008)
Dow's fire and explosion index (F&EI) $I_D^{(2)}$	$I_D = x_0 \cdot \sum_{i=1}^6 x_{i1} \cdot \sum_{i=1}^{12} x_{i2} \leq 96$	Dow (1994)
Fire safety evaluation system (FSSES) index $I_{FSSES}^{(3)}$	$I_{FSSES}(\mathbf{x}_i) = \prod_{i=1}^4 I_k(\mathbf{x}_{1i}, \mathbf{x}_{2i}) \geq 0$	Rasbash <i>et al.</i> (2004)
Hierarchical approach (HA) index $I_H^{(4)}$	$I_H = \sum_{i=1}^n w_i x_i \leq I_{H,tol}$	Rasbash <i>et al.</i> (2004), SFPE (2002)

(1) $A(\cdot)$ is the probability that a fire will start (the risk of activation); $P(\cdot)$ is the possible dangers (the potential risk); $N(\cdot)$ refers to standard measures; $S(\cdot)$ refers to special protection measures and $F(\cdot)$ is the fire resistance factor of the building; the components of the vectors x_1, x_2, x_3 are explained in Table A.1 (Annex A)

(2) The values 1 to 96 of I_D embrace the categories of the light and moderate hazard (potential damage); intermediate, heavy and severe hazard is represented by the intervals $I_D \in [97, 127]$, $I_D \in [128, 158]$, and $I_D \geq 158$ (Dow 1994); the components of the vectors x_1, x_2, x_3 are explained in Table A.3 (Annex A)

(3) $I_{jk}(x_{i2})$ = an indicator (zero-one) function related the fire safety parameter x_{i2} ; the components of the vectors x_1, x_2, x_3 are explained in Table A.2 (Annex A)

(4) The symbol w_i denotes the weights of normalized attributes x_i ; $I_{H,tol}$ is a tolerable value of the index I_H (not specified in the literature).

However, contrary to the results of the formal risk assessment, values of fire risk indices can used be verified, at listing in theory, by statistical data on fire accidents. The main advantage of fire risk indices seems to the relative implicitly of their calculation.

To illustrate the use of fire indices for the quantification of fire risk, the FRAME index $I_{FRAME,k}$ briefly described in Table 1.1 will be calculated for the a three-storey office building with open-plan floors shown in Fig. 1.1. The total area of the three floors is 8400 m². The value of one square meter of compartment and content is €1440. This amounts to the total value of the

building equal to €7 mln. The average number of people staying in each floor of the building during the workday is equal to 250. It is assumed that the building is used without standard fire protection measures (sprinklers and fire alarm).

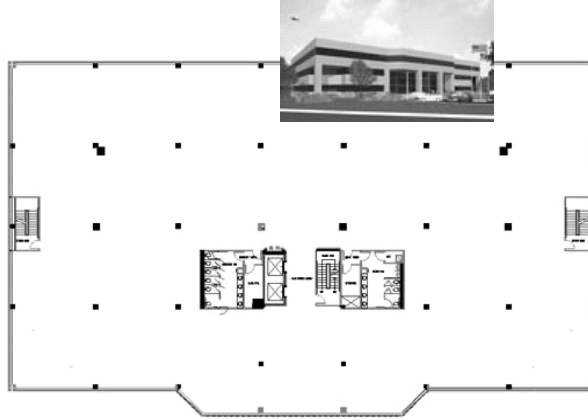


Fig. 1.1. A three open-plan office building with one area of fire origin in each floor

The general expression of the index under consideration, $I_{FRAME,k}$, is represented by the inequality

$$I_{FRAME,k} = \frac{\text{Potential risk}}{\text{Acceptable risk}} = \frac{\text{Probability of occurrence} \times \text{Severity}}{\text{Acceptable risk}} =$$

$$= \frac{1/D_k(\mathbf{x}_2, \mathbf{x}_3) P_k(\mathbf{x}_1, \mathbf{x}_2, \mathbf{x}_3)}{A_k(\mathbf{x}_1, \mathbf{x}_2, \mathbf{x}_3)} \leq 1.0 \quad (k = 1, 2, 3) \quad (1.1)$$

with the input vectors are explained in Table A.1 of Annex A. Values of components of these vectors are listed in Annex A Table A.4. Detailed expression used to calculate the quantities $P_k(\cdot)$, $A_k(\cdot)$, $D_k(\cdot)$ are given in the FRAME technical guide (FRAME 2008). The inverse value of the quantify $1/D_k(\cdot)$, that is, $D_k(\cdot)$, is called a protection level.

The FRAME index $I_{FRAME,k}$ can be calculated for three categories of potential fire risk: risk to building and its contents, risk to occupants, and risk to activities carried out in and in vicinity of the building. Correspondingly, there are three expressions for the calculation of $P_k(\cdot)$, $A_k(\cdot)$, and $D_k(\cdot)$. In the present example, values of $I_{FRAME,k}$ were calculated for the first two categories of fire risk:

$$I_{FRAME,1} = \frac{P_1(\mathbf{x}_1, \mathbf{x}_2, \mathbf{x}_3)}{A_1(\mathbf{x}_1, \mathbf{x}_2, \mathbf{x}_3) D_1(\mathbf{x}_2, \mathbf{x}_3)} = 0.61$$

$$I_{FRAME,2} = \frac{P_2(\mathbf{x}_1, \mathbf{x}_2, \mathbf{x}_3)}{A_2(\mathbf{x}_1, \mathbf{x}_2, \mathbf{x}_3)D_2(\mathbf{x}_2, \mathbf{x}_3)} = 1.27$$

where the subscripts “1” and “2” stand for building and its content and occupants, respectively. Values of $P_k(\cdot)$, $A_k(\cdot)$, and $D_k(\cdot)$ related to respective cases were calculated by means of formulas given in the manual FRAME (2008):

$$P_1(\cdot) = 2.25; A_1(\cdot) = 1.336, \text{ and } D_1(\cdot) = 2.762$$

$$P_2(\cdot) = 1.86; A_2(\cdot) = 1.09, \text{ and } D_2(\cdot) = 1.33$$

With these results, the indices $I_{FRAME,1}$ and $I_{FRAME,2}$ take on the following values: $I_{FRAME,1} = 0.61$ and $I_{FRAME,2} = 1.27$. They suggest that risk to building and content is acceptable, whereas the risk to occupants is too high. A sprinkler system and/or fire alarm may be necessary to install. This will allow to increase the protection level $D_2(\cdot)$ and so to decrease the value of $I_{FRAME,2}$.

The pros and cons of the fire risk indexing

The obvious advantage of fire risk indices is a relative simplicity of their calculation. Input information for this calculation (values of the fire safety attributes) can be specified with relative ease. The mathematical expressions of the indices themselves are trivial in terms of computational effort. Some indices are widely used in some countries and bring influence of fire safety culture of these countries (e.g., Kaiser 1979). Fire risk indices allow a simple comparison of fire risk of individual building with a formal quantification of this risk.

On the other hand, fire risk indices a “non-scientific” measures of fire safety (Kaiser 1979). It is difficult to say, how these indices are related to statistical data on fires. In addition, values of fire safety variables used for the calculation of indices are specified by experts; however, the process of specification is not documented. It is difficult to say, why a specific value of fire safety attribute, for instance, “1.4” was chosen why this value can not be changed.

Finally, fire risk indices are relatively different models and it is far from obvious that one of them should prevail against others. The use of a specific fire index seems to be a sort of tradition of a particular country (group of countries), rather than a choice based on some scientific reasoning.

1.1.2. Fire safety assessment by a quantitative risk analysis

Description of the approach

A very comprehensive measure of fire safety is the risk defined in line with quantitative risk assessment, that is, in the form of likelihood-outcome pairs

(Kumamoto and Henley 1996, Aven 2003, Ayyub 2003). The risk due to exposure to the fire i (fire originating in the area i or, in terms of quantitative risk assessment, the i th initiating event) will consist of possible outcomes (consequences) o_{ir} of the fire and likelihoods l_{ir} of these consequences.

Generally, each o_{ir} is represented by several measures of significance or, in brief, significances (e.g. Kumamoto and Henley 1996). Each o_{ir} can be characterised by several, say, n significances of different nature and with different measurement units. They can be grouped into the vector

$$\mathbf{s}_{ir} = (s_{ir1}, s_{ir2}, \dots, s_{irj}, \dots, s_{irm}) \quad (1.2)$$

Natural candidates for components of $\mathbf{s}_{ir}$ are direct monetary losses due to the fire i , (s_{ir1} , say), numbers of people killed and injured in this fire (s_{ir2} and s_{ir3}), the time of business interruption due to the fire (s_{ir4}), etc.

With l_{ir} , o_{ir} , $\mathbf{s}_{ir}$, the risk related to fire i takes the following form:

$$\text{Risk}_i \equiv \{ (l_{ir}, o_{ir}, \mathbf{s}_{ir}), r = 1, 2, \dots, n_i \} \quad (1.3)$$

In general, the total number of the outcomes, n_i , may vary from one fire to another. Let us consider the three-storey office building shown in Fig. 1.1. Fire can originate in each floor (i.e., three fires are possible, $i = 1, 2, 3$). Fig. 1.2 shows simplified event trees developed for these fires (initiating events E_{0i}). In this example, $n_1 = n_2 = 4$ and $n_3 = 3$.

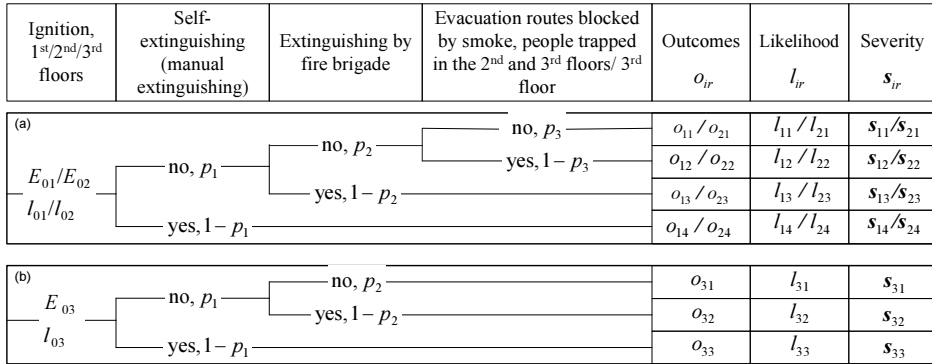


Fig. 1.2. Event tree diagrams developed for the initiation of fire in three floors of the building shown in Fig. 1.1: (a) diagrams for the fire initiation in the 1st and 2nd floors ($i = 1, 2$); (b) diagrams for the initiation in the 3rd floor ($i = 3$)

The risk (1.3) may express fairly diverse information, especially when the severity of each o_{ir} is represented by more than one significance measure. In the latter case the risk of the fire i will be associated with the matrix of significances

$$\begin{bmatrix} \mathbf{s}_{i1} \\ \mathbf{s}_{i2} \\ \vdots \\ \mathbf{s}_{ir} \\ \vdots \\ \mathbf{s}_{in_i} \end{bmatrix} = \begin{bmatrix} s_{i11} & s_{i12} & \cdots & s_{i1j} & \cdots & s_{i1n} \\ s_{i21} & s_{i22} & \cdots & s_{i2j} & \cdots & s_{i2n} \\ \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\ s_{ir1} & s_{ir2} & \cdots & s_{irj} & \cdots & s_{irn} \\ \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\ s_{in_i1} & s_{in_i2} & \cdots & s_{in_ij} & \cdots & s_{in_in} \end{bmatrix} \quad (1.4)$$

With this matrix, one can calculate n -dimensional vector of expected significances associated with the fire i and apply this vector to, say, a multi-attribute comparison of consequences of potential fires, namely,

$$\mathbf{c}_i = \left(\sum_{r=1}^{n_i} l_{ir} s_{ir1}, \sum_{r=1}^{n_i} l_{ir} s_{ir2}, \dots, \sum_{r=1}^{n_i} l_{ir} s_{irj}, \dots, \sum_{r=1}^{n_i} l_{ir} s_{irn} \right) \quad (1.5)$$

The corresponding components of the vectors $\mathbf{c}_i$ can be summed up and this will yield the vector

$$\mathbf{c} = \left(\sum_{i=1}^{n_f} \sum_{r=1}^{n_i} l_{ir} s_{irj}, j = 1, \dots, n \right) \quad (1.6)$$

where n_f is the number of potential fires. The vector can be used as a multi-attribute measure of fire safety calculated by means of quantitative risk assessment.

The expected significances in (1.5) contain the likelihoods l_{ir} , which in many cases can be estimated independently of s_{irj} (this independence should be assumed with caution, see Kumamoto and Henley 1996). Each l_{ir} can be expressed as annual frequency (number of occurrences per year).

The frequency of relatively rare occurrences of the fires and so of the outcomes o_{ir} can be estimated by means of classical Bayesian approach to quantitative risk assessment (Aven and Pörn 1998, Vaurio and Jänkälä 2006). In context of this approach, the likelihoods l_{ir} will be estimated in the form of epistemic uncertainty distributions related to true values of l_{ir} (Zavadskas and Vaidogas 2009). Such estimating is usually carried out by propagating epistemic uncertainties through such logical models of quantitative risk assessment as the event trees shown in Fig. 1.2.

Input information for the calculation with the event tree diagrams are the likelihoods of fire initiation (l_{0i}) and branching probabilities p_k . Both l_{0i} and p_k can be uncertain in the epistemic sense and so can be the outcome likelihoods l_{ir} of the outcomes o_{ir} . The calculation of the risk defined by Eq. (1.3) consists in the estimation of l_{ir} and assessment of the severities s_{ir} . Input information use for the calculation of risk consists mainly in hard statistical data and expert knowledge when this data is scarce or not available at all.

The fire risk assessment is similar to the general engineering risk analysis. The summation (1.5) indicates “total” risk from multiple scenarios. This type of fire risk analysis, commonly referred to as probabilistic risk assessment (PRA) or quantitative risk analysis (QRA), is widely used in the chemical process industry and for fire safety assessments of nuclear facilities (Apostolakis 1993), and is beginning to see broader application in fire protection engineering applications (NFPA 2009).

Let us return to the building shown in Fig. 1.1. In the case where the fire safety of this building is measured by means of a risk profile (1.3), fire scenarios leading to some specific and generally adverse outcomes must be identified. A simplified graphical representation of such scenarios is given in Fig. 1.2. These diagrams assume that fire can be initiated in each of the three floors and thus $i = 1, 2, 3$. The likelihoods of the outcomes of these scenarios are given by

$$\left. \begin{aligned} l_{i1} &= l_{0i} p_1 p_2 p_3 \\ l_{i2} &= l_{0i} p_1 p_2 (1 - p_3) \\ l_{i3} &= l_{0i} p_1 (1 - p_2) \\ l_{i4} &= l_{0i} (1 - p_1) \end{aligned} \right\} i = 1, 2; n_i = 4 \quad (1.7)$$

$$\left. \begin{aligned} l_{31} &= l_{03} p_1 p_2 \\ l_{32} &= l_{03} p_1 (1 - p_2) \\ l_{33} &= l_{03} (1 - p_1) \end{aligned} \right\} n_3 = 3 \quad (1.8)$$

One can see that the input information required to calculate the likelihoods l_{ir} consists of the fire initiation likelihoods l_{0i} as well as the branching probabilities p_k ($k = 1, 2, 3$). The initiation likelihoods l_{0i} can be estimated from the annual frequency calculated for the total floor area $A = 8400 \text{ m}^2$ by means of a generalised Barrois model (Hasofer *et al.* 2007):

$$\begin{aligned} f(A) &= c_1 A^r + c_2 A^s \\ &= 0.056 \cdot 8400^{-2} + 3 \cdot 10^{-6} \cdot 8400^{-0.05} \\ &= 1.910 \cdot 10^{-6} \text{ per square metre per annum} \end{aligned}$$

Then this frequency of fire initiation related to A will be equal to

$$A \cdot f(A) = 8400 \cdot 1.91 \cdot 10^{-6} = 0.016 \text{ per annum}$$

Consequently the fire can be expected every 62.3 years in average. As long as all three floors are used for identical occupancy, the fire initiation frequency 0.016 a^{-1} related to the entire floor area can be divided by the number of floors and the likelihoods l_{0i} obtained:

$$l_{0i} = 0.016/3 = 0.00533 \text{ a}^{-1} \quad (i = 1, 2, 3)$$

Further numerical input into the problem is the branching probabilities p_k , the hypothetical values of which are given in Table 1.2. Putting these values in the expressions (1.7) and (1.8) along with the fire initiation likelihoods l_{0i} yields the likelihoods of individual outcomes, l_{ir} (Table 1.3).

Table 1.2. Input information in for the quantification of risk represented by the event tree diagram shown in Fig. 1.2.

Event	Symbol	Value
Self-extinguishing of fire	p_1	0.1
Extinguishing of fire by fire brigade	p_2	0.87
Blockage of evacuation routes	p_3	0.07

The vectors of severities, s_{ir} , are assumed in this example to consist of three components, namely, direct monetary losses due to the fire i , (s_{ir1}), the number of fire victims (s_{ir2}), and the time during which the use of building is interrupted (s_{ir3}). Illustrative values of components of s_{ir} are summarised in Table 1.3. With these values as well as the likelihoods l_{ir} , one can calculate the vectors of expected severities defined by Eq. (1.5) and related to the three individual fires, namely, the vectors c_i . In this example, the vectors c_i will have three components:

$$c_1 = (105.77 \text{ €/a}; 0.19 \text{ victims/a}; 0.0083 \text{ months/a})$$

$$c_2 = (134.32 \text{ €/a}; 0.14 \text{ victims/a}; 0.0079 \text{ months/a})$$

$$c_3 = (149.06 \text{ €/a}; 0.046 \text{ victims/a}; 0.0095 \text{ months/a})$$

As all three fires lead to the outcomes characterised by the same triplet of severities, the expected severities c_i can be gathered up into one vector characterising all possible fires in the building:

$$c = (389.15 \text{ €/a}; 0.38 \text{ victims/a}; 0.0025 \text{ months/a})$$

Table 1.3. Illustrative values of the severities related to individual fire scenarios represented by the event tree diagram shown in Fig. 1.2.

Fire i	Outcome likelihoods l_{ir} , a^{-1} *	Scenario r	Severities s_{ir}		
			s_{ir1} , €	s_{ir2} , no of victims	s_{ir3} , months
$i = 1$	3.2×10^{-5}	$r = 1$	580 000	600	12
	43×10^{-5}	$r = 2$	180 000	400	7
	69×10^{-5}	$r = 3$	17 000	10	2
	479.7×10^{-5}	$r = 4$	1800	0	1
$i = 2$	3.2×10^{-5}	$r = 1$	440 000	400	11
	43×10^{-5}	$r = 2$	260 000	300	6
	69×10^{-5}	$r = 3$	18 000	15	2
	479.7×10^{-5}	$r = 4$	1500	0	1
$i = 3$	46×10^{-5}	$r = 1$	306 000	100	10
	69×10^{-5}	$r = 2$	16 000	7	2
	479.7×10^{-5}	$r = 3$	1500	0	1

* “a” is symbol for the year as a unit of time (for Latin *annus*)

The latter vector can be seen as a final result of a fire safety assessment by means of a formal QRA. This vector implies that one building is characterised by three attributes having different units of measurement. In principle, the number of such attributes can be increased by adding additional component to the severity vectors s_{ir} . Decisions and actions concerning fire safety can be directed towards reducing some or each of them. The calculation of the expected severities c is straightforward given the values l_{0i} and p_k as well as components of s_{ir} . Unfortunately, specification of these values is the most problematic part of QRA. This especially applies to the branching probabilities p_k . On the other hand, fires in buildings similar to the one considered in the present example are relatively frequent and well-investigated phenomena. One can suggest that the branching probabilities can be estimated by a combined application of data on similar fires, computer simulation of fire process and evacuation as well as expert judgement.

The pros and cons of the quantitative fire risk assessment

The advantage of an application of QRA methods to the fire risk assessment is obvious. Fire safety measures calculated on the basis of the risk defined by Eq. (1.3), for instance, the vector of expected significances, c , express the level

of fire safety in a very comprehensive way. The reason for this is that event tree modelling, qualitative and quantitative, widely used for QRA allows identifying all foreseeable scenarios which can be initiated by ignition or an event causing ignition. In addition, event trees can be adapted to a highly specific situation in an individual building subjected to its own fire hazards. For instance, QRA-based fire risk assessment can take into account such events as:

- A deliberate ignition (arson) as an act of sabotage or revenge;
- Failure of a fire safety system (e.g., sprinklers or fire alarm) leading to a dangerous escalation in the course of fire;
- Strange and unexpected behaviour of people during the fire (e.g., unwillingness to act for some time when fire alarm is activated).

A further advantage of the QRA-based fire risk assessment lies in the very nature of QRA methods. A quantification of risk in line with these methods requires an extensive use of statistical data and which is often combined with expert judgement. Consequently, the QRA-based fire risk assessment is able to utilise general statistical data on fires, component reliability data, data human reliability, and the vast knowledge of experts on various and sometimes highly specific aspects of fire safety. Such data and knowledge can be hardly utilised in a direct way when fire safety is assessed by means of fire indices.

A quantitative part of QRA used for a fire safety assessment allows to utilise the state-of-the-art methods developed to modelling the physical processes of fire and building evacuation. These methods, after some stochastic augmentation, can be used to estimate branching probabilities p_k (Hostikka and Keski-Rahkonen 2003).

The general engineering risk analysis is a world-wide spread methodology. It is well-documented by such organisations as International Atomic Energy Agency (e.g., IAEA 1992, 1995). Therefore final and intermediate results of fire-related applications of QRA can be understood and applied in various countries with relative ease. Data necessary for such an assessment can also be shared world-wide as long as such data is relevant to a particular risk assessment problem.

On the other hand, the comprehensiveness of QRA creates stumbling blocks for an application of this methodology to a practical assessment of fire risk. An accurate risk assessment requires a great deal of expertise, first and foremost, in the combined use of hard data and expert knowledge. QRA is, to a large degree, a process of an estimation of probabilities and frequencies which are transformed eventually into a risk profile. This process may include a subtle use of subjective information in combination with sparse empirical data. As compared to the calculation of fire risk indices, the estimation of probabilities

and frequencies involved in a fire-related QRA may be a demanding and tedious task.

1.2. The problem of multi-criteria decision making

The MCDM aims at determining the best alternative a^* or a subset of leading alternatives among a discrete set of alternatives represented by the vector $\mathbf{a} = (a_1, a_2, \dots, a_i, \dots, a_m)^T$. The quality of a_i is evaluated by means of a row-vector $\mathbf{c}_i = (c_{i1}, c_{i2}, \dots, c_{ij}, \dots, c_{im})$, the components of which, c_{ij} , are attributes (characteristics) of a_i used for MCDM. In terms of MCDM, the element c_{ij} expresses impact of the i th alternative on the j th attribute.

An algorithm of MCDM expressed in a simplified form is shown in Fig. 1.3. Data for solving an MCDM problem is formulated as an $m \times n$ decision making matrix

$$\mathbf{C} = [c_1, \dots, c_i, \dots, c_m]^T \quad (1.9)$$

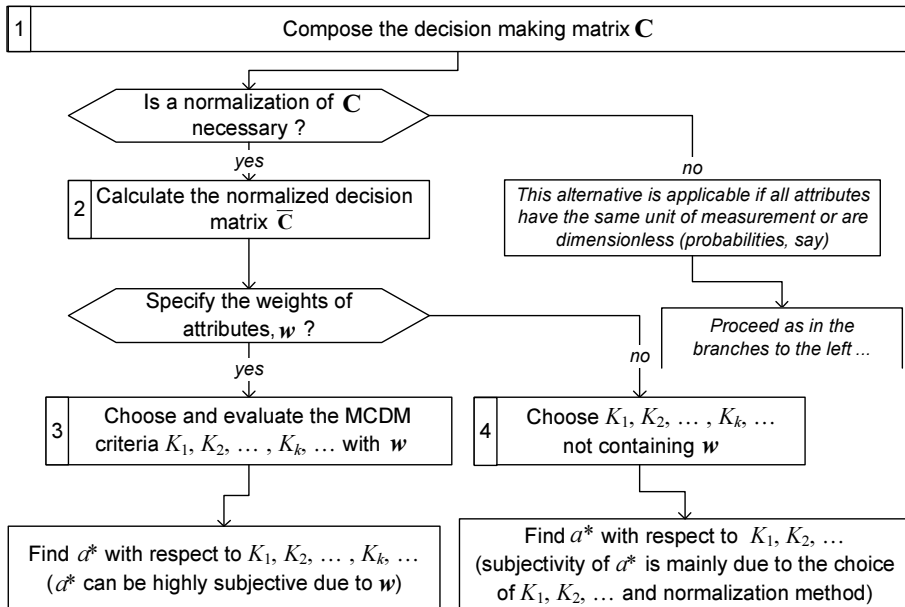


Fig. 1.3. General algorithm of multi-attribute selection

The values c_{ij} making up different columns of $\mathbf{C}$ are usually of different units. To facilitate inter-attribute comparisons, the components c_{ij} are normalised. A normalised (dimensionless) decision making matrix or,

alternatively, matrix of dimensionless attributes, $\bar{C}$, is obtained from the initial decision making matrix C (Block 2 in Fig. 1.3). The structure of $\bar{C}$ is

$$\bar{C} = [\bar{c}_1, \dots, \bar{c}_i, \dots, \bar{c}_m]^T \quad (1.10)$$

where $\bar{c}_i = (\bar{c}_{i1}, \bar{c}_{i2}, \dots, \bar{c}_{ij}, \dots, \bar{c}_{in})$ ($i = 1, 2, \dots, m$) is the row-vector calculated by normalizing components of the corresponding c_i . Most methods of MCDM select a^* with the normalised $\bar{C}$ and not the initial C (Hwang and Yoon 1981: Chapter III; Triantaphyllou 2000: Chapter 2). Examples of normalization formulas used to obtain $\bar{c}_{ij}$ from c_{ij} are given, among others, by Peldschus (1986) and Zavadskas *et al.* (2008, 2009ac).

The difference in significance of the attributes c_{ij} ($i = 1, 2, \dots, m$) is expressed by the vector of weights, $w = (w_1, w_2, \dots, w_j, \dots, w_n)^T$. Usually, the weights w_j are between 0 and 1 and add up to 1. If w is applied, the search for a^* is carried out by using the attribute values $w_j \bar{c}_{ij}$. A number of formal methods are suggested in literature for specifying w_j , both crisp and fuzzy (Hwang and Yoon 1981: 41, Triantaphyllou 2000: Chapters 4–7). These methods are used to elicit imprecise expert judgements and convert the judgements into the weights w_j . However, these methods do not fully eliminate the specifying of w from subjectivity. If the vector w is applied, the search for a^* is carried out using the so called matrix of estimates, $\hat{C}$, with elements $\hat{c}_{ij}$ defined by the product $w_j \bar{c}_{ij}$.

The key element of each MCDM method is the criterion, according to which a_i are ranked and the best one, a^* , is selected (MCDM criterion, in short). Criteria of several, say, n_k methods applied to selecting a^* will be denoted by the letters $K_1, K_2, \dots, K_k, \dots, K_{n_k}$ (Block 3 in Fig. 1.3) (French 1988: 36; Hodges and Lehman 1952). The buoyant literature devoted to the development and comparison of the criteria K_k is conveniently reviewed by French (1988), Triantaphyllou (2000), Figueira *et al.* (2005). Applications of MCDM criteria K_k to real-world problems are numerous and found in very different fields. In the field of fire safety, these criteria were applied mainly to ranking fire safety attributes (Rasbash *et al.* 2004, Zhao *et al.* 2004).

The specification of w , and the choice of K_k , together with the calculation of $\bar{C}$ require to make subjective decisions. For instance, different MCDM methods should be chosen for different decision making situations by answering subjective questions (Hwang and Yoon 1981: 211).

1.2.1. Normalisation in multi-attribute selection

Usually the values c_{ij} making up different columns of $\mathbf{C}$ are of different units. To facilitate inter-attribute comparisons, the components c_{ij} are normalised (Block 2 in Fig. 1.3). A practical implementation of MCDM meets the need to choose a normalisation method for calculating the matrix of dimensionless attributes, $\bar{\mathbf{C}}$. If necessary, the vector of weights, $\mathbf{w}$, is specified for obtaining the matrix of estimates, $\hat{\mathbf{C}}$. And lastly, one or more MCDM criteria are chosen to select the best alternative a^* on the basis of $\bar{\mathbf{C}}$ or $\hat{\mathbf{C}}$. Here do no more than apply several alternative normalisation methods and MCDM criteria to solving problems involving reliability. Alternative mathematical tools used in calculations with the same matrix of solution, $\mathbf{C}$, may lead to disagreeing selections of a^* .

After specifying the matrix $\mathbf{C}$, the next step of the MCDM process is the choice of a normalisation method. The following well-accepted normalisation methods are:

- The method of normalisation consisting in dividing components of the vector $\mathbf{c}_j = (c_{1j}, c_{2j}, \dots, c_{mj})^T$ by its norm $|\mathbf{c}_j|$ or, in brief, vector-norm-normalisation (Hwang and Yoon 1981):

$$\bar{c}_{ij} = c_{ij} / |\mathbf{c}_j| \quad (1.11a)$$

- The method of normalisation by a linear transformation (Weitendorf 1976):

$$\bar{c}_{ij} = \begin{cases} (c_{ij} - \min_i \{c_{ij}\}) / r_j & \text{if the maximal value of } c_j \text{ is preferred} \\ (\max_i \{c_{ij}\} - c_{ij}) / r_j & \text{if the minimal value of } c_j \text{ is preferred} \end{cases} \quad (1.11b)$$

- The method of non-linear transformation (Peldschus 1986):

$$\bar{c}_{ij} = \begin{cases} (\min_i \{c_{ij}\} / c_{ij})^3 & \text{if the minimal value of } c_j \text{ is preferred} \\ (c_{ij} / \max_i \{c_{ij}\})^2 & \text{if the maximal value of } c_j \text{ is preferred} \end{cases} \quad (1.11c)$$

- The method of normalisation suggested by Jüttler and Körth (1969):

$$\bar{c}_{ij} = \begin{cases} 1 - |(\max_i \{c_{ij}\} - c_{ij}) / \max_i \{c_{ij}\}| & \text{if the maximal value of } c_j \text{ is preferred} \\ 1 - |(\min_i \{c_{ij}\} - c_{ij}) / \min_i \{c_{ij}\}| & \text{if the minimal value of } c_j \text{ is preferred} \end{cases} \quad (1.11d)$$

In the formulas (1.11a) to (1.11d), $\max_i \{c_{ij}\} = \max\{c_{1j}, c_{2j}, \dots, c_{mj}\}$, $\min_i \{c_{ij}\} = \min\{c_{1j}, c_{2j}, \dots, c_{mj}\}$, $r_j = \max_i \{c_{ij}\} - \min_i \{c_{ij}\}$. The applicability of the

normalisation formula (1.11d) is limited by the condition $c_{ij}/\min_i\{c_{ij}\} \in [0, 2]$. In some cases the normalisation formulas (1.11a) to (1.11d) can be applied when the condition $c_{ij} > 0$ is satisfied for certain or all components of the vector c_j .

The main reason of normalising elements of $\mathbf{C}$ is dealing with different units of measurement of c_j . A normalisation aims at mapping components of c_j on measurement scale which is the same for all attributes and allows inter-attribute comparisons.

Normalization formulas have their pros and cons (see a review provided by Zavadskas *et al.* 1994, 2002, 2003). MCDM practice is to associate specific normalization formulas with individual MCDM methods. However, the same MCDM method can, at least formally, be applied to the matrices $\bar{\mathbf{C}}$ obtain by means of different formulas. This may lead to different solutions of an MCDM problem at the same $\mathbf{C}$.

1.2.2. Decision criteria used for multi-criteria decision making

The key element of each MCDM method is the criterion, according to which a_i ranked and the best one, a^* , selected. Criteria of several, say, n_k methods applied to selecting a^* will be denoted for convenience by the letters $K_1, K_2, \dots, K_k, \dots, K_{n_k}$ (see Blocks 3 and 4 in Fig. 1.3).

Some of these criteria were developed in the game theory. A review of MCDM criteria is given by Zavadskas *et al.* (2002, 2003). The following well-known criteria will be applied to solving MCDM problems considered in the examples:

- Wald's criterion (Wald 1945) (K_1 , say): a^* is a_i with the number i following from the solution of $\max_i \{ \min_j \{ \bar{c}_{ij} \} \}$, where $\bar{c}_{ij}$ is the component of $\bar{\mathbf{C}}$.
- Savage's criterion (Savage 1951) (K_2 , say): a^* is a_i with the number i following from the solution of $\min_i \{ \max_j \{ (\max_i \{ \bar{c}_{ij} \} - \bar{c}_{ij}) \} \}$.
- Bernoulli-Laplace's criterion (Bernoulli 1738) (K_3 , say): a^* is a_i with the number i following from the solution of $\max_i \left(n^{-1} \sum_{j=1}^n \bar{c}_{ij} \right)$.
- Hurwicz's criterion (Hurwicz 1951) (K_4 , say): a^* is a_i with the number i following from the solution of $\max_i \{ \lambda \min_j \{ \bar{c}_{ij} \} + (1 - \lambda) \max_j \{ \bar{c}_{ij} \} \}$, where $\lambda \in [0, 1]$ is the weighting factor (the value $\lambda = 1$ yields the most

pessimistic solution, the value $\lambda = 0$ allows considering the maximum values only).

- Bayes's criterion (Arrow 1949) (K_5 , say): a^* is a_i with the number i following from the solution of $\max_i \left(\sum_{j=1}^n w_j \bar{c}_{ij} \right)$ with $\sum_{j=1}^n w_j = 1$.
- Hodges-Lehman's criterion (Hodges and Lehman 1952) (K_6 , say): a^* is a_i with the number i following from the solution of $\max_i \{ \delta \sum_{j=1}^n w_j \bar{c}_{ij} + (1 - \delta) \min \{ \bar{c}_{ij} \} \}$, where $\delta \in [0, 1]$ is the confidence factor (the value $\delta = 0$ (no confidence) yields the Wald's criterion, and the value $\delta = 1$ (greatest confidence) results in Bayes's criterion).

The criteria K_1 to K_4 can be applied to calculations with either of the matrices $\bar{\mathbf{C}}$ and $\hat{\mathbf{C}}$. In other words, these criteria can be used with and without the vector of weights, $\mathbf{w}$. In the expressions of K_1 to K_4 , the elements $\bar{c}_{ij}$ of $\bar{\mathbf{C}}$ must be replaced by the elements $\hat{c}_{ij}$ of $\hat{\mathbf{C}}$ if a^* is selected with $\mathbf{w}$. The multiplier n^{-1} in the criterion K_3 can be interpreted as a component of the vector $\mathbf{w}$ which consists of equal weights $w_j = n^{-1}$. The criteria K_5 and K_6 incorporate components of $\mathbf{w}$. Thus, an application of K_5 and K_6 requires assigning weights to the attributes c_j . The criterion K_6 will turn into the criterion K_3 when $w_j = n^{-1}$ and $\delta = 1$. The presence of $\bar{c}_{ij}$ in the expressions of K_1 to K_6 implies that these criteria are applied to the normalised matrix $\bar{\mathbf{C}}$, no matter which normalisation formula is used to calculate $\bar{c}_{ij}$ from c_{ij} .

1.2.3. Multi-criteria decision making data and subjectivity sources

Composing $\mathbf{C}$ includes several steps, the most critical and least formal of which is defining $\mathbf{a}$ and $\mathbf{c}$ (Triantaphyllou 2000: Chapter 3). Further steps are more formal and can be captured by applying MCDM procedures for quantifying crisp and fuzzy c_{ij} , identifying those c_j , which might be in functional dependence, and eliminating "superfluous" c_j . They can be applied to quantifying "deterministic" part of $\mathbf{C}$ in case that $\mathbf{c}$ includes both deterministic and stochastic attributes. The presence of the latter kind of c_j in $\mathbf{c}$ can pose the problem of a potential stochastic dependence between attributes.

Most methods of MCDM select a^* with the normalised $\bar{\mathbf{C}}$ and not the initial $\mathbf{C}$ (Hwang and Yoon 1981: Chapter III, Triantaphyllou 2000: Chapter 2). The possibility (necessity) to choose among several normalization formulas introduces an element of subjectivity into MCDM. At the level of practical applications of MCDM, the ambiguity related to the normalisation of $\mathbf{C}$ is

bypassed by choosing one of the deterministic or fuzzified MCDM methods which are widely used in the real-world DM. These methods are strongly associated with specific normalization formulas.

The use of judgements as well as the need to choose among several candidate methods turns specifying the weights w_j makes MCDM into a highly subjective task, however well each of these methods transform expert knowledge into w_j . The specification of w , together with the choice of the normalization method used to calculate $\bar{C}$, introduces a great deal of subjectivity into selecting a^* . The choice of MCDM method K_k for determining a^* also contributes to subjectivity of MCDM results. There exist a large number of MCDM methods and their modifications. The need to choose the best one leads to the situation expressed by Triantaphyllou's paradox: "What DM method should be used to choose the best DM method?" (Triantaphyllou 2000: 5). The literature on MCDM addresses the problem of choice of the best method for the specific problem; however, it is generally recognised that a specific choice rule does not exist (e.g. Hwang and Yoon 1981: 210).

The three aforementioned sources of subjectivity make MCDM to a seemingly highly subjective and thus "dim" task. On the other hand, MCDM as such is not a means of ascertaining some "objective" true as are, say, methods of classical statistical inferencing. Different MCDM methods should be chosen for different DM situations by answering subjective questions (e.g., Hwang and Yoon 1981: 211).

1.2.4. Introducing reliability and safety measures into multi-criteria decision making

The introduction of safety and reliability measures into MCDM problem was considered by Vaidogas and Zavadskas (2007) and Vaidogas *et al.* (2007). The general idea of such an introduction is that probabilistic attributes (characteristics) of alternatives a_i can be used as attributes. The main of such attributes are reliability and availability of technical objects (e.g., Smith 2005).

In the simplest case the alternative a_i can be characterised by the failure probability of non-reparable objects, $p_f(x_i)$, or an average (mission) availability $\bar{A}_i(t_s)$ of reparable objects, where x_i and t_s is the vector used to a precise description of a_i and the nominal lifetime or service life of a_i , respectively. Components of x_i can be either nominal parameters of a_i or characteristics of probability distributions describing a_i , say, mean values. In either case the vector x_i should include the specified period of time, t_s , for which p_f is estimated. The values $p_f(x_i)$ can be easily included into the attribute vector c_i :

$$c_i = (p_f(x_i), c_{i2}, c_{i3}, \dots, c_{in}) \text{ or } c_i = (\bar{A}_i(t_s), c_{i2}, c_{i3}, \dots, c_{in}) \quad (1.12)$$

where $c_{i2}, c_{i3}, \dots, c_{in}$ are values of the attributes which are not necessarily probabilistic.

The failure probability can be introduced into the MCDM decision making matrix indirectly, through comparison of the total (life-cycle) utilities related to a_i :

$$U_{tot}(\mathbf{x}_i) = B(\mathbf{x}_i) - C_{ini}(\mathbf{x}_i) - C_m(\mathbf{x}_i) - \sum_{k_i} p_{fk_i}(\mathbf{x}_i) C_{fk_i}(\mathbf{x}_i) \quad (1.13)$$

where $B(\mathbf{x}_i)$ is the anticipated benefit derived from the existence of the alternative a_i ; $C_{ini}(\mathbf{x}_i)$ is the initial cost of a_i ; $C_m(\mathbf{x}_i)$ is the cost of maintenance of a_i ; $C_{fk_i}(\mathbf{x}_i)$ is the expected cost of failure according to the failure mode k_i ; and $p_{fk_i}(\mathbf{x}_i)$ is the probability that a_i will fail according to the mode k_i .

The failures of reparable a_i are usually associated with economic losses only and do not do harm to people. In this situation it should not be difficult to determine the cost of utility loss $C_{fk_i}(\mathbf{x}_i)$ due to unavailability of a_i related to the failure mode k_i . This cost depends on the type of a_i which can be a binary-state or a multi-state object. For a binary-state a_i , the failure k_i causes the total loss of utility, and then the expected utility $U(\mathbf{x}_i)$ can be calculated by

$$U(\mathbf{x}_i) = -C_{fk_i}(\mathbf{x}_i)(1 - \bar{A}_i(t_s)) \quad (1.14a)$$

where the difference $1 - \bar{A}_i(t_s)$ expresses the average unavailability of a_i (fraction of time that a_i is in the failed state, roughly speaking). For a multi-state a_i the expected utility $U(\mathbf{x}_i)$ can be determined in a similar manner:

$$U(\mathbf{x}_i) = -\sum_{l=1}^{n_{si}} C_{fl}(\mathbf{x}_i)(1 - \bar{A}_{il}(t_s)) \quad (1.14b)$$

where n_{si} is the number of states of a_i , in which a partial or total loss of availability poses the corresponding failure costs $C_{fl}(\mathbf{x}_i)$; $1 - \bar{A}_{il}(t_s)$ is the average unavailability related to the l th state.

A comparison of utility functions defined by Eqs. (1.13) and (1.14) and related to non-reparable and reparable alternative objects, respectively, within an MCDM is a straightforward problem as long as it is possible to compute point estimates of $U_{tot}(\mathbf{x}_i)$ and $U(\mathbf{x}_i)$. Each of them can be included into the attribute vector $\mathbf{c}_i$. However, despite the comprehensiveness of the expected utilities $U_{tot}(\mathbf{x}_i)$ and $U(\mathbf{x}_i)$, they may not reflect all properties of the alternatives a_i . The "mission" of MCDM lies in regarding those attributes of a_i which can not be

included into MCDM as arguments of $U_{tot}(\mathbf{x}_i)$ or $U(\mathbf{x}_i)$. Examples of such attributes are non-monetary characteristics of a_i : degree of aesthetical attractiveness, image or prestige of a_i , number of working places created by each a_i , vicinity of a_i to main public services. The non-monetary attributes can express losses suffered by individuals and groups of individuals due to the failures of a_i . These non-monetary attributes may be quantitative measures related to deaths, injuries, emotional distress etc.

Zavadskas and Vaidogas (2009) considered also introducing elements of risk expressed and estimated by means of QRA. They suggested to include expected severities of individual accident scenarios into the attribute vectors c_i . The number of risk-based components of c_i will be equal to the number of severity measures. Typically these measures include property loss, number of victims and expected outage of the object represented by a_i . The present work seeks to extend the ideas proposed by the aforementioned authors and adopt these ideas to solving fire safety problems.

1.2.5. Multi-criteria decision making with uncertainties related to elements of decision making matrix

The subjectivity of MCDM is a natural background for applying uncertain components of the decision making matrix, c_{ij} , both stochastic and fuzzy. Solving MCDM problems with incomplete and uncertain information is a rapidly developing subfield of MCDM. Several approaches to quantification of uncertainties (imprecisions) related to the attribute values c_{ij} have been suggested in the last four decades. Short reviews of these approaches are presented by Stewart (2005), Lahdelma *et al.* (2009), Fan *et al.* (2010), and Liu *et al.* (2011). The variety of methodological means used to quantify uncertainty within MCDM can be categorized into non-probabilistic and probabilistic approaches.

Non-probabilistic approaches to specifying the decision making matrix

The two main non-probabilistic approaches to modelling uncertainties in the elements of decision making matrix, c_{ij} , are:

- Intervals called the grey numbers and
- Fuzzy sets.

The concept of a “grey” number states that the exact value of c_{ij} can be unknown but the range within which c_{ij} lies is known. The grey numbers are expressed by the intervals $[\underline{c}_{ij}, \bar{c}_{ij}]$, $[-\infty, \bar{c}_{ij}]$ or $[\underline{c}_{ij}, \infty]$ and can be continuous or discrete within these intervals (Fig. 1.4a). An expression of the decision making

matrix components c_{ij} by these intervals will yield a decision making matrix, all or some components of which will consist of intervals. The criteria K_k developed for solving an MCDM problem with such a decision making matrix are known as COPRAS-G and ARAS-G methods (Zavadskas *et al.* 2008, 2009abc, Turskis and Zavadskas 2010, Zavadskas *et al.* 2011). The basic idea of these methods is to transform the initial problem of DM with interval values into MCDM problems with fixed decision matrices and solve these problems by conventional means of MCDM. COPRAS-G and ARAS-G methods are based on solving the MCDM problem with lower and upper limits of the intervals. The fact that some values of c_{ij} are more likely and some are less is simply ignored.

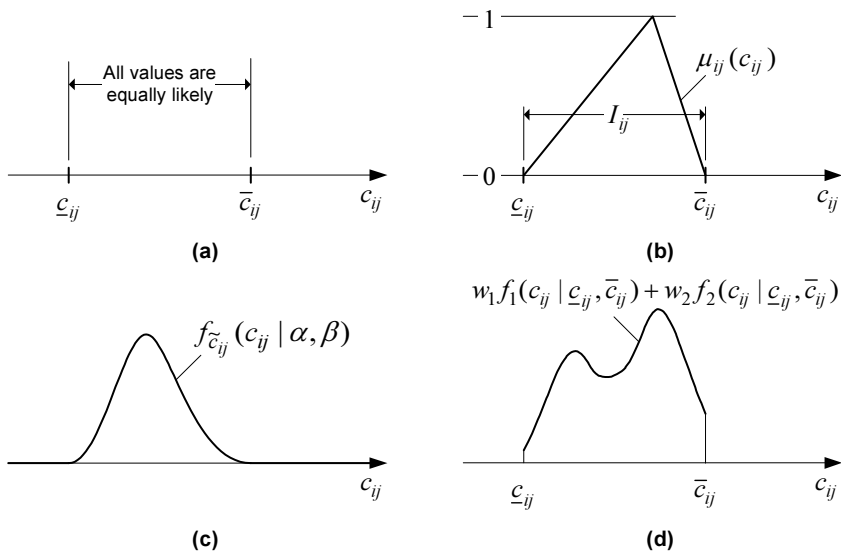


Fig. 1.4. Three ways of quantifying uncertainty in elements of decision making matrix, c_{ij} : (a) quantifying uncertainty by an interval (grey number); (b) expressing uncertainty by means of a triangular membership function $\mu_{ij}(c_{ij})$ (a fuzzy set component); (c, d) probabilistic modelling uncertainty by a standard skewed density $f_{\tilde{c}_{ij}}(c_{ij})$ function and a truncated, bimodal density function composed of two truncated unimodal densities $f_1(\cdot)$ and $f_2(\cdot)$

The shortcomings of the modelling the decision making matrix components c_{ij} by grey numbers are on the planer of uncertainty modelling and not one of MCDM:

1. The specification and treatment of the interval limits $\underline{c}_{ij}$ and/or $\bar{c}_{ij}$ as known values is inconsistent. How can we know the limits exactly, whereas the precise value c_{ij} is unknown?
2. What is the likelihood that the true, albeit unknown value of c_{ij} will not fall into the intervals?
3. Even if the intervals will include c_{ij} , some values of c_{ij} can be more likely and some less. Unfortunately, the use of the intervals $[\underline{c}_{ij}, \bar{c}_{ij}]$, $[-\infty, \bar{c}_{ij}]$ or $[\underline{c}_{ij}, \infty]$ assigns an equal likelihood to all values belonging to them.
4. The problem of uncertainty related to the limits $\underline{c}_{ij}$ and/or $\bar{c}_{ij}$ is addressed in the grey number theory by introducing further grey numbers expressing these limits. The value of c_{ij} expressed in such a way is called a “black number”. Unfortunately, such representation of c_{ij} is cumbersome and does not provide a complete and consistent answer to the above three questions.

The specification of the decision making matrix components c_{ij} in the form of intervals can in some cases be done in a consistent and natural way. The intervals $[\underline{c}_{ij}, \bar{c}_{ij}]$, $[-\infty, \bar{c}_{ij}]$ or $[\underline{c}_{ij}, \infty]$ can be one-sided or two-sided confidence intervals of population parameters computed by means of classical statistics. An MCDM problem can be used to compare mean values of uncertain quantities and these can be expressed by confidence intervals for means. In passing it should be noted that such probabilities as reliability and failure probability of technical objects can be expressed and estimated as a population mean (see, e.g., Vaidogas 2007ab). Non-statistical intervals computed by means of interval arithmetic can be used as estimates of uncertain probabilities or other quantities (Gao *et al.* 2010, Ni and Qiu 2010, Zhang *et al.* 2010, Zou *et al.* 2010, Zou *et al.* 2012). If an MCDM problem compares several technical objects in terms of reliability, safety or other uncertain characteristics, interval estimates can serve as attributes considered in this problem.

Since 1970, the presence of uncertainty in an MCDM problem was handled in a by introducing fuzzy sets into the decision making matrix (Kahraman 2008, Mesiar and Vavříková 2010, Turskis and Zavadskas 2010, Medineckiene *et al.* 2011). The frequently used MCDM techniques under fuzziness include fuzzy analytical hierarchy process (AHP) and fuzzy TOPSIS (Chen 2000, Demirel *et al.* 2008, Kahraman *et al.* 2008). In ELECTRE and PROMETHEE methods, the uncertainty was expressed by means of threshold methods (Brans and Vincke 1985, Papadopolous and Karagiannidis 2008).

Uncertainty expressed by fuzzy input has been handled by the use of Monte Carlo simulation (Olson and Wu 2008). The simulation was also applied as a

tool integrated in widely used MCDM methods. The best known are applications of simulation within the AHP method. Rosenbloom (1996), Zhao *et al.* (2004), Hsu and Pan (2009), Fan *et al.* (2010) applied simulation to pairwise comparisons used in AHP.

For a fuzzy set $\hat{c}_{ij}$ assigned to the decision making matrix element c_{ij} , the membership function is defined as $\mu_{ij}(c_{ij})$ for all c_{ij} that belong to the domain I_{ij} , namely, $\hat{c}_{ij} = \{(c_{ij}, \mu_{ij}(c_{ij})) | (c_{ij} \in I_{ij})(\mu_{ij}(c_{ij}) \in [0, 1])\}$ (Fig. 1.4b). If $\mu_{ij}(c_{ij}) = 1$, c_{ij} is definitely a member of the subset $\hat{c}_{ij}$. If $\mu_{ij}(c_{ij}) = 0$, c_{ij} is definitely not a member of $\hat{c}_{ij}$. For every c_{ij} with $0 < \mu_{ij}(c_{ij}) < 1$, the membership is not certain. The most frequently applied shapes for the membership functions are the triangular and Gaussian shape (Fig. 1.4b).

The concept of fuzzy sets appears to be very useful to represent non-deterministic properties of the decision making matrix element c_{ij} if the knowledge of uncertainty related to c_{ij} is based on expert opinion. However, if uncertainties in c_{ij} are of objective, rather than subjective, nature, quantifying them by models of probability theory appears more natural. Some authors are more categorical about the use of non-probabilistic means of uncertainty quantification, including the fuzzy logic, and state that “nothing is gained by moving outside the conventional probabilistic framework” (Melchers 1995). The probabilistic framework includes a well developed Bayesian statistical theory which is suitable to a consistent modelling of both expert opinions and objective information expressed by hard historic statistical data. This theory underlies QRA which is a natural means of dealing with the risk posed by building fires.

Probabilistic approaches to specifying the decision making matrix

The probabilistic approaches treat the attribute values c_{ij} as random variables denoted in the subsequent text by $\tilde{c}_{ij}$. These variables are used to compose alternative-related random attribute vectors $\tilde{\mathbf{c}}_i = (\tilde{c}_{i1}, \tilde{c}_{i2}, \dots, \tilde{c}_{ij}, \dots, \tilde{c}_{in})$ ($i = 1, 2, \dots, m$) and a random $m \times n$ decision making matrix $\tilde{\mathbf{C}}$. Uncertainty in components of $\tilde{\mathbf{C}}$ is quantified, in general, by a joint probability density function $f_{\tilde{\mathbf{C}}}(\mathbf{c})$ defined on the criteria space $\mathbb{R}^{m \times n}$. The components $\tilde{c}_{ij}$ are often treated as independent random variables and the joint density $f_{\tilde{\mathbf{C}}}(\mathbf{c})$ expressed as a product of marginal densities $\prod_{ij} f_{\tilde{c}_{ij}}(c_{ij})$. Examples of marginal densities are shown in Fig. 1.4cd.

Three broad approaches to solving MCDM problem with random decision making matrix $\tilde{\mathbf{C}}$ are:

- Multi-attribute utility theory (MAUT),
- Stochastic dominance concepts, primarily in the context of pairwise comparisons, and
- Stochastic multi-criteria acceptability analysis (SMAA).

MAUT uses utility functions to convert scales of the attributes c_{ij} to utility function scales (e.g., Dyer 2005). MAUT is based on the idea that any decision maker attempts unconsciously to maximise a multi-attribute utility function $u(\tilde{c}_i)$ which aggregates the utility of each attribute. A construction of the multi-attribute utility function $u(\tilde{c}_i)$ starts with the construction of partial or marginal utility functions individually for each attribute, say, $u(\tilde{c}_{ij})$. At this step, the weights w can be introduced in the utility function $u(\tilde{c}_i)$. For instance, an additive aggregation with w is defined as

$$u(\tilde{c}_i) \equiv u(\tilde{c}_i, w) = \sum_{j=1}^n w_j \tilde{c}_{ij} \quad (1.15)$$

Alternatives a_i are ranked by comparing values of the multi-attribute utility function. In essence, MAUT seeks to construct a utility function $u(\tilde{c}_i)$ such that for any two alternatives a_k and a_l , a_k is weakly preferred to a_l if $E(u(\tilde{c}_k)) \geq E(u(\tilde{c}_l))$, where the expectations are taken with respect to the probability distributions of the random functions $u(\tilde{c}_k)$ and $u(\tilde{c}_l)$. The disadvantage of MAUT is that it averages out uncertainties expressed by probability distributions of the random attribute values $\tilde{c}_{ij}$ to carry out inter-alternative comparisons. The aggregation of the marginal utility functions $u(\tilde{c}_{ij})$ into the multi-attribute one, $u(\tilde{c}_i)$, can be a real challenge (e.g., Stewart 2005: 451; Liu *et al.* 2011).

A construction of the utility function $u(\tilde{c}_i)$ in order to confirm whether one alternative is preferred to another is often not necessary. The conclusion about the preference may be derived from the concept of stochastic dominance (SD) (Stewart 2005: 455; Nowak 2007; Fan *et al.* 2010; Liu *et al.* 2011). The degree of SD of the probability distribution of one random variable $\tilde{c}_{kj}$ over another $\tilde{c}_{lj}$ with respect to the attribute j is expressed in various ways. If $\tilde{c}_{ij}$ and $\tilde{c}_{kl}$ are continuous random variables, the degrees of SD (denoted by $D_{\tilde{c}_{kj} \succ \tilde{c}_{lj}}$ and $D_{\tilde{c}_{ij} \succ \tilde{c}_{kl}}$) is expressed in the following form (Liu *et al.* 2011):

$$D_{\tilde{c}_{kj} \succ \tilde{c}_{lj}} = P(\tilde{c}_{kj} > \tilde{c}_{lj}) = \int_{-\infty}^{\infty} \phi(x) dx = \int_{-\infty}^{\infty} \int_{-\infty}^x f_{\tilde{c}_{kj}}(x) f_{\tilde{c}_{lj}}(y) dy dx \quad (1.16a)$$

$$D_{\tilde{c}_{lj} \succ \tilde{c}_{kj}} = P(\tilde{c}_{lj} > \tilde{c}_{kj}) = \int_{-\infty}^{\infty} \psi(x) dx = \int_{-\infty}^{\infty} \int_x^{\infty} f_{\tilde{c}_{kj}}(x) f_{\tilde{c}_{lj}}(y) dy dx \quad (1.16b)$$

The property of $D_{\tilde{c}_{kj} \succ \tilde{c}_{lj}}$ and $D_{\tilde{c}_{lj} \succ \tilde{c}_{kj}}$ is that $D_{\tilde{c}_{kj} \succ \tilde{c}_{lj}} + D_{\tilde{c}_{lj} \succ \tilde{c}_{kj}} = 1$.

The values $D_{\tilde{c}_{kj} \succ \tilde{c}_{lj}}$ and $D_{\tilde{c}_{lj} \succ \tilde{c}_{kj}}$ can be used to construct an $n \times n$ dominance degree matrix $\mathbf{D}_j$ containing SDs of pairwise comparisons with respect to the attribute j (Block 2, Fig. 1.5). An element of $\mathbf{D}_j$ denoted here by D_{klj} expresses the dominance of the alternative a_k over the alternative a_l with respect to the attribute j and $D_{klj} + D_{lkj} = 1$. Based on the matrices $\mathbf{D}_j$ ($j = 1, 2, \dots, n$), the overall dominance degree matrix $\mathbf{D}$ is constructed with the elements D_{kl} calculated as the sum $\sum_{j=1}^n w_j D_{klj}$ (Block 3, Fig. 1.5). The matrix elements D_{kl} satisfy the conditions $D_{kl} + D_{lk} = 1$ and $0 \leq D_{kl} \leq 1$. With the overall dominance degree matrix $\mathbf{D}$ the alternatives a_i can be ranked by applying rough set theory, outranking methods or interactive procedures (Liu *et al.* 2011) (Block 3, Fig. 1.5).

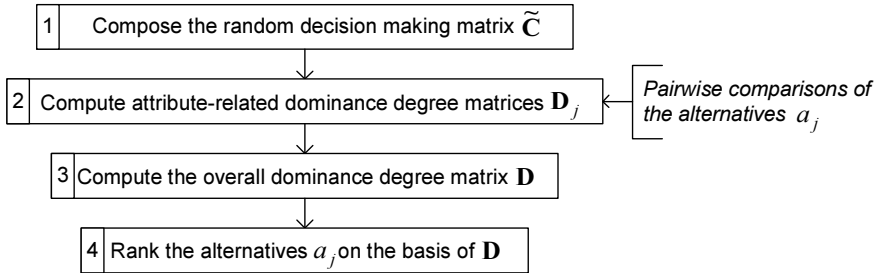


Fig. 1.5. The procedure for solving a selection problem using stochastic dominance rules (in line with Liu *et al.* (2011))

The pairwise comparisons of the alternatives a_i by applying quantitative expressions of SD degrees allows to replace the random decision making matrix $\tilde{\mathbf{C}}$ by the deterministic matrix $\mathbf{D}$. The decision is made on the basis of $\mathbf{D}$ and not on the basis of $\tilde{\mathbf{C}}$. Three problems limit the applicability of the pairwise comparisons on the basis of SD degrees:

- Assumption of independence of the random variables $\tilde{c}_{ij}$ and $\tilde{c}_{kl}$ is made, that is, the pairwise comparisons are based entirely on the marginal distributions of $\tilde{c}_{ij}$ and $\tilde{c}_{kl}$.
- There are several degrees of SD and rules to quantify them. This introduces arbitrariness in the formation of the deterministic decision making matrix $\mathbf{D}$. In addition, SD relations on some pairs of alternatives can not be identified using SD rules and, even if all SD relations are determined, the degree that one alternative dominates another may still be unknown (Fan *et al.* 2010). Consequently, it can be difficult for DMs to obtain a clear ranking of alternatives.
- The pairwise comparisons of the alternatives a_j is only one approach to solving MCDM problems. This approach belongs to the so-called relational MCDM models (e.g., Greco *et al.* 1999). The application of pairwise comparisons of a_j “shuts the door” on other MCDM models, collectively known as functional ones.

SMAA is another tool for supporting stochastic MCDM. SMAA is a family of methods developed for aiding group decision making in problems with the random matrix $\tilde{\mathbf{C}}$ and a random (uncertain) vector of weights $\tilde{\mathbf{w}}$ (Lahdelma and Samlinen 2010). SMAA can be considered as an inverse approach to the traditional MCDM approach, in which the best (most preferred) alternative is identified using criteria measurements c_j and DM's preferences expressed by $\mathbf{w}$ (Fig. 1.6a). SMAA is applied to identifying potentially optimal solutions among uncertainty ranges expressed by the random decision making matrix $\tilde{\mathbf{C}}$ and the random vector of weights, $\tilde{\mathbf{w}}$. A joint density of $\tilde{\mathbf{w}}$ will be denoted by $f_{\tilde{\mathbf{w}}}(\mathbf{w})$. SMAA is based on exploring the weight space in order to reveal what values of weights make each alternative most preferred one or give a certain rank for a specific alternative (Fig. 1.6b).

The main results of SMAA are rank acceptability indices, holistic acceptability index, central weight vectors and confidence factors, all computed for different alternatives a_i (Table 1.4). Expressions used to calculate these quantities in line with SMAA-2 method, which can be considered the basic SMAA method, are presented in Table 1.5. The primary result of SMAA-2 is the rank acceptability index b_i^r . It measures the variety of different preferences that grant alternative a_i the rank r . The index b_i^r is the share of all feasible weights which make a_i acceptable for a particular rank.

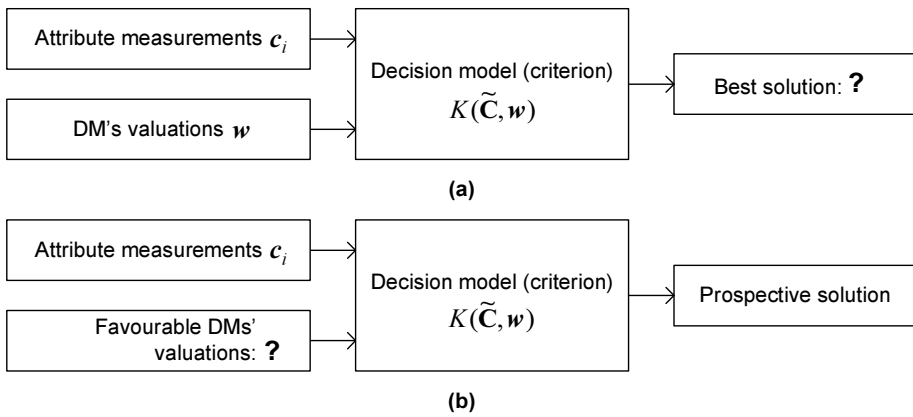


Fig. 1.6. Two approaches to multi-criteria decision making problem: (a) traditional approach based on attribute measurements and preferences of decision makers (DMs); (b) inverse approach used to identify preferences favourable for each alternative (after Lahdelma and Samlinen 2010)

Table 1.4. Main results of SMAA (according to Lahdelma and Samlinen 2010)

Result	Description
Rank acceptability index b_i^r	Describes variety of preferences resulting in a certain rank for the alternative a_i
Holistic acceptability index a_i^h	Measures the overall acceptability of a_i
Central weight vector w_i^c	Represents the typical preferences favouring a_i
Confidence factor p_i^c	Measures whether the measurements c_i are sufficiently accurate to make an informed decision

It can be seen from Table 1.5 that most of SMAA results are defined as integrals of the densities $f_{\tilde{C}}(\mathbf{c})$ and $f_{\tilde{w}}(\mathbf{w})$. They are evaluated by means of Monte Carlo simulation (Tervonen and Lahdelma 2007). In the simulation loop l , values of attributes and weights, c_{il} and w_l , are sampled from the probability distributions defined by $f_{\tilde{C}}(\mathbf{c})$ and $f_{\tilde{w}}(\mathbf{w})$ and the utility functions $u(c_{il}, w_l)$ are used to rank the alternatives a_i . Then statistics about the ranking are updated. For instance, the simulation-based estimate of the rank acceptability index b_i^r is computed by

Table 1.5. Mathematical expressions used to obtain the main results of SMAA (after Lahdelma and Samlinen 2010)

Expression	Subordinate expression(s)/comment
$b_i^r = \int f_{\tilde{C}}(\mathbf{c}) \int_{\mathbf{W}_i^r(\mathbf{c})} f_{\tilde{\mathbf{w}}}(\mathbf{w}) d\mathbf{w} d\mathbf{c}$	$\mathbf{W}_i^r(\mathbf{c}) = \{\mathbf{w} \in \mathbf{W} \mid \text{rank}_i(\mathbf{c}, \mathbf{w}) = r\}$ (the set of favourable rank weights)
$\mathbf{W} = \{\mathbf{w} \in \mathbb{R}^n \mid w_i \geq 0 \text{ and } \sum_{i=1}^n w_i = 1\}$ (the typical definition of the weight space)	
$\text{rank}_i(\mathbf{c}, \mathbf{w}) = 1 + \sum_{k=1}^m \rho(u(c_k, \mathbf{w}) > u(c_i, \mathbf{w}))$ ($\rho(\text{true})=1, \rho(\text{false})=0$) (the rank of a_i)	
$a_i^h = \sum_{r=1}^m \alpha_r b_i^r$	α_r are meta-weights weights used to emphasize the best ranks ($1 = \alpha_1 \geq \alpha_2 \geq \dots \geq \alpha_m$)
$w_i^c = \frac{1}{a_i} \int f_{\tilde{C}}(\mathbf{c}) \int_{\mathbf{W}_i^1(\mathbf{c})} f_{\tilde{\mathbf{w}}}(\mathbf{w}) \mathbf{w} d\mathbf{w} d\mathbf{c}$	a_i is the 1 st rank acceptability index ($a_i = b_i^1$); $\mathbf{W}_i^1(\mathbf{c})$ is the set of the first rank weights
$p_i^c = \int_{\mathbf{c} \in X: \mathbf{w}_i^c \in \mathbf{W}_i^1(\mathbf{c})} f_{\tilde{C}}(\mathbf{c}) d\mathbf{c}$	The probability for a_i to obtain the first rank when its central weight vector $\mathbf{w}_i^c$ is chosen

$$\hat{b}_i^r = \frac{B_{ir}}{N} \quad (1.17)$$

where B_{ir} is the number of times where the alternate a_i obtained rank r and N is the number of repetitions of the Monte Carlo loop.

In conclusion one can say that SMAA is not directly suitable to solve the traditional MCDM problem shown Fig. 1.6a. In addition, elegant mathematical models of SMAA and numerous results produced by these models may not be fully understandable to all participants in the decision making process. This may impair the transparency of MCDM. However, dealing with the SMAA problem shown in Fig. 1.6b by means of the Monte Carlo simulation can be useful for a solution of the traditional MCDM problem with the random decision making matrix $\tilde{\mathbf{C}}$. The idea to apply the simulation-based approach to solving stochastic MCDM problems is known at least since the late 1990s (e.g., Levary and Wan 1998). The following text explains how to implement this idea for solving MCDM problems, the attributes of which include elements of fire risk profile.

1.3. The need for combined application of multi-attribute selection and fire safety assessment

Fire is the main physical hazard to most of built property. Other hazards, such as explosions or toxic releases pose risk only to specific types of buildings and

constructed facilities. Fires can be initiated not only by actions and events occurring inside buildings but also from outside, by extreme natural phenomena (e.g., a rupture of gas pipes caused by an earthquake can set fire to a building). The presence of fire hazard is almost ubiquitous in built property. Consequences of fires can be very high in terms of both loss of human lives and damage to property. A management of fire risk is a complex problem because fire safety is influenced by large number of factors. An achievement of an acceptable level of fire safety requires to make complex decisions, especially, in balancing fire safety and expenditures on fire protection measures. The effectiveness of these measures can be quantified by formal, numerical indicators which should be included into the DM process.

MCDM is a natural framework for making complex decisions concerning the built property and such decisions should take into account fire safety. Formal measures of fire safety – fire risk indices and risk profile – can serve as MCDM attributes c_{ij} . Most risk indices are single numbers which can be easily compared and ranked along with other attributes describing the alternatives a_i . Contrary to the indices, the risk profile $\{(l_{ir}, o_{ir}, s_{ir}), r = 1, 2, \dots, n_i\}$ is, in essence, a multi-attribute characterisation of buildings (building designs, alternative fire protection systems in one specific building, etc.) under comparison. The complexity of information expressed by the risk profile makes a comparison of two or more risk profiles to a non-straightforward problem, especially, when components of the profiles are uncertain in the epistemic sense. The methodology of MCDM is well-developed and can be smoothly applied to such a comparison. Clearly, fire safety measures can be used in an MCDM problem along with other attributes, economic and non-economic, which are not necessarily related to fire safety.

1.4. First chapter conclusions

1. Multi-attribute selection (MCDM) is a widely developing decision making methodology which allows taking into consideration safety characteristics of the alternative objects (alternatives) being compared. These characteristics can be used to quantify the fire safety of buildings and other built property. MCDM methods allow to incorporate fire safety measures into the decision making process in the form of attributes describing individual alternatives.
2. The potential attributes of an MCDM problem, which, among other things, compares fire safety solutions of an individual building or a set of buildings, are fire risk indices and fire risk profile. The former are calculated as single numbers by means of relatively simple deterministic algorithms and the latter has a complex structure and is estimated by applying QRA methods.

A fire risk index can be introduced in an MCDM problem as an individual attribute whereas the risk profile will have to be represented by several attributes.

3. The methodology of MCDM is flexible enough to incorporate uncertainties related to elements of the decision making matrix. The currently available MCDM methods allow to deal mainly with uncertainties expressed by non-probabilistic methods (intervals and fuzzy sets) and representing expert opinions. Modelling uncertainties by probabilistic measures (probability distributions) was applied to two specific fields related to MCDM, namely, multi-attribute utility theory and stochastic multi-criteria acceptability analysis.
4. A clear answer to the question how deal with an MCDM decision making matrix, some or all components of which are modelled by probability distributions, is not available at present. Such a random matrix can be composed from elements of fire risk profile which are uncertain in the epistemic sense. A separate modelling of aleatory and epistemic uncertainties is a standard and widely used approach to QRA. In the case where MCDM problem will include QRA results, epistemic probability distributions will appear in the decision making matrix.

Multi-attribute decisions about built property will in many cases involve the need to quantify fire safety of individual buildings. An inclusion of fire safety measures into the decision making matrix will generate the need to express quantitatively those aspects of building fire safety which are of interest for individual decision making problems. A combined application of MCDM and fire safety assessment will require to achieve the following objectives:

1. To determine which quantitative measures of fire safety or fire risk are best suited to be attributes of a building-related MCDM.
2. To formulate and solve the building-related MCDM problems which are most likely to appear in practice and which take into account fire safety of buildings.
3. To integrate results of a formal fire risk assessment produced by QRA into MCDM.
4. To develop an MCDM method allowing to solve the multi-attribute decision problem with a random decision making matrix.

Integrating fire safety measures into the multi-attribute decision making

The second chapter proposes a formulation and solution of several problems of multi-attribute selection which take into account the fire safety of buildings. Two interested parties are considered, namely, the owners and buyers of buildings which are prone to a certain degree of fire risk. Three selection problems are considered: selection of a cost-effective fire safety system, selection among several alternative buildings with regard to fire safety of each of them and choice between alternative fire protective measures with respect to fire risk. Decision matrices of these selection problems are formulated as deterministic ones and random ones. The former are used for a conventional multi-attribute selection and the latter are integrated in the process of a simulation-based uncertainty propagation which allows to solve the selection problem in a unconventional way. The present chapter summarises results of investigation published by Šakėnaitė (2009) and Vaidogas and Šakėnaitė (2010b, 2011a and 2011b).

2.1. Fire safety in regulations and economic decisions

Society has responded to the hazard of fire in build property in many ways. They include fire brigades, insurance, building regulations, education on fire hazards, controls on construction products and the design of buildings to resist the effects of fire. The level of fire safety and protection in buildings reflects the general economic, social and cultural features of society.

The regulatory control of fire protection measures has mainly been achieved through a framework of prescriptive design requirements (e.g., SFPE 2002, Hasofer *et al.* 2007). These requirements generally relate to the provision of compartments with prescribed levels of fire resistance, the selection of building materials, the provision of escape facilities. The prescriptive requirements do not take sufficient account of the effectiveness of active fire protection measures such as sprinklers, ventilation systems and fire alarms. Prescriptive requirements, if enforced rigidly, can lead to costly over-design, particularly for some large and complex buildings (Ramachandran 1998).

A viable substitute for prescriptive approach is fire risk indexing and fire risk assessment (Barry 2002, SFPE 2002, Rasbash *et al.* 2004, Hasofer *et al.* 2007, Šakėnaitė and Vaidogas 2010a). This risk-based approach can produce alternative fire protection strategies, including combinations of passive and active measures which can provide equivalent levels of safety for life and property. From among such strategies, a property owner may select one which is economically optimum in terms of the costs and benefits involved.

Selecting the most cost-effective fire protection strategy would be a simple task for an economist with experience of practical applications. It may, however, be a complex and confusing exercise for a fire safety engineer or property owner (manager) confronted with several options that satisfy acceptable safety levels for life and property. Selected fire protection options should then be considered in combination with insurance options.

Economic decisions about fire safety in buildings can be made by a wide range of interested parties (Ramachandran 1998, 2002):

- authorities on national level;
- insurers;
- building designers (architects);
- manufacturers of fire protection systems;
- property owners and buyers.

The decision can be simply enforced by requirements specified in fire regulations, codes, and standards. In this case, the decision will be relatively

simple. For instance, the building owner will have no choice as to install sprinklers. However, restrictions imposed by legal requirements on the one hand and diversity of fire safety solutions on the other hand may lead to the necessity to choose among several alternative solutions. This leads to the need to consider simultaneously many, sometimes conflicting, attributes of alternative solutions and then to choose the best one by applying methods of MCDM.

There exists some knowledge on the subject of safety-related applications of MCDM. Measures of reliability and risk have been incorporated into the decision making matrix of MCDM problem (see Sec. 1.2.5). In one instance, components of the decision making matrix of MCDM was constructed using components of fire risk (Zavadskas and Vaidogas 2009). Methods of MCDM were applied to solve specific fire safety problems in the areas of forest fire management (Iliadis 2005, Diaz-Balteiro and Romero 2008, Ananda and Herath 2009) and territorial firefighting planning (see the surveys by Behzadian *et al.* 2010, Farahani *et al.* 2010 and references therein). An MCDM method known as the analytic hierarchy process (AHP) was used for the attribute ranking (weighting) in the development of the so-called Edinburgh method which, in turn, was used to develop a fire risk index (Rasbash *et al.* 2004). Zhao *et al.* (2004) used a stochastic version of AHP to rank fire safety attributes. To the best of our knowledge, the only application of MCDM, which has incorporated fire safety attributes into a multi-attribute evaluation of buildings, was proposed by Wong *et al.* (2008ab). They included characteristics (indicators) of fire detection and alarm systems among a large number of indicators of an intelligent building and then applied two MCDM methods, AHP and a related method called the analytic network process (ANP), to rank these indicators. However, Wong *et al.* (2008ab) did not formulate and solve the general problem of MCDM based on a decision making matrix and did not explicitly consider fire safety to be a goal of an operation of intelligent building.

There exists vast literature devoted to economics of fire safety (see, e.g., Ramachandran 1998 and references therein). Some authors consider in detail economic aspects of fire safety systems and their findings come close to the problems of MCDM; however, they did not apply MCDM formally (e.g., Brown 2005, Buttry *et al.* 2007). On the other hand, there are numerous publications devoted to an application MCDM to decision making concerning buildings, building systems and construction in general (e.g., Norris and Marshall 1995, Zavadskas *et al.* 2008, 2009abc, Park *et al.* 2009, Turskis 2008, Turskis *et al.* 2009, Liaudanskienė *et al.* 2009). As fire safety systems are widely used in buildings and fire is the dominating hazard in most of them, this body of knowledge is natural environment to incorporate characteristics of fire safety systems into MCDM problems.

This chapter presents an attempt to formulate and solve several MCDM problems which include attributes related to fire safety and which can be of interest to parties on several levels of decision making. The MCDM problems are formulated from the viewpoint of property owner, property buyer, and risk analyst (safety engineer).

2.2. Multi-attribute decisions concerning fire safety of an individual building

2.2.1. Types of decision problem

Among the potential decision makers, building owners and, sometimes, building renters are interested parties who have to carry the direct costs of providing passive and active fire protection measures. These measures can be required by fire safety regulations, codes and standards or, alternatively, can be applied voluntarily as a result of self-discipline (self-regulation).

It is obvious that decisions related to the choice of specific fire protection measures will require economic analysis, such as life-cycle costing and expenditures on insurance against fire (Dewar 2001, Brown 2005). However, these measures are also characterised by non-economic attributes, for instance, performance, effectiveness, and reliability (Rasbash *et al.* 2004). After all, fire protection measures are safety-related, risk-reducing building systems which can not be described by economic attributes alone.

In many cases, the decision maker will be faced with the possibility or necessity to choose among several fire protection measures by taking into account not only economic attributes of them. Typical situations of choice can include the following alternatives (Vaidogas and Šakėnaitė 2011b):

1. To install some fire protection measure(s) or not to install any measure(s);
2. To install only one specific protection measure or several measures, for instance, sprinklers or automatic detectors alone, or both sprinklers and detectors;
3. To choose among several types of a specific safety measure, for example, among several sprinkler types (dry-pipe sprinklers, wet-pipe sprinkles, etc.);
4. To choose among several producers (importers) of specific equipment used as a fire protection measure;
5. To choose among more complicated alternatives which can include specific combinations of fire protection measures as well as the alternative of “doing nothing” (not installing any fire protection if this is allowed by regulations) mentioned in the first alternative.

Each of these situations is amenable to a formal expression as an MCDM problem. Economic attributes and attributes expressing standard technical characteristics of fire protection measures can be a natural part of this problem. However, the MCDM problem should also include attributes which directly or indirectly express risk posed by potential fire. Fire protective measures are installed to reduce this risk and eventually their effectiveness should be measured in terms of risk reduction.

2.2.2. Potential attributes

The complexity of fire safety evaluation problems may require to compare the alternatives a_i by means of more than a single attribute c_{i1} . The attributes c_{ij} evaluating the alternatives a_i can be grouped into four categories (Vaidogas and Šakėnaitė 2011b):

- I. Attributes expressing technical characteristics of fire safety measures (performance, effectiveness, reliability (availability), e.g., see chapter 10 in Rasbash *et al.* (2004) for a description of such attributes).
- II. Economic (monetary) attributes of fire protection measures (life-cycle cost or costs specified on a detailed level: initial budget cost, maintenance cost, etc.; an example of life-cycle costing of a fire protection measure (sprinklers) is provided by Brown (2005).
- III. Attributes expressing different attitudes towards insurance against fire (e.g., see Chapters 6 and 11 in Ramachandran (1998) for a description of fire insurance).
- IV. Safety-related attributes expressing influence of individual alternative design a_i on the risk to life and property. As failures of fire protection measures in the course of fire can lead to severe escalation of an accident, the attribute “reliability” mentioned in the first group can be included in this category.

Attributes of categories I and II are of general nature and are applicable, in principle, to any building system. Finding the values for most of the attributes belonging to these categories should not be a difficult exercise. The exception is the attribute “reliability”. An estimation of reliability (demand availability) of such systems as automatic sprinklers, fire detectors, ventilation systems, smoke ventilators and fire doors can be a non-trivial task which must be solved by applying special methods of QRA (e.g., Hauptmanns *et al.* 2008).

The insurance-related attributes of category III can be assigned, formally, to the economic category II as insurance premiums are simple monetary quantities.

However, it makes sense to exclude them into a separate category because finding values of these attributes can be a difficult exercise, especially when MCDM is to be applied in the early stages of the design (prior to negotiations with individual insurers). In addition, insurance premiums can depend on the current economic situation in the insurance industry and only partially on the fire risk level of a building to be insured. In addition, insurers use their own indices of fire risk which substantially differ from the indices measures prevailing among fire safety engineers (Watts 2002). If necessary, the insurers' indices can be incorporated into an MCDM problem.

Attributes of category IV relate a specific alternative design a_i to the level of fire safety (or, alternatively, fire risk) of the building which can be achieved by means of a_i . It is natural to state that the effectiveness of a_i should be measured eventually by this level.

Table 2.1 presents several risk-related attributes which can be used as stand-alone attributes of an MCDM problem or can be included in the risk profile. Measures of consequences posed by a fire can be included in an MCDM as economic attributes, as long as they can be expressed in monetary units. In the selection problem, these consequence-related attributes will serve along with the main economic attributes, namely, cost of the system and potential reduction in insurance premiums, if such a reduction is possible in the case of a system installation (Table 2.1).

Table 2.1. Attributes for selecting a fire protection system to be installed in an individual building (Vaidogas and Šakėnaitė 2011b)

No	Attribute group	Individual attribute
1	Economic	Cost of system (monetary unit)
		Reduction in insurance premium
		Value of damaged property (monetary unit)
		Operation impairment (number of outage days or losses in monetary units)
2	Risk-related attributes	Fire risk index
		Components of risk profile
		Reliability (failure probability) of the system
		Probable number of victims
		Time to untenable conditions
		Area potentially damaged by fire

2.2.3. Attributes expressed by fire risk indices

A fire risk index, say, $I(\mathbf{x}_i)$ fits naturally as an MCDM attribute c_{ij} , that is, $c_{ij} \equiv I(\mathbf{x}_i)$. Most of the widely-known indices are calculated with relative ease as functions of a relatively large number of building characteristics relevant to fire safety. These characteristics are called “fire safety parameters or attributes”, albeit the term “attribute” is not used in the sense of MCDM (Watts and Kaplan 2001, Watts and Solomon 2002, Rasbash *et al.* 2004). In the context of MCDM, the fire safety characteristics are expressed by components of the vector $\mathbf{x}_i$ associated with the alternative building a_i .

Although fire risk indices $I(\mathbf{x}_i)$ are natural candidates to be used as MCDM attributes c_{ij} , their use in the framework of MCDM can be problematic due to a possible insufficient sensitivity to the differences presented by the alternative designs a_i . The indices may not have input variables (components of $\mathbf{x}_i$) which allow to distinguish between different types of fire protection measures, for instance, different types of sprinklers or sprinklers systems of the same type but with different level of reliability.

The FSES index denoted in this work by I_{FSES} can serve as a proof of the above statement. The index I_{FSES} can be expressed as a binary variable given by

$$I_{FSES}(\mathbf{x}_i) = \prod_{k=1}^4 I_k(\mathbf{x}_{1i}, \mathbf{x}_{2i}) \quad (2.1)$$

where $\mathbf{x}_{1i}$ and $\mathbf{x}_{2i}$ are two sub-vectors of $\mathbf{x}_i$ and the binary variable $I_k(\mathbf{x}_{1i}, \mathbf{x}_{2i})$ is given by

$$I_k(\mathbf{x}_{1i}, \mathbf{x}_{2i}) = \begin{cases} 1 & \text{if } S_k(\mathbf{x}_{1i}) \geq R_k(\mathbf{x}_{2i}) \\ 0 & \text{otherwise} \end{cases} \quad (2.2)$$

where $S_k(\mathbf{x}_{1i})$ is the variable expressing the k th aspect of the fire safety in building a_i ($S_1(\cdot)$ expresses fire containment safety, $S_2(\cdot)$ quantifies extinguishment safety, etc.) and $R_k(\mathbf{x}_{2i})$ is the variable used to measure fire risk related to the k th fire safety aspect of the building a_i (FSES 1996). The $I_{FSES}(\mathbf{x}_i)$ index takes on only two values: “fire safety is equivalent” ($I_{FSES}(\mathbf{x}_i) = 1$) and “fire safety is not equivalent” ($I_{FSES}(\mathbf{x}_i) = 0$). This binary result makes the $I_{FSES}(\mathbf{x}_i)$ index of limited usefulness for inter-alternative comparisons. Two buildings can be characterised by the same result $I_{FSES}(\mathbf{x}_i) = 1$ and, at the same time, the level of fire safety in them can be tangibly different. However, the $I_{FSES}(\mathbf{x}_i)$ index involves the calculation of four pairs ($S_k(\mathbf{x}_{1i}), R_k(\mathbf{x}_{2i})$) which quantitatively express four aspects of fire safety. These pairs allow to measure

the safety by the differences $S_k(\mathbf{x}_{1i}) - R_k(\mathbf{x}_{2i})$ which are safety margins in essence. This allows to apply the differences as four MCDM attributes:

$$c_{ik} = S_k(\mathbf{x}_{1i}) - R_k(\mathbf{x}_{2i}) \quad (k = 1, 2, 3, 4) \quad (2.3)$$

Characteristics of fire protection measures are expressed by components of the vector $\mathbf{x}_{1i}$. Consequently, the sensitivity of the attributes $S_k(\mathbf{x}_{1i}) - R_k(\mathbf{x}_{2i})$ to differences among alternative fire protection measures is determined by preset values of components of $\mathbf{x}_{1i}$. For instance, smoke detection and alarm systems and automatic sprinklers are characterised by the respective components x_{12i} and x_{13i} of $\mathbf{x}_{1i}$, the values of which are explained in Tables 2.2 and 2.3.

Table 2.2. Values of the input variable x_{12i} used to take into account the role of smoke detectors and alarm in the fire safety of the building a_i measured by the $I_{FSSES}(\mathbf{x}_i)$ index (FSSES 1996)

The coverage of building by smoke detectors and alarm	Value of x_{12i}
None	0
Corridors only	2
Rooms only	3
Corridors and habitable spaces	4
Total space	5

Table 2.3. The input variable x_{13i} used to reflect the contribution of sprinklers to the fire safety measured by the $I_{FSSES}(\mathbf{x}_i)$ index (FSSES 1996)

The coverage of building by automatic sprinklers	Value of x_{13i}
None	0
Corridors only	2
Corridors and habitable spaces	8
Total space	10

The above values of x_{12i} and x_{13i} make it clear that a distinction between, say, type of sprinkler systems in different alternatives a_i is impossible and so the attributes $S_k(\mathbf{x}_{1i}) - R_k(\mathbf{x}_{2i})$ are not sensitive to such differences. The similar can be said about detectors as well as other technical characteristics of sprinklers and detectors (reliability, capacity, sensitivity to heat and concentration of combustions products etc.).

Almost all fire risk indices are calculated as single (scalar) values and pretend to covering all fire consequences. The FRAME fire index is calculated in the form of three values, say, $I_{FRAME,1}(\mathbf{x}_i)$, $I_{FRAME,2}(\mathbf{x}_i)$ and $I_{FRAME,3}(\mathbf{x}_i)$ which express fire risk to building and its content, occupants and business activities, respectively (FRAME 2008). The distinguishing between different kinds of fire

consequences makes the FRAME index closer to the expression of risk used for QRA. The FRAME index can be incorporated into MCDM problem in the form of three separate attributes, for instance, $c_{ij} \equiv I_{FRAME,1}(\mathbf{x}_i)$, $c_{i,j+1} \equiv I_{FRAME,2}(\mathbf{x}_i)$ and $c_{i,j+2} \equiv I_{FRAME,3}(\mathbf{x}_i)$.

The FRAME index $I_{FRAME,k}$ is more comprehensive than the index I_{FSES} in reflecting the situation of building fire safety. However, the index $I_{FRAME,k}$ is also of limited usefulness for a subtle distinguishing between alternative fire protection measures. This index is calculated by the following formula:

$$I_{FRAME,k}(\mathbf{x}_i) \equiv I_k(\mathbf{x}_i) = \frac{P_k(\mathbf{x}_{1i}, \mathbf{x}_{2i}, \mathbf{x}_{3i})}{A_k(\mathbf{x}_{1i}, \mathbf{x}_{2i}, \mathbf{x}_{3i}) D_k(\mathbf{x}_{2i}, \mathbf{x}_{3i})} \quad (k = 1, 2, 3) \quad (2.4)$$

where the values of subscript k are related to the fire risk to building and its content, occupants and business activities, respectively; and $\mathbf{x}_{1i}$, $\mathbf{x}_{2i}$ and $\mathbf{x}_{3i}$ are subcomponents of $\mathbf{x}_i$. Functions on the right-hand side of the above formula are explained in Table 1.1. The presence of sprinklers and detectors in a building characterised by $I_{FRAME,1}(\mathbf{x}_i)$ is reflected by the protection level $D_1(\mathbf{x}_{2i}, \mathbf{x}_{3i})$. The value $D_1(\cdot)$ is calculated as the product $W(\mathbf{x}_{2i}, \mathbf{x}_{3i}) \times N(\mathbf{x}_{2i}, \mathbf{x}_{3i}) \times S(\mathbf{x}_{2i}, \mathbf{x}_{3i}) \times F(\mathbf{x}_{2i}, \mathbf{x}_{3i})$, the terms of which are factors expressing effectiveness of the transportation of water to the place of fire ($W(\cdot)$), effectiveness of normal (conventional) fire protection measures ($N(\cdot)$), effectiveness of special protection measures ($S(\cdot)$) and capability of building structures to resist fire ($F(\cdot)$). Sprinklers and detectors influence the values of $S(\cdot)$ through the expression

$$S(\mathbf{x}_{2i}, \mathbf{x}_{3i}) = 1.05^{x_{12i} + x_{22i} + x_{32i}} \quad (2.5)$$

where x_{l2i} ($l = 1, 2, 3$) are the components of $\mathbf{x}_{2i}$ characterising the role of sprinklers and detectors in fire protection (FRAME 2008: 86). Among these three values, x_{12i} expresses the available means of fire detection (Table 2.4) and x_{32i} reflects the type of automatic fire protection (Table 2.5).

Table 2.4. Values of the input variable x_{12i} used to calculate the index $I_{FRAME,1}$ and used to reflect the presence fire detection means (FRAME 2008: 87)

Means of automatic fire detection	Value of x_{12i}
By sprinklers	4
By thermal (heat) detectors	5
By smoke or flame detectors	8
With electronic supervision of the system	2
With individual identification of small fire zones	2
Smoke alarm unit	2

Table 2.5. Input variable x_{32} of the $I_{FRAME,1}$ index used to account for an available automatic protection system (FRAME 2008: 87)

Means of automatic fire protection	Value of x_{32i}
Sprinklers with one (public) water supply	11
Sprinklers with one independent water supply	14
Sprinklers with two independent water supplies	20
Other automatic extinguishing systems (CO ₂ , foam)	11

As in the case of the index $I_{FSES}(x_i)$, the variables of the $I_{FRAME,1}(x_i)$ index used to account for the presence of automatic fire detection and protection, x_{12i} and x_{32i} , are not very “flexible” as regards a detailed description of sprinklers and detectors. Values of x_{12i} and x_{32i} available in the $I_{FRAME,1}(x_i)$ calculation method do not allow to compare reliability, effectiveness, sensitivity and similar characteristics of automatic protection systems.

Other problems with the use of indices are not MCDM specific ones; however, these problems may reduce attractiveness of the indices $I(x_i)$ to the use within MCDM:

- (a) The indices $I(x_i)$ are fairly different systems used to quantify fire risk; it is difficult to compare results produced by different indices;
- (b) Different indices are used in different countries and their use seems to be a result of agreement between interested parties in a specific country rather than a result of some scientific reasoning;
- (c) Some of the indices are applicable to wide range of buildings; whereas some are applied to highly specific buildings and other kind of property;
- (d) Algorithms used to calculate the indices $I(x_i)$ and input information possess high degree subjectivity; a specification of this information is not well documented;
- (e) The indices $I(x_i)$ are generally “rigid” systems; they do not allow to take account of new developments in fire risk assessment.

The listed shortcoming of the fire risk indices $I(x_i)$ may limit their application to MCDM. An alternative approach to fire risk indexing is a fire risk assessment in line with QRA (Sec. 1.1.2). Results of QRA can serve as MCDM attributes related to fire safety (see the subsequent Sec. 2.4).

2.2.4. Attributes expressed by reliability of fire safety systems

Sprinkler and fire alarm systems can substantially contribute to the prevention of heavy fires and mitigation of fire consequences. Another obvious fact is that

sprinkler systems are not fail-safe technical objects. The percentage of fires, in which sprinkler systems do not carry out their extinguishing function, is relatively large (Rasbash *et al.* 2004: 236, Rönty *et al.* 2004, Nyysönen *et al.* 2005, Hall 2006, 2010, Koffel 2006).

Data on failures of sprinklers and other active fire protection measures collected over the past 50 years indicate that in some cases the chance of failure is unacceptably high. A brief summary of data on reliability of sprinkler systems is given in Table 2.6. Data on reliability of fire alarm systems is presented, among others, by Nyysönen *et al.* (2005). The possibility of severe fire incident escalation due to failure of a fire safety system makes sense to include estimates of systems failure (demand unavailability) into MCDM problems. These estimates can be included as stand-alone attributes c_{ij} or be regarded indirectly through risk profiles computed by means of QRA with respect to possible failures of fire safety systems.

Estimates of safety systems demand unavailabilities may be expressed by fixed numbers, intervals or epistemic uncertainty probabilities. The latter case is considered by Siu and Apostolakis (1986, 1988). In the case where an MCDM decision making matrix includes point or interval estimates of the demand unavailability, the problem can be solved by means of standard methods of MCDM. If the demand unavailability of the alternative system a_i is expressed by epistemic distributions, the MCDM problem with a random decision making matrix can be solved by applying a simulation-based procedure presented in Sec. 2.4.2.

The problem of failure of fire safety systems was addressed by many authors who applied various approaches. They range from a simple calculation of country-specific failure rates to an estimation of reliability by applying methodological means of quantitative risk assessment (QRA) based on Bayesian reasoning (e.g., Siu and Apostolakis 1986, 1988, Hauptmans *et al.* 2008, Malm and Pettersson 2008). However, the analysis of availability and quality of data on safety system failure carried out by Vaidogas and Šakėnaitė (2011a) led to the general conclusion that the present situation of data on fire safety systems reliability is not mature enough to make reliability assessment a routine procedure applicable to sprinklered environments of most conventional buildings. In some countries the data situation is better than in others; however, the lack of well-established exchange of sprinkler failure data recorded in conventional buildings will not facilitate reliability assessment. A detailed description of the data analysis can be found in Annex B. Here we will present reasons for the above general conclusion by paying attention to reliability of sprinkler systems:

1. Failure data recorded after fires in sprinklered buildings and possibly routine inspections of sprinklers are undoubtedly available. In some countries, collection and reporting of data is well-organised outside industrial and military environments. However, the compilation of the entire body of data was made without a general, international agreement, and therefore the body of collected data is not sufficiently systematic.

2. The main obstacles to an systematic collection of data sets which would allow a smooth assessment of sprinkler reliability can be detected with relative ease: (i) differences in definition and naming of failure modes; (ii) differences in failure data reporting; (iii) the prevalence of human factor among causes of sprinkler failures in conventional building; (iv) the influence of ageing, modifications and repairs on reliability (Fig. 2.1).

3. The accumulation, availability and quality of data on sprinkler system failures is negatively influenced by several factors: (i) the limited relevance of data collected in sprinklered environments with different safety culture, operation conditions and different sprinkler components; (ii) ageing of data collected in the past; (iii) concealment of data and/high cost of data; (iv) poor documentation and explanation of data in available data bases (Fig. 2.2).

4. Several authors have demonstrated that assessment of sprinkler system reliability is possible by a fault tree analysis. The input data necessary for the analysis consists of component failure rates and human failure (error) probabilities. Despite the fact that there are numerous failure rate data sources, any sprinkler-specific databases, which would yield a ready-to-use input information for a fault tree analysis, does not seem to be available.

5. The amount of data available for assessment of sprinkler reliability on system and component level can vary from case to case. If the set of failure data is small, an application of Bayesian inference is a natural choice for reliability assessment. The standard scheme of Bayesian inference based on homogenous binomial distribution is directly applicable to this end. On the other hand, the standard (homogeneous) binomial scheme is not fully correct because it ignores ageing of sprinklers and other changes in time.

6. An in-depth study, which allows to say with certainty about the influence of time effects on sprinkler reliability, seems not to exist. In theory, the formal schemes developed and applied mainly in nuclear field could allow to test for presence of trend in sprinkler failure probability and to model this trend. However, sprinkler-specific data expressed as binned binomial data necessary for the trend analysis was not extracted and reported in any publication to date.

7. Theoretical models allowing to relate maintenance, repairs and modifications of sprinklers to reliability were not developed to this day. Thus a collection of data which could “feed” these models remains a task to be solved in the future.

Table 2.6. A brief summary of data on sprinkler reliability (Vaidogas and Šakėnaitė 2011a)

Country	Reference	Reliability (success rate)	Failure rate
Sweden	Malm and Pettersson (2008)	69 % in from 690 fire incidents	31 %
Finland		38 % in from 351 fire incidents	62 %
Norway		74 % in from 457 fire incidents	26 %
UK	Rutstein and Cooke (1979)	92–97 % for various types of occupancies	3–8 %
		95.6 % for all industrial buildings	4.4 %
		97.8 % (including fires not reported to the brigade)	2.2 %
	Malm and Pettersson (2008)	85 % from 163 fire incidents in London	15 %
Australia	Marryatt (1988)	99 % for all building categories	1 %
New Zealand	Malm and Pettersson (2008)	96 % for 483 fire incidents in 2002–2008	4 %
US	Anon (1970)	90 % for all building categories	10 %
	Miller (1974)	96 % (all building categories for the period 1897–1964, NFPA data)	4 %
		85 % (for the period 1970–1972, Factory Manual Research data)	15 %
		95 % (for the period 1966–1970, US Navy data)	5 %
		86 % for wet-pipe sprinkler system	14 %
		83 % for dry-pipe sprinkler system	17 %
		63 % for deluge system	37 %
	Budnick (2001)	81–95 % from a review of 13 reliability estimates	5–19 %
	Koffel (2006)	91 % for all building categories	9 %

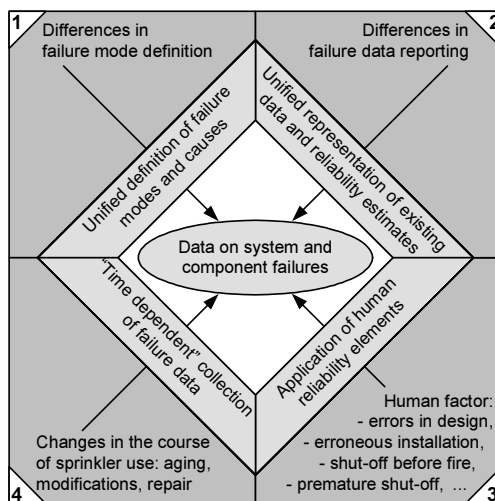


Fig. 2.1. Four factors complicating the collection and exchange of data on sprinkler reliability (corners 1 to 4) and steps towards possible solutions (inclined segments) (Vaidogas and Šakėnaitė 2011a)

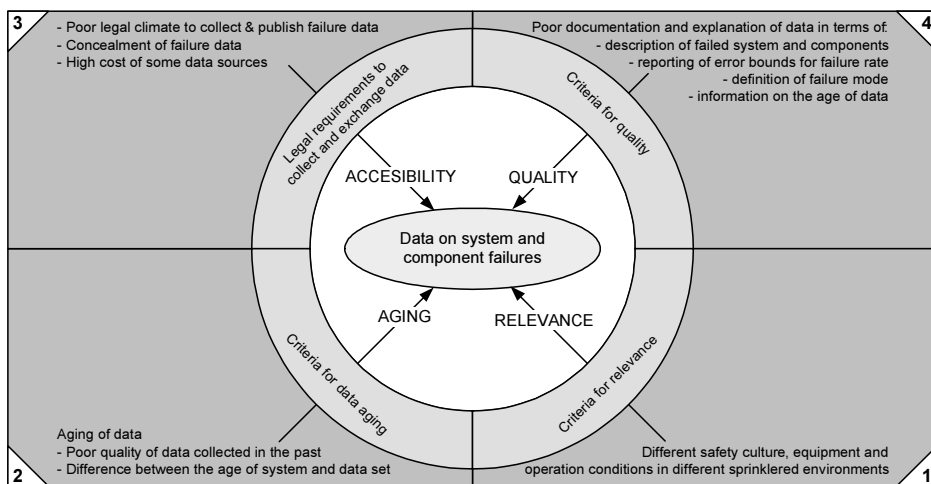


Fig. 2.2. Four problems related to collection and use of data on failures of sprinkler systems and components: problems are shown in the corners 1 to 4; the approaches to their solutions are shown in the ring (Vaidogas and Šakėnaitė 2011a)

The differences between alternative fire safety systems represented by the MCDM alternatives a_i may be very subtle in terms of data necessary for the

estimation of demand unavailability. For example, if two alternatives a_i and a_j represent two sprinkler systems of the same type but manufactured by two different companies, an estimation of unavailabilities of a_i and a_j and a subsequent comparison of them within an MCDM problem will require highly case-specific data which is collected by the manufacturer, installer or insurer. Such data will not necessarily be available to other interested parties. Generic data on sprinkler failure may be unsuitable to estimate the difference in demand unavailabilities of highly specific alternatives a_i and a_j .

The failure modes of sprinklers include also an accidental activation (discharge of water in the absence of fire). The non-fire activation is mainly due to a manufacturing defect, an improper installation or user error. The data on accidental system activations are presented, among others, by Jensen *et al.* (2006), Butry *et al.* (2007), Hall (2010). At present, the author of this work is not aware of any open data source which would contain component level data related to non-fire activations.

2.3. Fire safety consideration in the selection among several buildings

2.3.1. The decision problem

The five problems listed in the previous section consist in a selection among fire protection measures on a detailed level of characteristics of these safety systems. A provision of these measures influences the fire safety of the entire building. As fire is the main physical hazard threatening most of built property, the property buyer may be interested in attributes expressing the fire safety when he/she makes a choice on a more general level, namely, among several buildings.

Fire safety attributes should depend on the main factors influencing the risk of fire. They can be used along with economic attributes as well as non-economic attributes which are not directly related to fire safety.

2.3.2. Potential attributes

A list of the attributes that most decision makers find important in building decisions was suggested by Norris and Marshall (1995) and is presented in Table 2.7. The list contains 15 attribute groups which can be classed as follows:

Table 2.7. Attributes for building-related decisions introduced by Norris and Marshall (1995) and supplemented by attributes related to fire safety (Vaidogas and Šakėnaitė 2011b)

No	Attribute group	Attributes within the groups
1	Economics	Cost budget requirements, life-cycle costs, net savings, return
2	Operation and maintenance	Ease and staff requirements of operation and maintenance, cost of running and maintenance
3	Occupancy availability	Time to being available for new occupancy
4	Building function	Layout, space (for office, shipping, etc.), plant
5	Aesthetics	Attractiveness of design inside and outside
6	Environmental impacts	Energy consumed, soil pollution concentration, etc.
7	Flexibility in functional use and disposition	Retrofitting costs, demolition costs
8	Location	Acceptance of clients, customers, staff
9	Technology	Telecommunications and computer infrastructure, equipment
10	Sound and visual environment	Aural privacy and ambient noise, light and glare, view to the outside
11	Thermal environment and air quality	Air quality, occupant control of conditions, temperature, humidity, ventilation
12	Transportation	Efficiency and ease of movement of people to the site and on the site
13	Durability	Random lifetime and design working life (performance requirement)
14	Reliability	Survival (failure) probabilities of building structures and utilities
15	Security	Protection during and outside normal hours of workers and visitors inside and outside the building on the site
16	Fire safety	Fire risk indices, risk of fire
17	Fire department	Fire department response time, fire department effectiveness

- I. Attributes of economic nature can constitute the first class (attribute groups 1 and 2, Table 2.7);
- II. Attributes belonging to the second class express the functionality and environment of building alternatives (attribute groups 3 to 13, Table 2.7);
- III. The third class of attributes is related to specific characteristics of building alternatives, namely, reliability and security (attribute groups 14 and 15, Table 2.7).

Reliability has a clearly defined aspect of safety. For instance, unreliable elevators can fail and cause accidents involving harm to occupants and visitors. Reliability is also related to fire safety, because building equipment failures can cause ignitions which in turn can escalate into fires. However, reliability alone is insufficient to express the risk of fire. The attribute list from Table 2.7 should be supplemented by at least two attribute groups (attributes) which take into account the hazard of fire: fire safety and proximity of the fire brigade with respect to the building under analysis.

2.3.3. Attributes related to fire safety of buildings under comparison

Attribute group „fire safety“

“Fire safety” can be expressed either by fire risk indices and/or by risk of fire. The fire risk indices are relatively simple-to-calculate and so attractive-to-practitioners quantities, in most cases expressed by a single value (Secs. 1.1.1 and 2.2.3). A risk index depends on various characteristics of the building a_i which are relevant to fire safety and it can be used with relative ease as an individual MCDM attribute c_{ij} to compare several buildings. The risk of fire is a more complicated concept than the fire risk index (Sec. 1.1.2). The risk is expressed by a risk profile (likelihood-outcome pairs) which can be transformed into the vector of expected severities (e.g., Yung 2008). Components of this vector can be introduced into an MCDM problem through as several attributes c_{ij} (see the subsequent Sec. 2.4).

“Fire safety” is related to economic attributes, because fire protection measures require investments for purchasing and installing sprinkler systems, fire alarms, smoke, flame or thermal (heat) detectors, etc. “Fire safety” is also related to another economic aspect, namely, fire insurance. In many countries, insurance companies offer a significant discount on their premiums for installation of fire protection measures (e. g., SFPE 2002, Yung 2008). Thus the MCDM attributes used for the quantification of fire safety will be dependent on economic ones.

Attribute group “fire department”

Some fire risk indices include input variables describing characteristics of the fire department (FD) nearest to the building a_i (the first responding fire station). An example of such an index is the FRAME index which includes factors taking account of two characteristics of the local FD: FD intervention time and the type of fire station (FRAME 2008). If the FRAME index is used as an MCDM attribute c_{ij} , the attribute group “Fire department” becomes redundant, unless the analyst wants to consider the role of FD in greater detail. This may be the case in practice because the aforementioned factors reflects only a small amount of values of fire department characteristics, for instance, the response time is represented by sufficiently wide and so uncertain intervals ≤ 10 min, (10 min, 15 min), (15 min, 30 min) and ≥ 30 min.

A specification of MCDM attributes c_{ij} for the group “Fire department” can be based on several publications which suggest models for an evaluation of FD’s operations (Bénichou *et al.* 2002, Phillips 2002, Yung 2008: 172). These models (stand-alone models or submodels of larger models) specify two quantitative measures of firefighting operations:

- FD response time, and
- FD effectiveness in minimising loss of life and property.

The FD response time, say, t_r is elapses from the moment the FD is notified until the moment when the first fire unit arrives at the scene (Fig. 2.3). In the model proposed by Bénichou *et al.* (2002), the response time t_r includes:

- Dispatch time t_d (the time between the receipt of information about a fire and the FD notification by the dispatcher),
- Preparation time t_p (the time required for the dispatched unit to prepare and be ready to leave the FD),
- Travel time t_t (the time required by the first unit to travel from the FD to the scene of the fire).

The response time t_r is a simple sum of the above-listed times and t_r fits naturally to MCDM attributes:

$$c_{ij} \equiv t_r = t_d + t_p + t_t \quad (2.6)$$

The estimation of the times in Eq. (2.6) requires statistical data on t_d , t_p and t_t as well as use of coefficients which are judgemental by their nature (Bénichou *et al.* 2002). For instance, the departure time is estimated by the expression

$$t_d = t_{d,basic} \left(1 + \sum_{i=1}^7 f_i \right) (1 + r_{calls}) \quad (2.7)$$

where $t_{d,basic}$ is the basic dispatch time supplied by the statistical database; f_i are coefficients accounting for factors which can increase the departure time ($f_i \geq 0$, f_1 considers the way of notification about a fire incident, f_2 takes into account experience of the firefighters, etc.); r_{call} is the coefficient used for a further increase of the dispatch time t_d due to concurrent calls of the building users to FD.

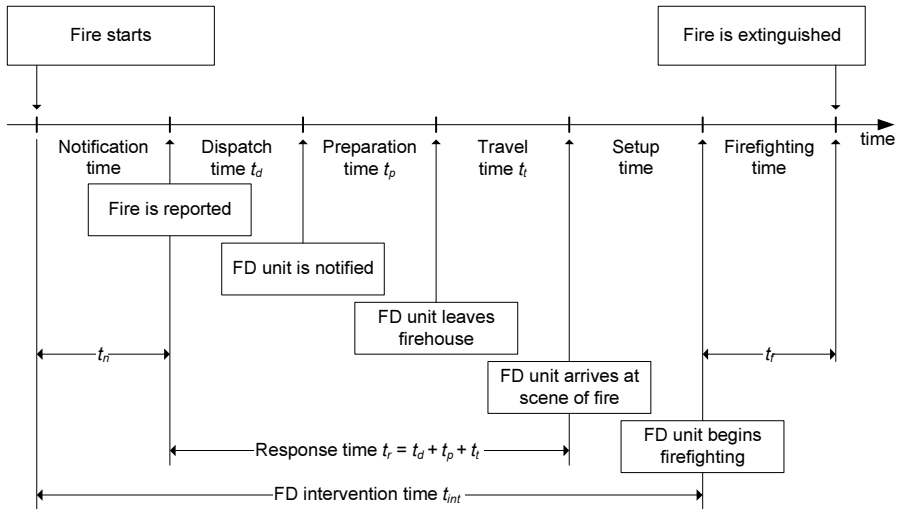


Fig. 2.3. A usual sequence of events starting from ignition and ending with extinguishment (FD = fire department; modified from Bénichou *et al.* (1999, 2002))

The MCDM attribute given by Eq. (2.6) is a “costly” one because it requires presence of statistical data for the estimation t_d , t_p and t_t . Some data on these times is presented by Bénichou *et al.* (1999) and Yung (2008: 168–172); however, such data can be country-specific or specific to a particular FD and so not fully relevant to a set of buildings compared in an MCDM problem. On the other hand, the attribute given by Eq. (2.6) allows to analyse and compare in detail the role of local FDs in extinguishing potential fires in highly case-specific situations.

The response time t_r is preceded by the notification time t_n (the time between the moment of fire initiation and notification of FD in consequence of detection by automatic means or by building occupants) and succeeded by the

firefighting time t_f (the time required by firefighters to extinguish the fire) (Fig. 2.3). An inclusion of t_n into t_r makes little sense because t_n does not depend on the FD capabilities. On the other hand, the notification time t_n is included in the FD intervention time t_{int} (Fig. 2.3). Firefighting effectiveness and rescue effectiveness depend on t_{int} (Yung 2008: 173). The quicker is t_{int} , the less severe is the fire and, with adequate resources, the greater is the fire extinguishment effectiveness. Similarly, the quicker is t_{int} , the less severe is the smoke spread, the lesser is the number of trapped occupants and the greater is the rescue effectiveness, provided that adequate resources are available.

FD effectiveness can be expressed by a model which considers parameters of fire influenced by fire suppression operations: reduced heat release rates, heat fluxes, ceiling impingement temperatures, etc. (Bénichou *et al.* 2002). However, an estimation of these parameters requires special skills and results produced by the model are, in essence, time histories which are difficult to include in the MCDM decision making matrix. In a simpler and more practicable way, the FD effectiveness can be expressed through three factors which can be used as three MCDM attributes:

- Fire unit's crew size n_{crew} (MCDM attribute c_{ij} , say),
- Firefighting effectiveness P_{fe} (probability of fire extinguishment considered an MCDM attribute $c_{i,j+1}$, Fig. 2.4), and
- Rescue effectiveness P_{re} (rescue probability used as an MCDM attribute $c_{i,j+2}$, Fig. 2.5).

The crew size n_{crew} affects both the occupant rescue and fire extinguishment efforts. The more firefighters are dispatched to the fire scene, relative to the number of trapped occupants, the more effective is the rescue effort. Also, the more firefighters are dispatched to the fire scene, relative to the size of the fire, the more effective is the fire extinguishment effort to contain and the fire.

The effectiveness of fire extinguishment, P_{fe} , can be modelled as a function of the ratio of the firefighter's intervention time to the flashover time t_{FO} (Bénichou *et al.* 1999, Yung 2008: 175). Modelling of P_{fe} with the increase in the ratio t_{int} to t_{FO} is shown in Fig. 2.4. If firefighting action begins before the fire reaches flashover, the fire will be extinguished with the probability equal to one, provided that there are adequate water and manpower resources.

Values of the probability P_{fe} can be computed by a fitted equation

$$P_{fe} = \begin{cases} 1 & \text{if } t_{int}/t_{FO} \leq 1 \\ 4.36 e^{-t_{int}/(t_{FO} 0.672)} & \text{if } t_{int}/t_{FO} > 1 \end{cases} \quad (2.8)$$

The effectiveness of firefighter's occupant rescue effort can be modelled as a function of the ratio of the number of trapped occupants, n_T , to the firefighter's crew size n_{crew} (Bénichou *et al.* 1999, Yung 2008: 174). The larger is the ratio n_T to n_{crew} , the larger is the number of trapped occupants, and the less effective is the rescue effort. Fig. 2.5 shows modelling of the rescue effectiveness P_{re} with the increase in the ratio of n_T to n_{crew} .

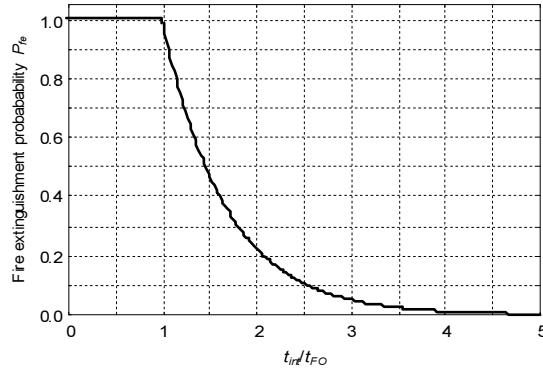


Fig. 2.4. Fire extinguishment probability P_{fe} expressed as a function of the intervention time t_{int} to the flashover time t_{FO} (modified from Bénichou *et al.* (1999))

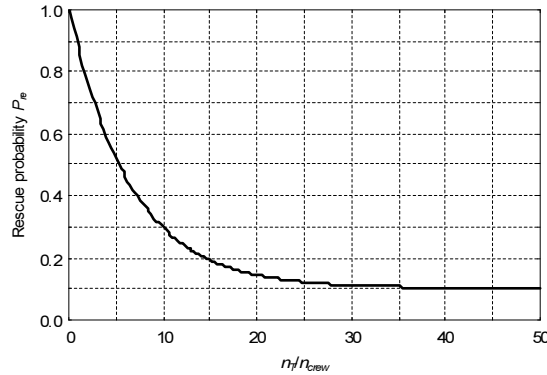


Fig. 2.5. Occupant rescue probability P_{re} expressed as a function of the number of trapped occupants, n_T , to the crew size n_{crew} (modified from Bénichou *et al.* (1999))

Values of the probability P_{re} can be computed by a fitted equation

$$P_{re} = 0.1 + 0.91 e^{-n_T/(n_{crew}^{6.5})}, \quad n_T/n_{crew} \geq 0 \quad (2.9)$$

It is obvious that the MCDM attributes graphically defined in Figs. 2.4 and 2.5 are not “exhaustive” measures of the FD effectiveness. However, the relative simplicity of them allows considering at least some aspects of this effectiveness and reflecting them in the decision making. An application of more complicated models of FD effectiveness may lead to the situation where a specification of attributes from the group “Fire department” will be more complicated than the solution of MCDM problem, in which they are used.

2.4. The combination of multi-attribute selection and fire risk assessment

2.4.1. Performance-based fire safety codes and fire risk

Although the application of QRA is possible, at least in principle, on the low level of decision making (by building owners, insurers, manufacturers and constructors, installing fire protection systems), the prevailing approaches to fire safety design conforming to building regulations are known as prescriptive fire codes and performance-based fire codes.

The practice of fire safety designs is changing from following traditional prescriptive design codes to more flexible performance-based codes (e.g., Natorianni 2002). The fire designs in line with these two types of codes can be viewed as two principal attitudes towards an application of risk assessment for fire safety provision.

The prescriptive codes are still widely used in many countries, including Lithuania. The prescriptive design requirements generally relate to the provision of compartments with prescribed levels of fire resistance, the selection of building materials, the provision of escape facilities. The prescriptive requirements do not take sufficient account of the effectiveness of active fire protection measures such as sprinklers, ventilation systems and fire alarms. Prescriptive requirements, if enforced rigidly, can lead to costly over-design, particularly for some large and complex buildings (Ramachandran 1998). The prescriptive design approach has been criticised by many publications for inability to provide the most cost-effective design solutions, to maintain a consistent level of fire safety in buildings, and, in general, for restricting innovation (Hasofer *et al.* 2007).

The performance-based codes allow flexibility in fire safety designs as long as the designs can provide the required level of fire safety to the occupants. The major objective of the performance-based design is to achieve satisfactory level of fire safety to the occupants and fire department personnel. Levels of fire safety (or, alternatively, fire risk) are assessed by applying risk assessment, either qualitative or quantitative (Guanquan and Jinhua 2008, Yung 2008,

Hasofer *et al.* 2007). In other words, the performance-based approach is a risk-based one.

The aim of performance-based fire design is, in essence, an optimisation task: to achieve the required level of fire safety (tolerable fire risk) by using minimum expenditures. The explicit use of fire risk measures opens up the possibilities to apply formal methods of optimisation to decision making which is concerned with fire safety. The specific forms of optimisation problems depend on the level of a decision maker. This level can range from a particular property owner to a state government (Ramachandran 1998: 11).

The assessment of fire risk by means of QRA results in a discrete set of estimates (likelihood-outcome pairs). Therefore, the main result of QRA, the expression of risk, can be embedded into an MCDM problem with relative ease. The “marriage” of QRA and MCDM can allow to make fire safety related decisions which implement the performance-based goals and are based on formal tools of MCDM.

2.4.2. Incorporating quantitative risk assessment fire risk measures into multi-criteria decision making

Fire risk in decision making matrix

A very comprehensive attribute of the alternative fire designs a_i is the risk defined in line with QRA, i.e. in the form of likelihood-outcome pairs (Yung 2008, Hasofer *et al.* 2007). In the context of this chapter, the risk of a_i due to exposure to a potential fire will consist of possible outcomes (consequences) o_{ir} of this situation and likelihoods l_{ir} of o_{ir} . Generally, each o_{ir} is represented by several measures of significance or, in brief, significances (Kumamoto and Henley 1996: 13). Each o_{ir} can be characterised by several, say, n significances of a different nature and with different measurement units. The significances can be grouped into the row-vector defined by Eq. (1.2). With the values l_{ir} , o_{ir} , s_{ir} , the fire risk related to a_i takes the form given by Eq. (1.3).

The alternatives a_i with different level of risk can be generated by comparing the fire designs with different probabilities of failure (success) given a fire. This will require to estimate failure probabilities of alternative automatic sprinkler systems and fire detection and alarm systems. Methods and data used for such estimation are considered, among others, by Hall (2010), Hauptmanns *et al.* (2008), Nyssönen *et al.* (2005), Rönty *et al.* (2004). In many cases the estimation of the failure probabilities will be a non-trivial task. Potential points of the alternative fire designs with different failure probabilities are shown in Fig. 2.6.

The total number of the outcomes, n_i , may vary from alternative to alternative. The risk (1.3) may express fairly diverse information, especially

when the severity of each o_{ir} is represented by more than one significance measure. The vectors s_{ir} ($r = 1, 2, \dots, n_i$) can be grouped in the $n_i \times n$ matrix defined by Eq. (1.4).

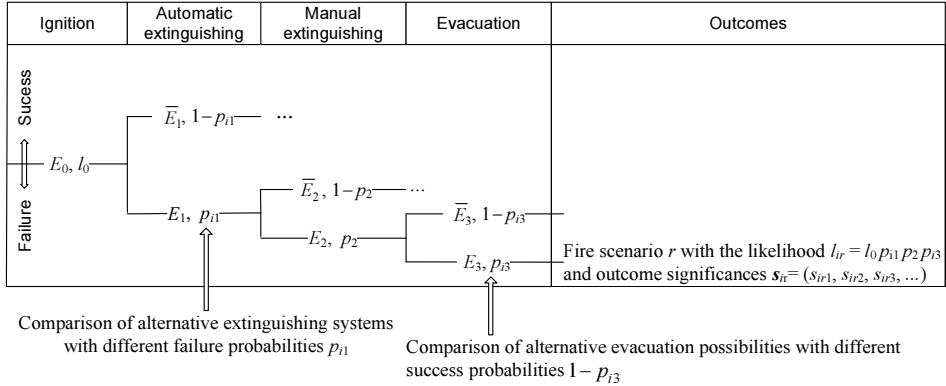


Fig. 2.6. A fragment of an event tree diagram with the event tree path expressing the fire scenario r ; the diagram also shows potential points of consideration of alternative fire design solutions

Each column of the above matrix consists of significances with the same measurement unit. With this matrix, one can calculate n -dimensional vector of expected significances which are associated with i th alternative and apply this vector within MCDM, namely, the vector c_i defined by Eq. (1.5). In the case that the severity of each o_{ir} is represented by a single significance s_{ir} (vectors s_{ir} consist of a single component), the expected significance $\sum_{r=1}^{n_i} l_{ir} s_{irj}$ will be a scalar value and comparison of a_i will be straightforward, provided that further attributes are not introduced into the MCDM problem.

The expected significances in Eq. (1.5) contain the likelihoods l_{ir} , which in many cases can be estimated independently of the significances s_{irj} (e.g., Kumamoto and Henley 1996: 23). Each l_{ir} can be expressed as probability of o_{ir} per fire. Frequencies (numbers of occurrences per year) are also used as l_{ir} .

If l_{ir} is associated with r th event tree path consisting of n_{br} branching points, l_{ir} is calculated as $l_{ir} = l_0 \prod_{b=1}^{n_{br}} p'_b$, where l_0 and p'_b is the likelihood of an initiating event E_0 and the probability of b th branching point represented by an event pair E_b and $\bar{E}_b$, respectively (e.g., the event tree diagram in Fig. 2.6 shows that $l_{ir} = l_0 p'_1 p'_2 p'_3$ and $n_{br} = 3$).

The need to deal with uncertainties

The prevailing method of uncertainty quantification in QRA is the classical Bayesian approach to QRA (Bayesian approach). In line with the Bayesian approach, the uncertainty in parameters and input of QRA models is divided into aleatory (stochastic) and epistemic (state-of-knowledge) uncertainty (e.g., Helton and Oberkampf 2004, Aven and Pörn 1998). This division is used due to the sparseness of data related to QRA models and for the convenience of modelling. The Bayesian approach produces estimates of risk and failure probabilities expressed in terms of epistemic uncertainty distributions. An incorporation of these distributions into MCDM requires selecting α^* in the presence of uncertain components c_{ij} of $\mathbf{C}$.

In the context of the Bayesian approach, l_{ir} will be estimated in the form of epistemic uncertainty distributions related to true, albeit unknown values of l_{ir} . Such estimations are usually carried out by propagating epistemic uncertainties through such QRA models as event trees (Aven and Pörn 1998, Vaurio and Jänkälä 2006). Fire-specific applications of the separate modelling of aleatory and epistemic uncertainties were suggested in previous decades by Siu and Apostolakis (1988) and Bradyberry and Apostolakis (1991).

In the context of the Bayesian approach, l_0 and the branching probabilities p'_b ($b = 1, 2, \dots, n_{br}$) may be uncertain in the epistemic sense. Such an uncertainty can be quantified by the respective random variables L_0 and $\tilde{p}'_b$. Then the epistemic uncertainty in the likelihoods l_{ir} can be expressed by the random variable $L_{ir} = L_0 \prod_{b=1}^{n_{br}} \tilde{p}'_b$. With the random likelihoods L_{ir} ($r = 1, 2, \dots, n_i$), the expected significance $\sum_{r=1}^{n_i} l_{ir} s_{irj}$ turns into the epistemic random variable $\tilde{c}_{ij} = \sum_{r=1}^{n_i} L_{ir} s_{irj}$. This replacement yields an MCDM problem with stochastic attribute vectors

$$\tilde{\mathbf{c}}_i = (\tilde{c}_{i1}, \tilde{c}_{i2}, \dots, \tilde{c}_{ij}, \dots, \tilde{c}_{in}) \quad (2.10)$$

Replacing c_i in the initial deterministic decision making matrix $\mathbf{C}$ by $\tilde{\mathbf{c}}_i$ defined by either Eq. (2.10) will yield a stochastic decision making matrix:

$$\tilde{\mathbf{C}} = [\tilde{\mathbf{c}}_1, \dots, \tilde{\mathbf{c}}_i, \dots, \tilde{\mathbf{c}}_m]^T \quad (2.11)$$

The uncertainties expressed by elements of $\tilde{\mathbf{C}}$ may not necessarily be epistemic ones. Apart from the epistemic random variables $\sum_{r=1}^{n_i} L_{ir} s_{irj}$, the matrix $\tilde{\mathbf{C}}$ may contain elements that are uncertain in the aleatory sense.

The MCDM problem formulated in the form of $\tilde{C}$ can be solved by applying the propagation of epistemic and, if necessary, aleatory uncertainties. The solution will consist in sampling values $\tilde{C}_l$ of $\tilde{C}$ by means of stochastic (Monte Carlo) simulation ($l = 1, 2, \dots, N_l$) (Block 2 in Fig. 2.7). The MCDM problem can be solved and the best alternative can be chosen for each $\tilde{C}_l$ (Block 3 in Fig. 2.7). The simulation will yield the frequencies of the selection of individual alternatives a_i as the best ones in N_l trials (Block 4 in Fig. 2.7). Then the alternative with the highest frequency of selection can be chosen as a^* (Block 5 in Fig. 2.7). This can be expressed by the criterion

$$a^* = a_i, \text{ where } i = \operatorname{argmax}\{fr_i, i = 1, 2, \dots, m\} \quad (2.12a)$$

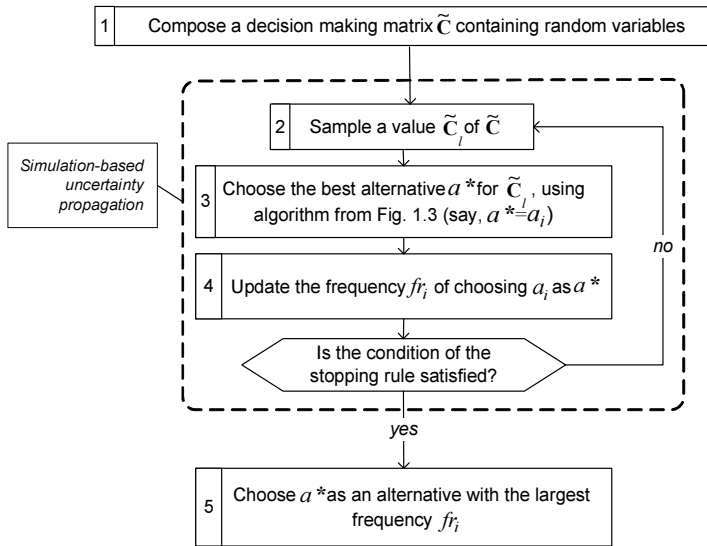


Fig. 2.7. The algorithm including a Monte Carlo loop with N_l repetitions and used for the selection of the best alternative a^* with the random decision making matrix $\tilde{C}$

The approach expressed by Eq. (2.12a) can be extended to statistical interpretation of indifference and preference related to the alternatives a_i (see, e.g., French (1988: 62), for the definition of these terms). In practical applications this can be necessary when two frequencies fr_i and fr_j are very close to each other or when the number of available Monte Carlo loop repetitions, N_l , is relatively small.

The indifference of a_i and a_j ($i \neq j$) denoted by $a_i \sim a_j$ can be checked by interpreting the frequencies fr_i and fr_j as estimates of two binomial proportions p_i and p_j . The indifference can be found by verifying the statistical hypothesis $H_0: p_i = p_j$ against the two-sided alternative $H_1: p_i \neq p_j$. In classical statistics, H_0 is called the hypothesis concerning proportions (e.g. Miller and Freund 1977: 253). The decision concerning H_0 can be based on the statistic

$$z_{ij} = \frac{fr_i - fr_j}{\sqrt{0.5 \hat{fr}(1 - \hat{fr})/N_i}} \text{ with } \hat{fr} = \frac{s_i + s_j}{2N_i} \quad (2.12b)$$

where s_i and s_j are the number of times of choosing the respective alternatives a_i and a_j as the best ones.

For the values $N_i p_i \geq 5$, the sampling distribution of z_{ij} is approximately the standard normal distribution. Roughly, the statistic can be applied when $N_i \geq 100$ (Miller and Freund 1977: 252). The critical region is defined by the inequality

$$|z_{ij}| \leq z_{1-\alpha/2} \quad (2.12c)$$

where $z_{1-\alpha/2}$ is the quantile of the standard normal distribution. The inequality (2.12c) can be used to construct a stopping rule for the simulation process shown in Fig. 2.7. The simulation can be stopped as soon as the inequalities

$$|z_{ij}| > z_{1-\alpha/2} \quad (2.12d)$$

are satisfied for all i and j ($i \neq j$). In the case where the number of simulations N_i is less than 100, the decision concerning H_0 can be made by means of a statistic based on hypogeometric distribution (e.g., Čekanavičius and Murauskas 2009: 187).

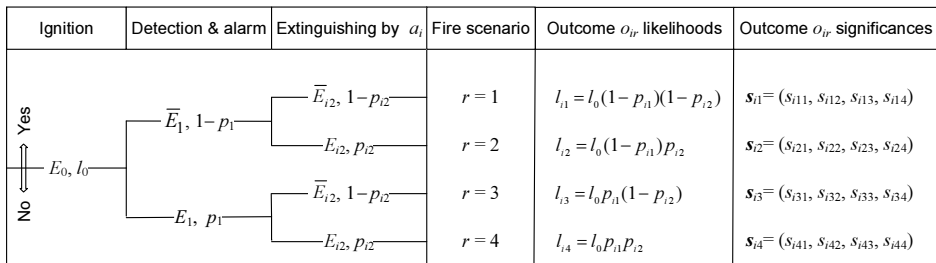
The simulation-based algorithm shown in Fig. 2.7 was implemented in the computer code MCS (multi-attribute selection). This code is presented in Annex C. An illustration of an application of this algorithm is described in the subsequent section.

2.4.3. Numerical illustration

A sprinkler system is to be chosen among three alternative systems a_1 , a_2 , and a_3 . The alternatives a_1 , a_2 , and a_3 denote dry pipe, deluge and pre-action sprinklers, respectively (Table 2.8). The most appropriate one, a^* , will serve along with automatic fire detectors and an alarm system as a fire protection measure in an industrial building. A potential fire accident in this building has four possible scenarios represented by the event tree given in Fig. 2.8.

Table 2.8. Initial data used for the selection from alternative sprinkler systems

System	Fire likelihood l_0 (year ⁻¹)
All systems a_1, a_2, a_3	$L_0 \sim G(3, 20)$ (a gamma distribution with the mode of 0.10)
	Alarm failure probability p_{f1}
All systems a_1, a_2, a_3	$\tilde{p}_1 \sim \text{Be}(4, 58)$ with the mode of 0.05
	Sprinkler failure probability p_{f2}
Dry pipe a_1	$\tilde{p}_{12} \sim \text{Be}(4, 55)$ (beta distribution)
Deluge a_2	$\tilde{p}_{22} \sim \text{Be}(4, 60)$
Pre-action a_3	$\tilde{p}_{32} \sim \text{Be}(3, 30)$
	Mode of the distribution of p_{f2}
Dry pipe a_1	0.0526
Deluge a_2	0.0484
Pre-action a_3	0.0645
	Cost c_{i5} of a_i (€mln)
Dry pipe a_1	$c_{15} = 0.30$
Deluge a_2	$c_{25} = 0.24$
Pre-action a_3	$c_{35} = 0.27$

**Fig. 2.8.** Simplified event tree diagram for a fire in a sprinklered building with a fire detection and alarm system

The structure of the event tree diagram is identical for all three sprinkler systems a_1 , a_2 , and a_3 . The fire risk related to the sprinklered building is given by

$$\text{Risk}_i \equiv \{ (l_{ir}, o_{ir}, s_{ir}), r = 1, 2, 3, 4 \} \quad (2.13)$$

where the index i refers to the alternative a_i ($i = 1, 2, 3$); l_{ir} is the likelihood of the scenario r with the outcome o_{ir} in the building with sprinklers a_i ; and s_{ir} is the vector of significances of o_{ir} .

As shown in Fig. 2.8, the vectors s_{ir} are expressed as $s_{ir} = (s_{ir1}, s_{ir2}, s_{ir3}, s_{ir4})$, where s_{ir1} is the property loss due to fire and/or fire suppression (€th.); s_{ir2} is the number of possible deaths among workers; s_{ir3} is the possible number of injured workers; and s_{ir4} is the outage of the industrial building in consequence of the fire (days).

The likelihood l_{ir} must be estimated from the following quantities:

- The likelihood of ignition (initiating event) E_0 , l_0 ;
- The conditional probability of alarm failure, $p_1 = P(E_1 | E_0)$; and
- The conditional probabilities that sprinklers a_i will fail given $E_0 \cap E_1$ or $E_0 \cap \bar{E}_1$, namely, $p_{i2} = P(E_{i2} | E_0 \cap E_1)$ (Fig. 2.8).

The expression of the risk given by Eq (2.13) will be used to form the attribute vector $c_i = (c_{i1}, c_{i2}, c_{i3}, c_{i4}, c_{i5})$, in which c_{i1} to c_{i4} are expected significances treated later as random variables and c_{i5} will be the fixed (deterministic) cost of a_i (€mln) (the values of c_{i5} are given in Table 2.8).

The fire E_0 in a specific building is generally a rare and difficult-to-predict event and so are the failures of alarm and sprinklers, E_1 and E_{i2} , given E_0 . Therefore l_0 , p_1 , and p_{i2} can be uncertain in the epistemic sense (e.g., Bradyberry and Apostolakis 1991). In the present example, the uncertainty in l_0 , p_1 , and p_{i2} is quantified by respective epistemic random variables L_0 , $\tilde{p}_1$, and $\tilde{p}_{i2}$ with the hypothetical probability distributions specified in Table 2.8 (the definition of the QRA term “epistemic uncertainty” is given, for instance, by Aven (2003).

The epistemic uncertainty in the likelihoods l_{ir} is modelled by the random variables L_{ir} expressed through the epistemic random variables defined in Table 2.8:

$$L_{i1} = L_0(1 - \tilde{p}_1)(1 - \tilde{p}_{i2})$$

$$L_{i2} = L_0(1 - \tilde{p}_1)\tilde{p}_{i2}$$

$$L_{i3} = L_0\tilde{p}_1(1 - \tilde{p}_{i2})$$

$$L_{i4} = L_0 \tilde{P}_1 \tilde{P}_{i2} \quad (2.14)$$

Components of the vectors s_{ir} are assumed to be random variables and denoted by the symbols $\tilde{s}_{ir1}$, $\tilde{s}_{ir2}$, $\tilde{s}_{ir3}$ and $\tilde{s}_{ir4}$. They are grouped to a random vector $\tilde{s}_{ir} = (\tilde{s}_{ir1}, \tilde{s}_{ir2}, \tilde{s}_{ir3}, \tilde{s}_{ir4})$. The property loss due to fire, $\tilde{s}_{ir1}$, obeys a lognormal distribution (Rasbash *et al.* 2004: 198). The parameters μ_{ir} and σ_{ir} of the random variable $\tilde{s}_{ir1} \sim L(\mu_{ir}, \sigma_{ir})$ are given in Table 2.9. The values of μ_{ir} and σ_{ir} were calculated by using mean values of $\tilde{s}_{ir1}$ obtained from the statistics of fires in industry (Ramachandran 1998: 188). Values of standard deviations of $\tilde{s}_{ir1}$ given in Table 2.9 were assumed hypothetically.

Table 2.9. Components of the random significance vectors $\tilde{s}_{ir}^*$

Dry pipe system a_1	
Vectors $\tilde{s}_{ir}$ ($i = 1; r = 1, 2, 3, 4$)	The mean μ_{ir} and std. dev. σ_{ir} of $\tilde{s}_{ir1}$ (€th)
$\begin{bmatrix} \tilde{s}_{11} \\ \tilde{s}_{12} \\ \tilde{s}_{13} \\ \tilde{s}_{14} \end{bmatrix} = \begin{bmatrix} L(0.348, 0.198) & 0 & B(20, 0.01) & P(2.0) \\ L(1.637, 0.246) & B(20, 0.10) & B(20, 0.30) & P(17.0) \\ L(0.348, 0.198) & B(20, 0.05) & B(20, 0.15) & P(2.0) \\ L(1.778, 0.246) & B(20, 0.25) & B(20, 0.45) & P(19.0) \end{bmatrix}$	$\tilde{s}_{111} : \mu_{11} = 1.5, \sigma_{11} = 0.3$
	$\tilde{s}_{121} : \mu_{12} = 5.3, \sigma_{12} = 1.325$
	$\tilde{s}_{131} : \mu_{13} = 1.5, \sigma_{13} = 0.3$
	$\tilde{s}_{141} : \mu_{14} = 6.1, \sigma_{14} = 1.525$
Deluge system a_2	
Vectors $\tilde{s}_{2r}$ ($i = 2; r = 1, 2, 3, 4$)	The mean μ_{ir} and std. dev. σ_{ir} of $\tilde{s}_{ir1}$ (€th)
$\begin{bmatrix} \tilde{s}_{21} \\ \tilde{s}_{22} \\ \tilde{s}_{23} \\ \tilde{s}_{24} \end{bmatrix} = \begin{bmatrix} L(1.013, 0.601) & 0 & B(20, 0.01) & P(4.0) \\ L(1.637, 0.246) & B(20, 0.10) & B(20, 0.30) & P(17.0) \\ L(1.013, 0.601) & 0 & B(20, 0.05) & P(4.0) \\ L(1.778, 0.246) & B(20, 0.25) & B(20, 0.45) & P(19.0) \end{bmatrix}$	$\tilde{s}_{211} : \mu_{21} = 3.3, \sigma_{21} = 0.66$
	$\tilde{s}_{221} : \mu_{22} = 5.3, \sigma_{22} = 1.325$
	$\tilde{s}_{231} : \mu_{23} = 3.3, \sigma_{23} = 0.66$

Table 2.9. Continued

	$\tilde{s}_{241} : \mu_{24} = 6.1, \sigma_{24} = 1.525$
Pre-action system a_3	
Vectors $\tilde{s}_{3r}$ ($i = 3; r = 1, 2, 3, 4$)	The mean μ_{ir} and std. dev. σ_{ir} of $\tilde{s}_{ir1}$ (€th)
	$\tilde{s}_{311} : \mu_{31} = 1.7, \sigma_{31} = 0.34$
$\begin{bmatrix} \tilde{s}_{31} \\ \tilde{s}_{32} \\ \tilde{s}_{33} \\ \tilde{s}_{34} \end{bmatrix} = \begin{bmatrix} L(0.475, 0.331) & 0 & B(20, 0.01) & P(2.0) \\ L(1.637, 0.246) & B(20, 0.10) & B(20, 0.30) & P(17.0) \\ L(0.475, 0.331) & B(20, 0.05) & B(20, 0.15) & P(2.0) \\ L(1.778, 0.246) & B(20, 0.25) & B(20, 0.45) & P(19.0) \end{bmatrix}$	$\tilde{s}_{321} : \mu_{32} = 5.3, \sigma_{32} = 1.325$
	$\tilde{s}_{331} : \mu_{33} = 1.7, \sigma_{33} = 0.34$
	$\tilde{s}_{341} : \mu_{34} = 6.1, \sigma_{34} = 1.525$

* The probability distributions and their parameters presented in the table are hypothetical; L($\cdot$), B($\cdot$) and P($\cdot$) denotes lognormal, binomial and Poisson distribution, respectively

The number of employees in the building under analysis is assumed to be fixed and equal to 20. The numbers of victims (fatalities and injuries), on the contrary, are modelled by random variables $\tilde{s}_{ir2}$ and $\tilde{s}_{ir3}$ which obey a binomial distribution, that is, $\tilde{s}_{ir2} \sim B(20, \phi_{ir2})$ and $\tilde{s}_{ir3} \sim B(20, \phi_{ir3})$, where ϕ_{ir2} and ϕ_{ir3} are binomial parameters used to specify probabilities of individual numbers of victims. The binomial distributions are used to express the analyst's uncertainty in the numbers of fire victims. Values of ϕ_{ir2} and ϕ_{ir3} are given in Table 2.9. Fig. 2.9 illustrates the distribution of the random significance $\tilde{s}_{123} \sim B(20, \phi_{123})$.

The durations of outage are also treated as random quantities and modelled by the random variables $\tilde{s}_{ir4}$. The analyst's uncertainty in the outage duration is expressed by means of Poisson distribution, namely, $\tilde{s}_{ir4} \sim P(\lambda_{ir})$. Values of λ_{ir} related to individual alternatives and fire scenarios are given in Table 2.9. Fig. 2.10 shows the probability mass function for the uncertain outage $\tilde{s}_{114} \sim P(\lambda_{14})$.

With the random vectors $\tilde{s}_{ir}$ and the random likelihoods L_{ir} , the attribute vector c_i becomes a vector with four random and one fixed components:

$$\begin{aligned} \tilde{c}_i &= (\tilde{c}_{i1}, \tilde{c}_{i2}, \tilde{c}_{i3}, \tilde{c}_{i4}, c_{i5}) = \\ &= \left(\sum_{r=1}^4 L_{ir} \tilde{s}_{ir1}, \sum_{r=1}^4 L_{ir} \tilde{s}_{ir2}, \sum_{r=1}^4 L_{ir} \tilde{s}_{ir3}, \sum_{r=1}^4 L_{ir} \tilde{s}_{ir4}, c_{i5} \right) \end{aligned} \quad (2.15)$$

The random components of $\tilde{c}_i$ are expected significances.

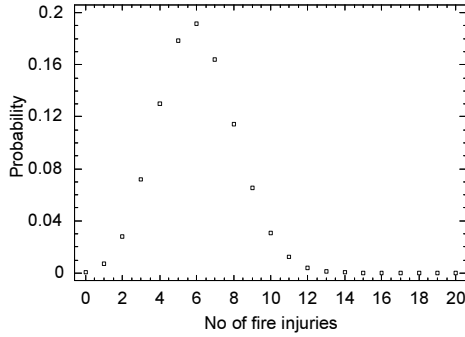


Fig. 2.9. Probability mass function of the random number of injured persons, $\tilde{s}_{123}$ (sprinkler system a_1 , fire scenario $r = 2$); $\tilde{s}_{123} \sim B(20, 0.3)$

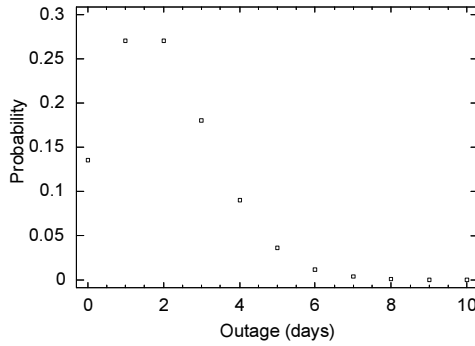


Fig. 2.10. Probability mass function of the random duration of outage, $\tilde{s}_{114}$ (sprinkler system a_1 , fire scenario $r = 1$); $\tilde{s}_{114} \sim P(2.0)$

The vectors $\tilde{c}_i$ defined by Eq. (2.15) form a 3×5 stochastic decision making matrix $\tilde{C} = [\tilde{c}_1, \tilde{c}_2, \tilde{c}_3]^T$. The selection of a^* with $\tilde{C}$ is based on sampling the matrices $\tilde{C}_l$.

Components of $\tilde{c}_i$ are functions of common random variables and so they are stochastically dependent, a practical implementation of sampling of $\tilde{C}_l$ is problematic. However, the components of $\tilde{c}_i$ are represented by relatively simple Eqs. (2.14) and (2.15), in which the random variables L_0 , $\tilde{p}_1$ and $\tilde{p}_{12}$ as well as components of $\tilde{s}_{ir}$ can be assumed to be independent. Therefore the sampling from joint probability distributions of $\tilde{c}_i$ can be replaced by a simpler sampling from epistemic distributions of L_0 , $\tilde{p}_1$ and $\tilde{p}_{12}$ as well as distributions of the components of the vectors $\tilde{s}_{ir}$ and calculating values of $\tilde{c}_i$ by means of Eqs. (2.14) and (2.15). Results of such a sampling are illustrated for the vector $\tilde{c}_1$ in Figs. 2.11 and 2.12.

For each sampled value $\tilde{C}_l$, a value of the normalized decision making matrix $\bar{C}_l$ was calculated using the vector normalization formula

$$NM: \bar{c}_{ij} = \tilde{c}_{ijl} / (\sum_{i=1}^m \tilde{c}_{ij}^2)^{-0.5} \quad (2.16)$$

where $\tilde{c}_{ijl}$ is the value of the random component $\tilde{c}_{ij}$ of $\tilde{C}$ sampled in the simulation step l . The MCDM criteria K_1 to K_3 presented in Table 2.10 were applied to $\bar{C}_l$ with the weights

$$\mathbf{w} = (0.20, 0.30, 0.25, 0.10, 0.15)^T \quad (2.17)$$

The components of $\mathbf{w}$ mean that the greatest significance was assigned to the attributes associated with the possible harm to people. The above weights have been chosen only as an example.

A total of 1×10^4 simulation steps were carried out to propagate the epistemic uncertainty in l_0 , p_1 , and p_{12} and components of $\tilde{s}_{ir}$ through the expressions (2.14) and (2.15) and then through the expressions of the criteria K_1 to K_3 given in Table 2.10 ($N_l = 1 \times 10^4$).

In each step, K_1 to K_3 were used to find the best sprinklers a^* on the basis of $\tilde{C}_l$. The simulation yielded the frequencies f_{ri} given in Table 2.10. All three criteria K_1 , K_2 and K_3 suggest a_3 as a^* .

Results obtained in this example are dependent on the vector normalization formula (2.16) used together with the criteria K_1 to K_3 . The application of other normalization formulas may lead to different results of MCDM. Therefore, results of MCDM are conditioned on the use of specific normalization formula.

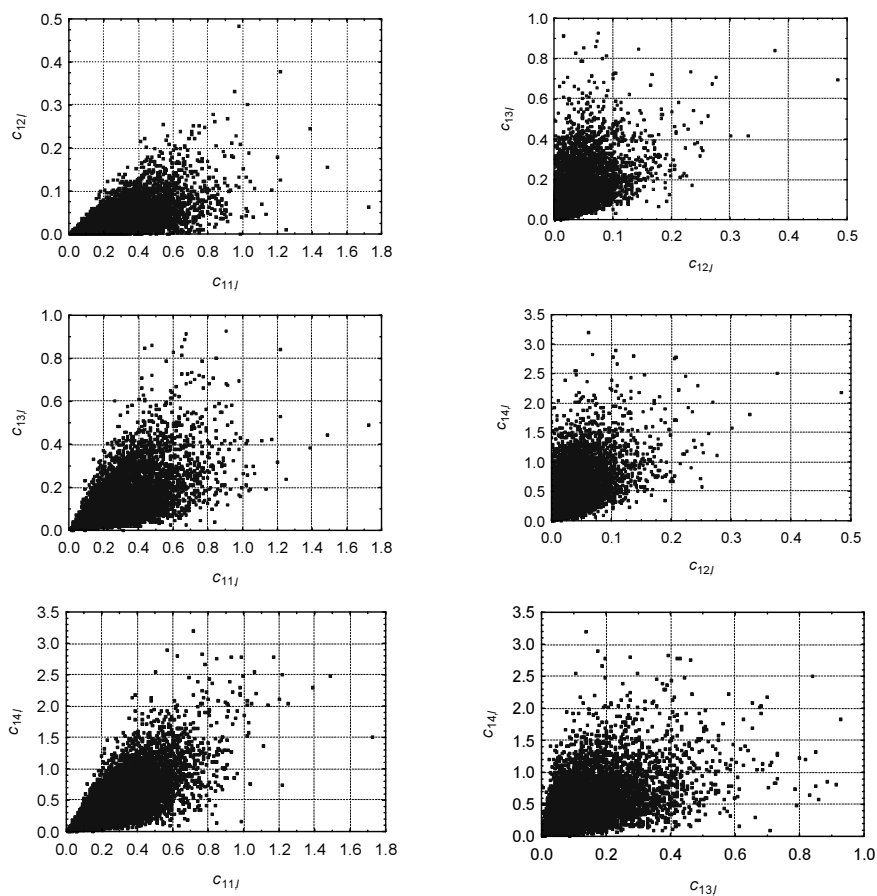


Fig. 2.11. Scatter diagrams drawn for pairs of the simulated values $\tilde{c}_{11,l}$, $\tilde{c}_{12,l}$, $\tilde{c}_{13,l}$, and $\tilde{c}_{14,l}$ of the components of the random decision making matrix $\tilde{\mathbf{C}}$ ($l = 1, 2, \dots, 10\,000$)

Table 2.10. Results of selection from alternative sprinkler systems

Frequency $f\hat{r}_i$	MCDM criteria used in the example		
	Laplace's, K_1	Bayes's, K_2	Hodges-Lehman's, K_3
$f\hat{r}_1$	0.2978	0.3164	0.3070
$f\hat{r}_2$	0.2857	0.2230	0.2340
$f\hat{r}_3$	0.4165 ^{*(1)}	0.4607*	0.4590*

⁽¹⁾ The symbol “*” indicates the best alternative determined by respective criterion

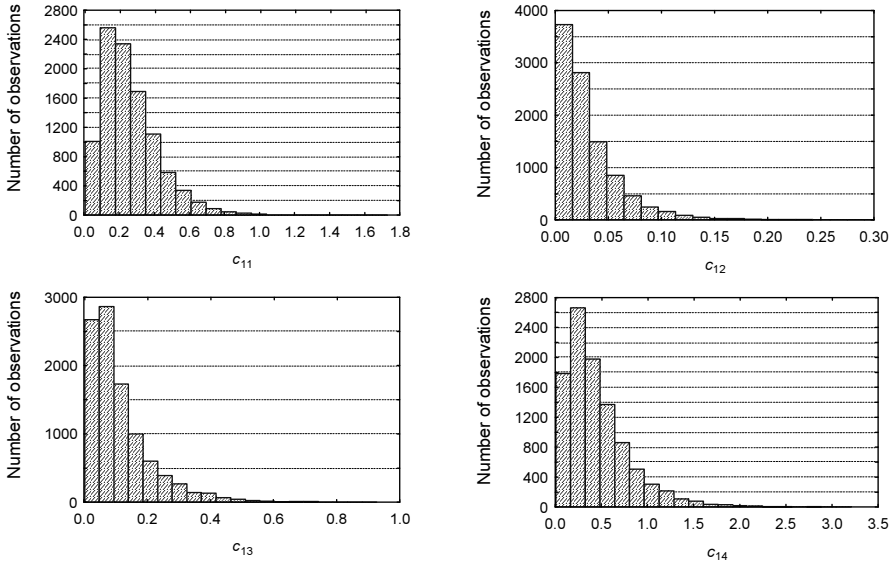


Fig. 2.12. Histograms drawn for the simulated values $\tilde{c}_{11,l}$, $\tilde{c}_{12,l}$, $\tilde{c}_{13,l}$, and $\tilde{c}_{14,l}$ of the components of the random decision making matrix $\tilde{C}$ ($l = 1, 2, \dots, 10\,000$)

The sequences of the frequencies fr_i computed in the simulation steps $l = 1, 2, \dots, N_l$ with the Laplace's criterion K_1 are shown in Fig. 2.13. Progressive values of fr_i become stable in a relatively early part of the simulation run. This convergence and stabilisation suggest that the initially assumed number of simulations, N_l , can be reduced. The simulation can be stopped by applying the stopping rule defined by Eq. (2.12d). This rule was used with the level of significance $\alpha = 0.1$ and so with the quantile $z_{0.95} = 1.64$. Eq. (2.12b) was used to compute three values z_{12} , z_{13} and z_{23} of the statistic z_{ij} . Progressive results of the computation of z_{12} , z_{13} and z_{23} are shown in Fig. 2.14. The inequality $|z_{ij}| > 1.64$ was satisfied for all three values z_{12} , z_{13} and z_{23} in the simulation step 3311. The frequencies fr_i computed in this step were $fr_1 = 0.06$, $fr_2 = 0.325$ and $fr_2 = 0.613$. This result suggests that the alternative a_3 can be identified as a^* with substantially smaller number of simulations, N_l , than the one assumed initially.

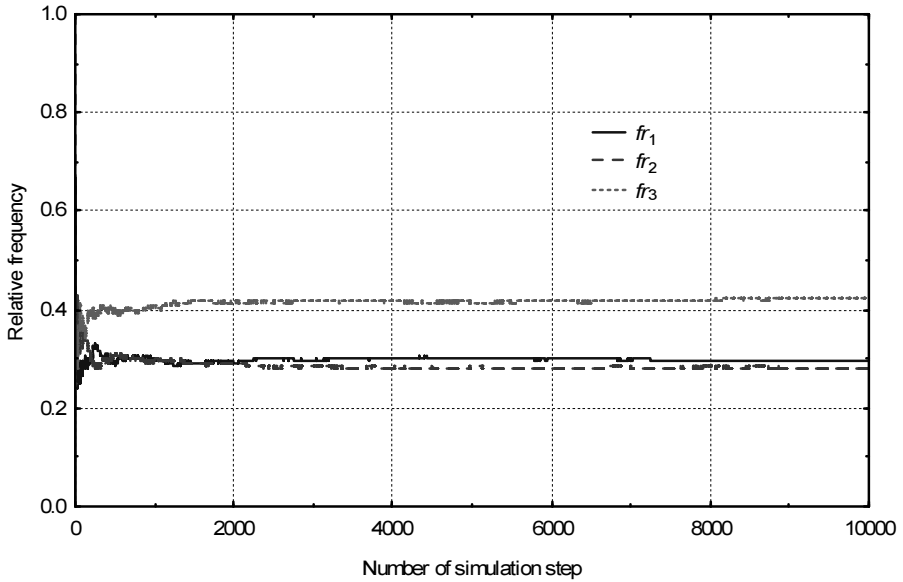


Fig. 2.13. Progressive results of computing the frequencies fr_i in the simulation run consisting of 10 000 steps

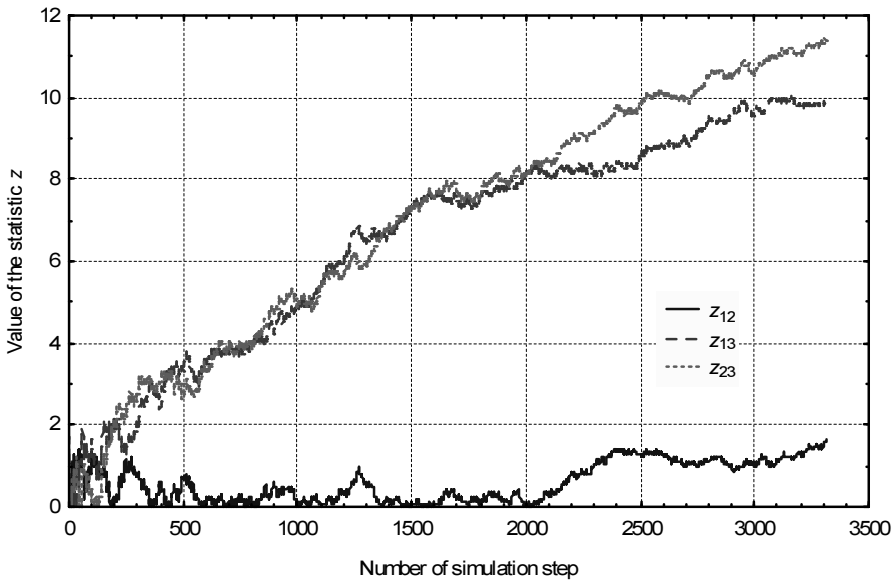


Fig. 2.14. Progressive values $|z_{12}|$, $|z_{13}|$ and $|z_{23}|$ of the statistic z_{ij} computed until the simulation step 3311, in which the condition of the stopping rule, $|z_{ij}| > 1.64$, was satisfied for all $i \neq j$

2.5. Second chapter conclusions

1. Economic decisions about fire safety in buildings can be made by a wide range of interested parties. The front-line decision makers are property owners, who are interested in the most cost-effective fire protection system, property buyers, who may be interested in the minimum level of fire risk in the building(s) on purchase, and architects, who have to juggle simultaneously a large of building characteristics in the design process. These three parties carry direct financial or professional responsibility for their decisions and can be interested in facilitating these decisions by means of MCDM.
2. MCDM can be applied to making decisions concerning fire safety of an individual building. MCDM methods can be applied to select among several fire protection measures by taking into account economic attributes of them. The interested party in such a selection is the building owner who may be forced to make a selection by requirement of fire regulations and/or the need to choose the most cost effective fire protection measure.
3. MCDM can be applied to the choice among several buildings by taking into account fire safety of each of them. The interested party in this type decision making will be the property buyer. The choice of the best building may include attributes which quantify fire safety resulting from design of buildings under comparison and internal content of them. However, MCDM can be used to compare several buildings in terms of response and effectiveness of the local fire brigades which are in charge of suppressing potential fires in them. The MCDM attributes which will reflect this aspect of building fire safety can be the response time of fire department and measures of fire suppressions effectiveness.
4. Comparison of alternative fire safety systems and buildings by means of MCDM is possible by considering attributes which quantify fire safety even in the case when such attributes are not common practice of a specific country and are not required by fire codes and regulations. Lithuania introduced the prescriptive for fire safety design. However, fire risk indices and fire risk estimated can be applied for inter-alternative comparison.
5. The choice of the best fire protection measure (combination of measures) among available ones will require to associate each of them with a quantitative measure of building fire safety. This fire safety measure should express effectiveness of fire protection system and may serve as key attribute of an MCDM problem. Fire risk indices and components of fire risk profile are the best candidates for such attributes.
6. Fire risk indices are a non-probabilistic approach to fire safety quantification. They can be introduced into an MCDM problem with

relative ease and are relatively simple to calculate. However, fire safety indices have limited sensitivity to changes in fire protection measures of an individual building and so can reflect subtle differences among MCDM alternatives only to a certain degree. Fire risk indices do not reflect such critical characteristics of fire protection system as the demand availability of sprinkler and alarm systems.

7. Estimates of fire risk can be incorporated into an MCDM problem by calculating expected severities related to individual outcomes (scenarios) of fire disaster. The fire risk can be related to alternative fire design solutions by estimating reliabilities (failure probabilities) of fire protection measures provided by individual designs. Fire risk profile is a very comprehensive measure of fire safety; however, an estimation of fire risk for a set of fire protection measures compared within MCDM can be complicated and costly process.
8. The estimation of fire risk requires to estimate the demand availability of sprinkler system, fire alarm systems and other components of fire safety system. Although theoretical models used for such estimation are well-developed, the practical estimation is problematic because it may face the need of relevant failure data on the behaviour of components of such systems.
9. The inclusion of fire safety attributes into an MCDM problem may lead to a situation where some components of an MCDM decision making matrix will be random variables. This can be especially the case where elements of risk profile (likelihoods and severities of fire accident consequences) are either directly used as MCDM attributes or are used to calculate attribute values. Elements of risk profile are usually uncertain in the epistemic sense and are modelled by epistemic probability distributions. This will generate the need to solve an MCDM problem with a random (stochastic) decision making matrix.
10. The MCDM problem with a random decision making matrix can be solved by propagating uncertainties expressed by random matrix elements by means of Monte Carlo simulation. The propagation is carried out by a repetitive solving of MCDM problem within a Monte Carlo loop and counting the frequency of selecting alternatives under comparison as the best ones. The final result of MCDM will be the alternative with the highest frequency of selection.

Application of investigation results to healthcare facilities

This chapter describes a combined application of multi-attribute selection and fire safety assessment to making decisions concerning medical facilities. An increased fire risk level in medical occupancies is identified and illustrated by fire incident data. Three examples of the multi-attribute selection with respect to fire safety are presented. The first example considers a selection of a fire safety system for a hospital building. The fire safety attribute used in the selection problem is expressed by FSES fire risk index. The second example deals with a multi-attribute selection of a building for a nursing home. The FRAME fire risk index is used in this problem as a safety-related attribute. The third example describes a multi-attribute selection among several alternative designs of a floor in a hospital building. Fire safety is expressed through the risk to lives of patients and hospital personnel. The attribute considering this risk is quantified as time to untenable conditions in rooms of the building under analysis. This time is assessed by applying a computer-aided fire simulation. The third chapter presents results of investigation published by Vaidogas and Šakėnaitė (2011b).

3.1. The anatomy of fires at healthcare occupancies

Healthcare facilities include hospitals, clinics, ambulatory healthcare occupancies, nursing homes and other facilities which provide care to the sick and injured. Hospitals and other healthcare facilities are traditionally seen by general public as places of safety. However, these institutions are not immune from disruptive accidents presenting challenges, including increased needs of their occupants during the time of crisis. Hospitals and other healthcare facilities are well-prepared for major external incidents and events which cause a surge in patient numbers. However, circumstances resulting in internal accidents such as fire, escape of gases or dangerous substances, utility failure and non-structural or structural damage may necessitate the evacuation of a hospital or healthcare facility, either as a whole or part. These events can be more disruptive than external incidents, as they put increased stress on the facilities which traditionally operate at full capacity (Wapling *et al.* 2009).

Types of facilities where fires start

Fires in healthcare facilities may be particularly worrying, not only from flames and heat generated, but also the smoke which can travel long distances inside buildings aided by air-conditioning systems. The type of smoke or products of combustion generated will vary from the type of fire (blazing or smouldering) to the sort of material being burnt such as the building, the roofing, or hospital plastics or waste to more specific material such as hospital gases, drugs or even radioactive sources.

According to the US data collected in the years from 2004 to 2006, nursing homes account for 44 % of all healthcare facility fires (Fig. 3.1). Hospital fires are the second most common type of healthcare facility fires (23 %), followed by developmental disability facilities (14 %). Facilities providing 24-hours care – nursing homes, hospitals, developmental facilities, abuse recovery centres, mental institutions and hospices – represent 89 % of fires in healthcare facilities. Fires in doctor's offices and clinics account for the remaining 11 % (FEMA 2009). Seventy percent of the direct property damage due to fires in healthcare facilities occurs in clinics or doctor's offices, whereas fires in hospitals and mental health or substance abuse facilities cause 20 % and 10 % of direct damage (Flynn 2009).

Characteristics of occupants

Occupants of healthcare facilities are generally presumed to be incapable of self-preservation. A significant percentage of occupants in hospitals and nursing homes are incapable of self-evacuation or are ambulatory but incapable of perceiving a fire danger and choosing a rational response.

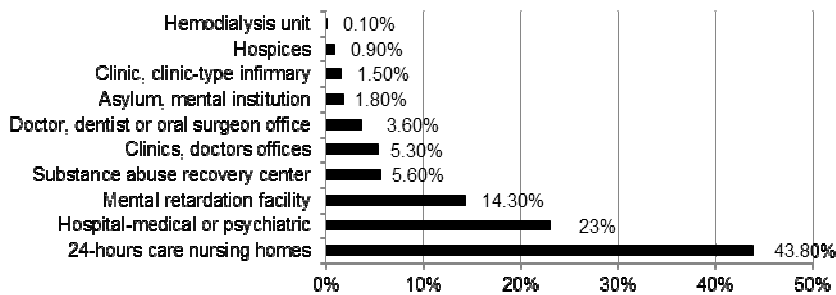


Fig. 3.1. Type of medical facilities where fires start (data from 11 737 fire accidents extracted from the NFIRS system (NFIRS 2012, FEMA 2009))

There are three types of care in most modern hospitals:

- Ambulatory care,
- General care,
- Intense care.

Ambulatory patients can manage their own way to safety if they are given proper directions, unless smoke and heat is intense. General care patients may be transported on stretchers or wheelchairs with some difficulty. Horizontal and even some vertical movement are generally possible, although independent evacuation is not. Patients in intensive care are likely to be connected to various life support devices, making movement for even short distances very difficult and evacuation is almost impossible without further endangering lives of these patients.

Occupants of nursing homes vary from geriatric residents, who are capable of evacuation with limited assistance to residents, who are comatose and require close supervision with evacuation being very difficult.

Fire loss measures

Table 3.1 presents the loss measures for fires in the US healthcare facilities and compares these measures to those in nonresidential buildings. The loss measures were averaged over three-year periods from 1996 to 1998 and from 2004 to 2006.

Types of fire and ignition sources

Fires in medical buildings are of two major categories:

- Confined fires (fires which are confined to specific types of equipment or objects), and
- Nonconfined fires (fires which spread far outside the fire source).

Most medical facility building fires are small, confined ones (Flynn 2009). Data from the three-year period from 2004 to 2006 indicate that 65 % of medical facility fires incidents are confined fires (Table 3.2). Confined cooking fires alone account for 55 % of medical facility fires. 24-hours care facilities account for 94 % of confined cooking fires in medical occupancies.

Table 3.1. Averaged loss measures for healthcare facility fires compared to those in nonresidential buildings (US data of two three-year periods, US Fire Administration (2001) and FEMA (2009))

Averaged loss measure	Healthcare facility fires	Nonresidential building fires
	From 1996 to 1998	
Fatalities per 1000 fires	2.2	1.7
Injuries per 1000 fires	59.2	22.1
Dollar loss per fire	\$4286	\$21 878
	From 2004 to 2006	
Fatalities per 1000 fires	1.2	0.8
Injuries per 1000 fires	26.6	12.3
Dollar loss per fire	\$5312	\$21 898

Causes of nonconfined medical facility fires

While cooking is undoubtedly the leading cause of fires in medical facilities overall (64 %), it plays a very small role in medical facility nonconfined fires. As shown in Fig. 3.2, electrical malfunction (15 %), appliances (12 %), and equipment misoperation (10 %) are the leading causes of nonconfined fires in medical facilities. These three causes account for 37 % of the nonconfined fires in medical facilities when the cause is known. For 23 % of medical facility fires, the cause is unknown. For 26 % of fires where the equipment involved in the fire ignition is specified, clothes dryers were reported as the leading equipment involved.

Areas of fire origin in nonconfined medical facility fires

As shown in Table 3.3, three leading areas of fire origin are laundry area, bedrooms, and kitchens which reflect the predominance of 24-hours care facilities in medical facility fires. The laundry area is the leading area of the origin of nonconfined medical facility fires (15 %), followed closely by bedrooms (14 %). Kitchens and other cooking areas are the third leading area of fire origin, accounting for 10 % of medical facility fires.

Table 3.2 Medical facility fires by the type of incident (US data of two three-year periods, US Fire Administration (2001), FEMA (2009), NFIRS (2012))

Incident type	Percent
From 1996 to 1998 (all fires)	
Cooking	20
Appliances, A/C	18
Other equipment	14
Electrical distribution	13.5
Incendiary/suspicious	10
Smoking	8
Open flame	8
Heating	7
Other heating	1
Natural	2
Exposure	2
From 2004 to 2006 (fires categorised into confined and nonconfined ones)	
Nonconfined fires	34.6
Confined fires	65.4
Cooking fire, confined to container	55.0
Chimney or flue fire, confined to chimney or flue	0.5
Incinerator overload or malfunction, fire confined	0.3
Fuel burner/boiler malfunction, fire confined	2.9
Commercial compactor fire, confined to rubbish	0.3
Trash or rubbish fire, contained	6.3

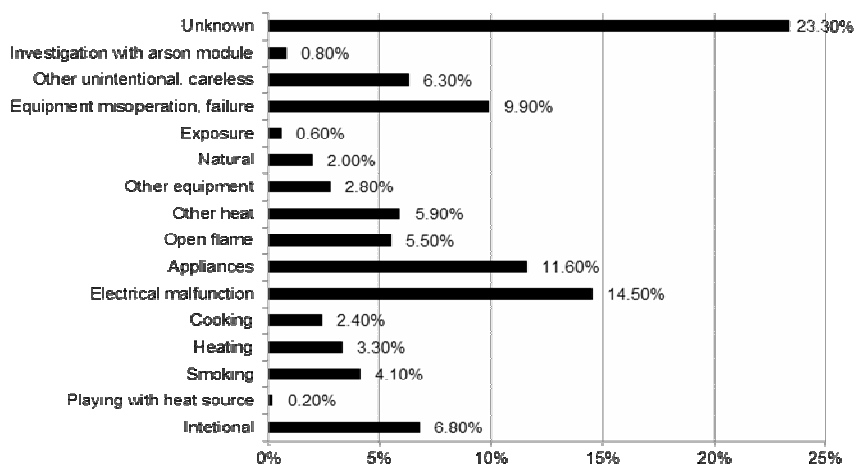
**Fig. 3.2.** Nonconfined medical facility fires (data from 11 737 fire accidents extracted from the NFIRS system (NFIRS 2012, FEMA 2009))

Table 3.3. Leading areas of fire origin in nonconfined medical facility fires (US data of from the three-year period from 2004 to 2006, FEMA (2009))

Area of fire origin	Percent of nonconfined medical facility fires
Laundry area, wash house (laundry)	15
Bedrooms	14
Cooking area, kitchen	10
Data collected in 4065 incidents, 185 incidents with area of fire origin undetermined	

Ignition materials in nonconfined medical facility fires

The category “general materials” is the leading category of items first ignited and accounts for 24 % of nonconfined medical facility fires. Within this category, the insulation around electrical wiring is the leading type of item first ignited overall, accounting for 18 % of all medical facility fires. This finding is consistent with electrical malfunction as the leading cause of nonconfined medical facility fires. Soft goods (such as linen) and wearing apparel are the items first ignited for 17 % of medical facility fires.

Another leading category of items first ignited as seen in Fig. 3.3, is “structural components or finishes” (12 %). This includes insulation, roofing, doors, carpets, and the like, though none of these subcomponents alone account for a large portion of nonconfined medical facility fires.

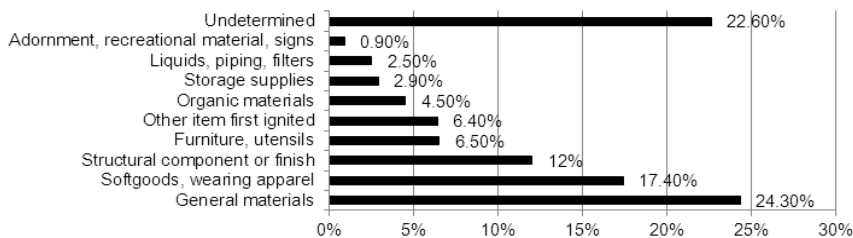


Fig. 3.3. Item first ignited in nonconfined medical facility fires (from 2004 to 2006) (data from 11 737 fire accidents extracted from the NFIRS system (NFIRS 2012, FEMA 2009))

Heat source for nonconfined medical facility fires

A clear majority of nonconfined medical facility fires derive their heat source from powered equipment (54 %). The subcomponents of this category are the leading sources of heat, not only within this category, but also in all nonconfined medical facility fires: unspecified types of powered equipment are responsible for 24 % of all fires; electrical arcing – 18 %; radiated or conducted heat from powered equipment – 17 %; and sparks from operating equipment – 7 % (Fig. 3.4).

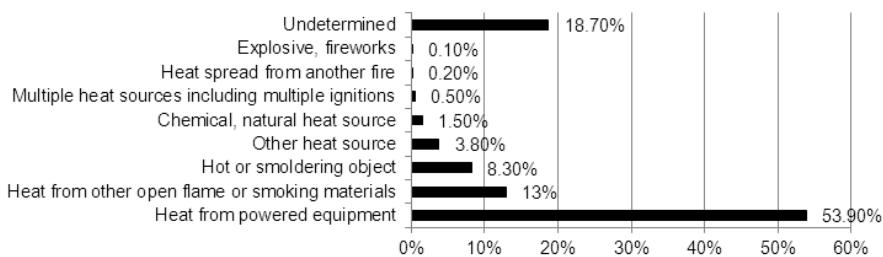


Fig. 3.4. Sources of heat in nonconfined medical facility fires (from 2004 to 2006) (data from 11 737 fire accidents extracted from the NFIRS system (NFIRS 2012, FEMA 2009))

The next leading category of heat sources in nonconfined medical facility fires is heat from other open flames or smoking materials (13 %). Within this category, the most prevalent source of heat is from cigarettes, accounting for approximately 5 % of all nonconfined medical facility fires.

Factors contributing to ignition in nonconfined medical facility fires

An electrical failure or malfunction cause 31 % of nonconfined medical facility fires (Fig. 3.5). The next leading category is the misuse of materials at 28 %. Within this category, heat sources that are left too close to combustibles account for 9 % of all medical facility fires, and abandoned or discarded materials account for 7 %.

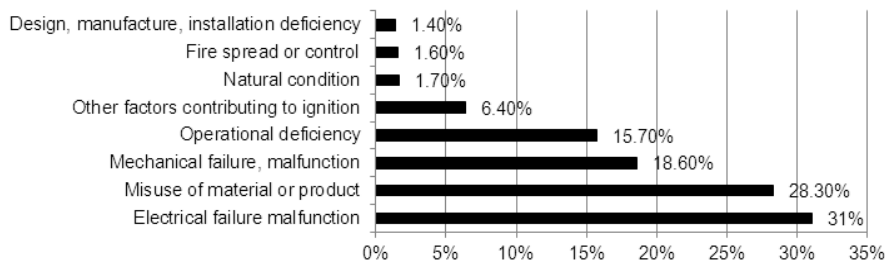


Fig. 3.5. Factors contributing to the ignition of nonconfined medical facility fires (from 2004 to 2006) (data from 11 737 fire accidents extracted from the NFIRS system (NFIRS 2012, FEMA 2009))

Data on automatic suppression systems

Data on 1600 fires in medical facilities collected during 2003–2006 in NFIRS system indicate that some automatic extinguishing system was present in 53 % of fires (Flynn 2009, NFIRS 2012). In more than three out of four reported fires,

the type of automatic extinguishing system present was wet pipe sprinkler. Sprinklers operated and were effective in more than 90 % of incidents where fires were large enough to activate sprinklers. For 84 % of the reported medical, mental health, and substance abuse structure fires, the fire was too small to activate sprinklers.

Of the sprinklers which failed to operate, 62 % were due to manual intervention and 38 % were due to the fact that it was an inappropriate system for the hazard.

3.2. A brief look at major fires at healthcare occupancies

Romainiai hospital fire in Lithuania

On January 25, 2012 there was a fire at Romainiai Tuberculosis hospital in Kaunas. Firefighters arrived quickly to the location. The hospital corridor was smoke full and in the second floor ward on the bed linen was burning on the bed. The fire was quickly extinguished. Fortunately, people were not injured and minor damage was done. The fire broke out because of fire safety violations while electric appliances were used.

Achern hospital fire in Germany

On May 30, 1980 there was a fire at Achern hospital in Germany. A fire started in the basement of an eight-storey hospital building in Achern in Germany. Firefighters arrived quickly to the scene. However, after a while smoke began to spread to the adjacent stairwell. Due to a small opening in a shaft, the fire then spread from its origin. There was heavy smoke production from the fire, which inhibited movement via the stairwells. The fire quickly affected floors one to three.

Evacuation had to take place via ladders from the outside, as smoke prevented escape via the inside escape routes. 100 patients were evacuated down the ladders. Among the casualties were those whose lives were dependent on medical technology, which failed because of the fire. Insufficient integration and insulation of fire compartments were the main causes of the consequences of the fire. There 10 people died in a fire.

Dardanelle nursing home fire in USA

The next cause of fire at the nursing home in Dardanelle in the USA is unknown. On March 13, 1990, there was a fire at the nursing home in Dardanelle in the USA. The fire started in a linen storage room, spread via a space above the inner ceiling to adjacent corridors and nursing rooms. The door to the fire room was open when the fire started and it was never closed. The cause of the fire is unknown.

The loss of life and property was mainly due to the absence of a fire suppression system, the spread of flames and smoke via spaces and the lack of integrity in the fire separating construction. Four patients died from smoke inhalation in this fire.

Huddinge hospital fire in Sweden

In 1991 there was a fire at the Swedish hospital in Huddinge, from which a number of interesting conclusions could be drawn (Olsson 1999). The fire started on one of the hospital wards when a patient set light to some clothes. The ward was situated on the ground level. There was heavy smoke production and due to a few mistakes there was extensive and unnecessary smoke spread in the building.

After the members of staff discovered the fire the door that separated the ward into two fire compartments was closed. This door was later opened by the firefighters, which led to smoke spreading into the escape stairwell. The door from the second escape route was left open which led to smoke spread in the entire main stairwell. Locked doors also blocked some escape routes. What should have been an easy task for the firefighters turned out to be a complex situation, which could have resulted in a number of fatalities due to incorrect human actions.

Leningrad hospital fire in Russia

In 1999 there was a fire at Leningrad hospital in Russia. 21 people died in a fire that broke out on Tuesday morning in a single-storey wooden hospital where 85 severely mentally retarded patients were sleeping. Three of the survivors suffered burns and smoke inhalation and were hospitalized, and the rest were taken to other psychiatric institutions. 85 patients ranged in age from 18 to 80, and many had lived in the institution for most of their lives. Short circuit or arson was possible cause of the fire. The patients were watching television rather late last night and something may have gone wrong with the wiring.

Moscow hospital fire in Russia

On December 9, 2006 there was a fire at Drug Treatment hospital in Moscow. A fire started on the second floor of the eight-storey hospital building early Saturday at 1.40 a.m. Moscow time. The fire occurred in a wooden cabinet in a kitchen at one end of a corridor. The main emergency exit was blocked by a locked gate and the only other way out was cut off by choking smoke. The barred windows were shut with locks that hospital personnel, who had the keys, apparently did not have time to open. All 45 women were dead by the time firefighters arrived. Secondly, the hospital personnel worked very badly. They did not take steps to evacuate people in the early stages of the fire. 160 people

were evacuated from the five-storey building, and 10 people were hospitalized with carbon monoxide poisoning. Most victims died of asphyxiation.

Nursing home fires in Russia

On March 20, 2007, 62 people died in a fire in a nursing home in southern Russia. Many of the dead were confined to their beds and unable to flee the smoke and flames. The fire erupted in a government nursing home in Kamyshevatskaya, a small village on the Azov Sea. Of 35 people who escaped, at least 30 were hospitalized, some with serious injuries. The dead ranged in ages from 46 to 86.

At the nursing home, a fire alarm system that had not been fully installed signalled three times, but a watchman at the facility outside the building ignored the first two alarms and reported the fire only after he had seen flames. In addition, nursing home personnel were absent from their posts when the fire broke out, slowing efforts to find keys and open an emergency exit. Three orderlies and a nurse were in the building, but it was not enough to quickly evacuate the elderly residents.

The reason was that instead of informing the fire department about the tragedy and emergency, the watchman shut off the gas, began calling his bosses and informed the nurses and medical personnel. Only after this, did the guard call the authorities to report the fire. The closest fire station was in Yeisk, more than 30 miles away. It took nearly an hour for firefighters to arrive.

Renovation work had been carried out in the building and the interior wall panels released toxic gases when they burned, filling the second storey with smoke. Most of the victims died from smoke inhalation.

On November 6, 2007, 32 patients were killed in a nursing home in the Tula region in the south of Moscow. The fire broke out on Sunday afternoon in the two-storey home for elderly and disabled people and burned quickly through the 55-year-old brick building with wooden walls before the flames were extinguished.

Some elderly residents were evacuated on stretchers while others jumped from the second floor windows in the latest deadly blaze. More than 250 people escaped or were evacuated from the building and hospitalized or placed in other nursing homes.

Earlier fire inspectors had asked courts to order the nursing home closed because of fire safety violations, including the lack of an alarm system. The fire was likely caused by a short circuit or carelessness. Firefighters were only alerted of the blaze half an hour after it broke out, and employees “did not organize the effective evacuation” of residents. A nearby fire station had been shut, and it took firefighters almost an hour to get to the site from a larger town after a night watchman ignored two fire alarms before reporting the blaze. The

building had no fire alarm and no system that would automatically alert the fire department of a blaze.

On February 11, 2009, there was a fire in a nursing home in Komi region of Russia's northwest. The fire swept quickly through the wooden building. Three residents of the home were rescued and 23 died in the fire.

The town had a fire station, but it could not cope with the size of the fire and more firefighters had to be called from a nearby town. The reason of the fire was a canister of flammable liquid in the room where the fire started, leading to the speculation that the resident set himself ablaze. "Careless smoking" was the likely cause of the fire.

Calderon Guardia hospital fire in Costa Rica

On July 12, 2005, there was a fire at the Calderon Guardia hospital in San Jose, Costa Rica's capital. 18 people, mostly patients, were killed by a fire that broke out at the neurosurgery and intensive care wards of one of Costa Rica's main hospitals on Tuesday. Of the 18 victims, 16 died on the fifth floor, and two others on the fourth floor. Some of the hospital 522 patients had under their beds.

The fire was thought to have started in the oldest part of the hospital, where its archives and outpatient services were located on the fourth floor of the five-storey building, and quickly spread to the fifth and third floors, destroying the neurosurgery and men's surgery departments.

The cause of the blaze was a gas leak. It took firefighters three hours to bring the flames under control. Nurses broke windows to try to help people escape and firefighters used ladders to bring patients down from the upper floors. Ambulances, taxis and private vehicles were used to transfer the patients to nearby hospitals.

The cause was not immediately known. Like most other medical facilities in Costa Rica, the Calderon Guardia hospital lacked an adequate evacuation plan. It also lacked safety measures required under recently implemented national fire regulations – including fire hoses, emergency lighting, and a fire escape. The hospital alarm system failed to sound, and two small staircases designed for evacuations reached only the third floor. Firefighters and Red Cross rescue workers used hydraulic ladders to evacuate people. In January, a small fire broke out in the building but no one was injured. The hospital fire alarms also failed to work then.

Sydney nursing home fire in Australia

On November 18, 2011 there was a fire in a nursing home in Sydney in Australia. Three people died at the scene and other six people died in hospital

later. Their age ranged from 73 to 97 years. Nearly 100 people lived at a nursing home. About 50 people were injured, some seriously.

Firefighters arrived six minutes after an alarm was activated to find a fiercely burning blaze with thick acrid smoke. Nearly 100 fire crews battled the flames.

The cause of the fire was not immediately known. The blaze started shortly before 05:00 local time on Friday. The fire was started by a male nurse who worked at the Quakers Hill nursing home in a western suburb of the city. He has now been charged with four murders, allegedly using a cigarette lighter to set fire to bed sheets in two rooms. There was no sprinkler system in the nursing home as they are not required under state laws.

Kalkota hospital fire in India

On December 9, 2011 there was a fire at Kalkota hospital in India (Loria *et al.* 2012). There 61 people were killed among whom were many patients. Most of them died of smoke poisoning. Firefighters smashed windows. Upper floors were out to patients who otherwise would choke. Rescuers transported some patients in wheelchairs or stretchers to another hospital nearby. The fire started in the basement of the building, which was full of flammable substances such as oxygen cylinders, and thick smoke quickly overflowed the whole building. Firefighters arrived in more than an hour after the fire starts. It was difficult for large fire trucks to move along the narrow streets of the district.

3.3. The selection of fire safety system for a hospital building

3.3.1. The building and alternative fire safety systems

A hospital in the Lithuanian town Kėdainiai is analysed in this case study. The main hospital building consists of five storeys and a basement (Fig. 3.6). The five-storey building is occupied by therapy department, patient care department and traumatology department.



Fig. 3.6. The main building of the Kėdainiai hospital complex

A hospital administration is choosing fire protection system for retrofitting the five-storey building. It wants to improve fire safety in the building where patients with impaired movement capabilities stay. This physical condition can result in problems with evacuation of patients and, in part, personnel in case of fire. The administration seeks to reach the maximum level of fire safety, but at the same time it does not want to appear as being uneconomic in its choice of fire protection. Furthermore, the administration does not want to impair the continuous operation of the hospital building.

The alternatives used in this problem, a_i , represent four variants of installing two fire protection measures:

- Alternative A (or a_1): smoke detectors and alarm in corridors only; no sprinklers;
- Alternative B (or a_2): smoke detectors and alarm in the total space of building; no sprinklers;
- Alternative C (or a_3): smoke detectors, alarm and automatic sprinklers in corridors only;
- Alternative D (or a_4): smoke detectors, alarm and automatic sprinklers covering the total space of the building.

The alternative fire protection measures will provide different fire safety levels or, alternatively, different levels of fire risk. In the present case study, this risk will be expressed by FSES fire risk index (e.g., SFPE 2002: 5-129).

3.3.2. Calculation of fire risk index

The FSES fire risk index was used to specify fire safety related attributes which will be included into the decision making matrix. The FSES fire risk index is expressed through fire safety variables $S_k(\mathbf{x}_{1i})$ and fire risk variables $R_k(\mathbf{x}_{2i})$. They appear in the expression of the index denoted by $I_{FSES}(\mathbf{x}_i)$ ($k = 1, 2, 3, 4$) (Eqs. (2.1) and (2.2)). Four pairs $S_k(\mathbf{x}_{1i})$ and $R_k(\mathbf{x}_{2i})$ were calculated in Annex D for patient care department, therapy department and traumatology department. The differences $S_k(\mathbf{x}_{1i}) - R_k(\mathbf{x}_{2i})$ ($k = 1, 2, 3, 4$) can be used as four individual MCDM attributes (Eqs. (2.3)). However, the fourth safety variable $S_4(\mathbf{x}_{1i})$ depends on the values of the first three safety variables $S_k(\mathbf{x}_{1i})$ ($k = 1, 2, 3$) and so the fourth difference $S_4(\mathbf{x}_{1i}) - R_4(\mathbf{x}_{2i})$ is the most informative, integral measure of fire safety (FSES 1996). Therefore, the difference $S_4(\mathbf{x}_{1i}) - R_4(\mathbf{x}_{2i})$ was applied as an attribute characterizing each of the four alternatives a_i :

$$c_{i1} = S_4(\mathbf{x}_{1i}) - R_4(\mathbf{x}_{2i}) \quad (i = 1, 2, 3, 4) \quad (3.1)$$

The values c_{i1} calculated for each hospital department are summarized in Table 3.4. These values imply that the patient care department is the most critical in terms fire safety measured by FSES index.

Table 3.4. Differences between the general safety and occupancy risk, $S_4 - R_4$, calculated according to the FSES index for the alternative fire protection systems A to D and individual departments of the hospital

Fire safety related attributes	Patient care	Therapy	Traumatology
c_{11}	10.3	11.7	11.8
c_{21}	13.3	14.7	14.8
c_{31}	18.3	19.7	19.8
c_{41}	23.3	24.7	24.8

3.3.3. The multi-criteria decision making problem

The hospital administration selects five attributes $c_1, c_2, \dots, c_5$ for evaluating the fire safety systems. The fire safety is expressed quantitatively by the fire safety index I_{FSES} (attribute c_1). Values of this index are given in the first column of Table 3.4. As I_{FSES} does not take a direct account of possible fire damage to people and property, two additional attributes are introduced to express the fire system effectiveness: the expected number of victims, c_3 , and the relative estimate of the value of property damaged by fire despite or in consequence of protective system operation, c_4 . The values of c_3 and c_4 can be estimated by means of a coupled modelling of building evacuation and spread of fire in it (e.g., Hostikka *et al.*, 2007; Machado Tavares and Galea, 2009). The second attribute c_2 is economic one and takes into account the first budget requirements of each system. Finally, the desired smooth operation of the hospital building during the system installation is expressed by the attribute c_5 . Values of this attribute can be obtained by a detailed consideration of timing and technology of installation of fire protective measures.

Components of the initial MCDM decision making matrix **C** consisting of the values of the attributes $c_1, c_2, \dots, c_5$ are given in Table 3.5. The difference in significance of the attributes c_1 to c_5 is expressed by assigning the common weight of 0.5 to economy-related attributes c_2 and c_5 and the equal common weight 0.5 to the safety-related attributes c_1, c_3 and c_4 (the significance of economy is equated with significance of safety). A further division of these fifty-fifty weights is presented in Table 3.5 by the weights w_1 to w_5 . The relatively large weight of the safety index c_1 is due to the ability of this quantity

to reflect various factors influencing fire safety. The values of w_i ($i = 1, 2, \dots, 5$) were assigned subjectively. If necessary, a number of formal, albeit not fully subjectivity-free, methods can be used for specifying w_i (e.g., Triantaphyllou, 2000; Wong *et al.*, 2008ab; Zavadskas *et al.*, 2011).

Table 3.5. The transposed initial decision making matrix C^{-1} (shaded cells) composed for the choice among fire protection systems in a hospital

Attributes	Unit of measur. of c_i	Preference	Attribute weights, w_j	Alternative fire protection system			
				A	B	C	D
Fire safety index (FSES index), c_1	–	Max	0.25	10.3	13.3	18.3	23.3
Cost of system, c_2	LTL/m ²	Min	0.35	9.9	114	26.4	304
Probable number of victims, c_3	point	Min	0.15	4	2	1	0
Value of damaged property, c_4	%	Min	0.10	10	10	8.5	7
Operation impairment, c_5	week	Min	0.15	1	3	6	10

3.3.4. The result of multi-criteria decision making

The alternatives A to D were ranked by applying the MCDM methods developed in the game theory and described in Sec. 1.2.2 (criteria K_1 to K_6). All criteria were applied to the matrix of estimates, $\hat{C}$, obtained from the matrix of dimensionless attributes, $\bar{C}$, with the attribute weights w_j given in Table 3.5. The matrix $\bar{C}$ was computed with the vector-norm normalisation method expressed by Eq. (1.11a) in Sec. 1.2.1. A discussion on the choice of normalisation formulas is given by Brauers and Zavadskas (2007) as well as Zavadskas and Turskis (2008). Results of application of the criteria K_1 to K_6 are summarised in Table 3.6.

The alternative fire protection system B was preferred by the criteria K_1 and K_2 , whereas the system D was preferred by the criteria K_3 to K_6 . The alternative D was preferred by the largest number of criteria and therefore D can be considered as a final result a^* .

Table 3.6. Results of the selection among alternative fire protection systems for a hospital obtained with criteria of the game theory and vector-norm normalisation given by Eq. (1.11a)

MCDM criterion	Alternative fire protection measures			
	A	B	C	D
Wald's K_1	0.3038×10^{-1}	0.2483 ⁽³⁾	0.8101×10^{-1}	0
Savage's K_2	0.9024	0.5830	0.8518	0.8729
Bernoulli-Laplace's K_3	0.3685	0.3961	0.3615	0.5675
Hurwicz's $K_4^{(1)}$	0.7078×10^{-1}	0.7984×10^{-1}	0.8135×10^{-1}	0.1632
Bayes's K_5	0.2844	0.3780	0.3173	0.6613
Hodges-Lehman's $K_6^{(2)}$	0.1475	0.2076	0.1728	0.3307

⁽¹⁾ The weighting factor in the Hurwicz's criterion, λ , was assumed to be equal to 0.5 (the middle between the most optimistic and most pessimistic attitude), Sec. 1.2.2.

⁽²⁾ The confidence factor in the Hodges-Lehman's criterion, δ , was assumed to be equal to 0.5 (the middle between the greatest confidence and no confidence), Sec. 1.2.2.

⁽³⁾ The shaded cells indicate the best alternative a^* .

3.4. The selection of building for a nursing home

3.4.1. The selection problem

A state agency needs to find, within 6 months, a building for a nursing home. It seeks a location of 20–60 minutes from the city centre. It has also requirements for basic utilities which allow functioning of the nursing home and special building functions, such as suitable layout of rooms and availability of elevators or possibility to install them. The agency is also aware of fires in nursing homes which occurred in previous decades and had heavy death toll. Thus the high level of fire safety will limit the search along with the location and building function requirements. Having up to 6 months to occupy does not allow to construct a new building and the choice is to be made among existing buildings which can be retrofitted in terms of utility and, if necessary, fire safety.

First of all a state agency needs to estimate positive and negative characteristics of buildings in order to select the best building which is suitable for a nursing home. The agent has to evaluate criteria which characterise the alternative buildings. For example, initial building price, retrofitting cost, annual running cost, occupancy availability, layout, noise environment, accessibility, etc. The agent has to choose a building after a thorough analysis of the available variants.

While choosing a building not only its aesthetical view is important, but also building materials, from which it is built, the height, compactness and

functioning of its living quarters, fire safety, the security of the building, annual fuel expenditures, etc. The buildings under consideration are in Vilnius city. The variants of these buildings (three MCDM alternatives a_i) are presented in Fig. 3.7.



Alternative A (or a_1):
a building in
Pylimas street



Alternative B (or a_2):
a building in
Jeruzalė street



Alternative C (or a_3):
a building in
Kirtimai street

Fig. 3.7. Three alternative buildings for a nursing home

The first building is in Pylimas street in Senamiestis catchment. Its space is 780 m², its price is 6.9 mln. LTL. This building has two storeys, a basement and tooled loft. The approach road to the building is good. The building is masonry, restored in full in 2005. A system of modern ventilation and conditioning, fire safety systems are installed in the building. Sprinklers system, smoke detectors are equipped in the entire building. The height of rooms is 2.8 m. Two entrances are from the building and there is one evacuation exist. A floorboard is of ceramic tiles. The layout can be replaced. A kitchen, sanitarian units are on every floor.

The second building is in Jeruzalė street in Santariškės catchment. Its space is 1500 m², its price is 6.5 mln. LTL. This building has two storeys, a basement and tooled loft. The approach road to the building from all sides is good. The building is masonry, it is restored in full. A system of modern ventilation and conditioning, smoke detectors are installed, there are fire-extinguishers in the entire building. A height of rooms is 3 m. There are two entrances and three evacuation routes. A floorboard is of ceramic tiles in some rooms, whereas parquet floor is in other rooms. The layout can be replaced.

The third building is in Kirtimai street in Paneriai district. Its space is 1600 m², its price is 4.1 mln. LTL. This building is two storey and with a tooled loft. The approach road to the building from all sides is good. The building is masonry, it is restored in full too. A system of modern ventilation and conditioning and smoke detectors are installed in the entire building. The building is equipped with fire alarm; there are fire-extinguishers too. A height of rooms is 2.6 m. Two entrances are from the building and there are three

evacuations exist. A floorboard is of ceramic tiles in some rooms, whereas there is linoleum floor in other rooms. It is difficult to replace the layout as some walls have bearings. The building is near a pinery.

3.4.2. Values of fire risk index

The fire safety of the buildings under comparison will be quantified by the fire FRAME risk index denoted by $I_{FRAME,k}$ (Table 1.1). This index expresses the fire safety of a building and its occupants in a relatively comprehensive way. The index is calculated by Eq. (2.4) and compared with a tolerable risk level R . In this case study, the index $I_{FRAME,k}$ will be included into the decision making matrix as the attribute c_8 (safety of building and its content) and the attribute c_9 (safety of building occupants). The initial data used for the calculation of $I_{FRAME,k}$ for the alternatives buildings A, B, and C is given in Annex E. The same annex contains calculation of $I_{FRAME,k}$ for these alternatives. Table 3.7 presents intermediate results of the calculation, namely, values of the functions $P_k(\cdot)$, $A_k(\cdot)$ and $D_k(\cdot)$. This table contains also values of the tolerable risk R calculated for each of the alternatives and type of risk. The final result of the calculation is as follows: $c_{8A} = 0.22$, $c_{8B} = 0.23$ and $c_{8C} = 0.21$ as well as $c_{9A} = 0.72$, $c_{9B} = 1.32$ and $c_{9C} = 1.11$.

Table 3.7. Data obtained by calculating $I_{FRAME,k}$ of three nursing buildings

Alternatives	Risk for a building and its content				Risk for occupants			
	I_1	P_1	A_1	D_1	I_2	P_2	A_2	D_2
A	0.22	1.12	1.2	4.34	0.72	1.96	0.85	3.19
B	0.23	1.14	1.3	3.83	1.32	2.11	0.85	1.89
C	0.21	0.91	1.15	3.64	1.11	1.62	0.75	1.962

The results suggest that the risk to all three buildings and their content is acceptable. The risk to occupants is acceptable only for the alternative A. A sprinkler system and/or fire alarm may be necessary to install. This will allow to increase the protection level $D_k(\cdot)$ and so to decrease the value of $I_{FRAME,k}$.

3.4.3. The initial decision making matrix

An MCDM analysis can help the agency to choose the building by taking into account ten attributes $c_1, c_2, \dots, c_{10}$ explained and evaluated in the transposed initial decision making matrix C^{-1} shown in Table 3.8. These attributes are grouped in three classes I to III listed above. As the fire safety plays an

important role in the exploitation of a nursing home, the largest common weight was assigned to class III attributes, whereas the common weights assigned to class I and class II attributes were equal to 0.25. The weights subjectively assigned to individual attributes, w_i , are given in Table 3.8.

Table 3.8. The transposed initial decision making matrix C^{-1} (shaded cells) used for the choice of a building for a nursing home

Criteria		Unit of measur. of a_i	Preference	Attribute weights, w_j	Alternative building (Fig. 3.7)		
					A	B	C
Economy (attribute class I)	Initial building price, c_1	LTL	Max	0.1	6.9	6.5	4.1
	Retrofitting cost, c_2	LTL	Min	0.1	0.5	0.8	0.965
	Annual running cost, c_3	LTL	Min	0.05	0.1	0.15	0.09
Function (attribute class II)	Occupancy availability, c_4	months	Min	0.1	2	3	6
	Layout, c_5	points ⁽¹⁾	Max	0.05	3	4	4
	Noise environment, c_6	points	Max	0.05	2	2	5
	Accessibility, c_7	points	Max	0.05	5	5	2
Fire safety (attribute class III)	Fire safety index $I_{FRAME, 1}$, c_8	—	Max	0.2	0.22	0.23	0.21
	Fire safety index $I_{FRAME, 2}$, c_9	—	Max	0.2	0.72	1.32	1.11
	Distance to fire station c_{10}	km	Min	0.1	1.33	3.23	8.05

⁽¹⁾ Points is a 5 points system: 1 = very bad, ..., 5 = very good

The numerical values of the economic attribute c_1 are taken from real-estate agency. The numerical values of the economic attributes c_2 and c_3 given in Table 3.8 are hypothetical ones and are used only as an example. The main fire related attributes c_8 and c_9 are the so-called FRAME's index denoted here by $I_{FRAME,k}$. Almost all fire risk indices are calculated as single (scalar) values and pretend to cover all fire consequences. The FRAME fire risk index is calculated in the form of two values, say, $I_{FRAME,1}(x_i)$ and $I_{FRAME,2}(x_i)$ which express fire risk

to a building and its content and occupants, respectively (FRAME 2008). Values of $I_{FRAME,k}$ are considered to be acceptable when they do not exceed 1.0. The attribute a_{10} is also related to fire safety. It was added as “auxiliary” measure of fire safety because the index $I_{FRAME,k}$ does not involve explicitly the distance to the nearest fire station.

3.4.4. The result of multi-criteria decision making

The alternatives A, B and C were compared by applying the MCDM methods developed in the game theory and described in Sec. 1.2.2 (criteria K_1 to K_6). All criteria were applied to the matrix of estimates, $\hat{C}$, obtained from the matrix of dimensionless attributes, $\bar{C}$, with the attribute weights w_j given in Table 3.8. The matrix $\bar{C}$ was computed with the vector-norm normalisation method expressed by Eq. (1.11a) in Sec. 1.2.1. Results of application of the criteria K_1 to K_6 are summarised in Table 3.9.

Table 3.9. Results of the choice among alternative buildings for a nursing home

MCDM criterion	A	B	C
Wald's K_1	0.1516	0.3482 ⁽³⁾	0.2722
Savage's K_2	0.7658	0.5493	0.4082
Bernoulli-Laplace's K_3	0.4431	0.5726	0.6245
Hurwicz's $K_4^{(1)}$	0.6527×10^{-1}	0.7933×10^{-1}	0.6620×10^{-1}
Bayes's K_5	0.4397	0.5837	0.6283
Hodges-Lehman's $K_6^{(2)}$	0.2274	0.3005	0.3209

⁽¹⁾ In the Hurwicz's criterion, $\lambda = 0.5$ (Sec. 1.2.2).

⁽²⁾ In the Hodges-Lehman's criterion, $\delta = 0.5$ (Sec. 1.2.2).

⁽³⁾ The shaded cells indicate the best alternative a^* .

The alternative building B was preferred by the criteria K_1 and K_4 , whereas the building C was preferred by the criteria K_2 , K_3 , K_5 and K_6 . The alternative C was preferred by the largest number of criteria and therefore C can be considered as a final result a^* .

3.5. The selection of a floor plan for a hospital unit with respect to life safety

3.5.1. The building and alternative floor plans

The present case study considers a two-storey wing of a hospital building in the Lithuanian town Kėdainiai (Fig. 3.8). The first floor of the wing accommodates a hemodialysis unit and the second floor is used for a catering department (Figs.

3.9 and 3.10). The two-storey building has a basement connected to the first and second floors by a freight elevator. The elevator is used for supplying kitchen with ingredients for patient meal production and distribution of meals served to patients in the medical units of the hospital. The doors to the elevator, ED_1 and ED_2 , are operated manually (Figs. 3.9 and 3.10).

Smoke detectors are installed in all rooms of the building. In case of fire, smoke detectors activate an alarm system. A ventilation system supplies fresh air to all rooms and removes used air through via metal ducts. The air is moved by fans which run constantly during the daytime. The fresh air supply fans are supposed to automatically shut down when the fire alarm is activated.



Fig. 3.8. A two-storey building considered in the multi-criteria decision making problem

A hospital administration is going to reconstruct the catering department and to open a canteen in the second floor. The canteen will take care of the food service needs for patients, employees and hospital visitors. The kitchen of the canteen will continue the catering service for the hospital. The administration wants to create the most functional and efficient floor plan for running the canteen. At the same time, the hospital administration knows that cooking is the leading cause of fires in healthcare facilities. The administration is aware of the dangerous proximity of the kitchen area to the medical units in the first floor and wants to take fire safety into consideration when making decisions concerning the floor plan of the canteen and kitchen.

Three new floor plans are considered in the design (Figs. 3.11 to 3.13). They differ in wall plans and the position of the potential room of fire initiation (the room with stoves and ovens). The three floor plans will constitute the alternatives of an MCDM problem:

- Alternative A: a floor plan with single-room seating area (66.1 m^2) and large service area (31.4 m^2) (Fig 3.11); a relatively large number of openings allowing a convenient movement of kitchen staff and products; the kitchen area is the smallest among the alternative floor plans (Table 3.10).
- Alternative B: two-room seating area (51.9 m^2 and 26.3 m^2), relatively small service area (11 m^2) (Fig 3.12); among the three alternative plans, the room of potential fire initiation in the plan B is at the largest distance from freight elevator, stairwell and hospital units in the first floor.
- Alternative C: two-room seating area (50 m^2 and 18 m^2), relatively small service area (12.3 m^2) (Fig 3.13); the room of potential fire initiation is relatively well isolated from other rooms by compartmentation; the kitchen area is the largest among the alternative floor plans (Table 3.10).

Table 3.10. Characteristics of the floor plans A, B, and C shown in the respective Figs. 3.11, 3.12 and 3.13 (the shaded rows indicate characteristics of the alternatives which will be used as MCDM attributes)

Floor plan characteristic	Alternative plan A	Alternative plan B	Alternative plan C
Seating area, m^2	66.1	78.2	68.0
Kitchen area, m^2	42.7	49.1	57.2
Service area, m^2	31.4	11.0	12.3
Sum of the above three areas, m^2	140	138	132
Floor reconstruction cost, thousands of LTL	458.0	298.5	315.6
Estimated reconstruction time, months	3.5	2.1	2.0

In terms of fire safety, the alternatives A, B and C can be characterised as follows:

- Alternative A: the floor plan with the least effective compartmentation; the room of potential fire initiation is in front of the freight elevator and relatively close to the stairwell; gaseous combustion products may flow

from the fire room to the inside through two horizontal vents (door D_{25} and delivery opening DO_1 , Fig. 3.11); in case of fire, the combustion products will first affect kitchen staff and then visitors of the canteen; the horizontal evacuation is possible through the escape routes ending with the doors D_{21} and $D_{2,12}$ (Figs. 3.10 and 3.11).

- Alternative B: the floor plan with the with the most remote position of the fire room with respect to the elevator and stairwell; an average compartmentation in comparison to the plans A and C; there are two horizontal vents for the flow of gaseous combustion products to the inside (the doors $D_{2,10}$ and $D_{2,11}$, Fig. 3.12); in case of fire, the staff in the fire room and visitors of the canteen will be affected first by combustion products; the horizontal evacuation is possible through the escape route ending with the door D_{21} , whereas the evacuation through $D_{2,12}$ can be problematic (Figs. 3.10 and 3.12).
- Alternative C: the floor plan with a relatively effective compartmentation with respect to the position of the fire room; gaseous combustion products may flow from the fire room to the inside only through the door D_{28} (Fig. 3.13); the possible paths of horizontal evacuation ending with the doors D_{21} and $D_{1,12}$ are similar to those in the plan A.

The alternatives A to C will differ in the economic sense and, to a certain degree, in the necessary operations of reconstruction. For instance, the floor plan A requires to provide a large opening in the load-bearing masonry wall for cabinet and cashier (Fig. 3.11). This opening will be 6 m wide and must be covered by a lintel with a relatively wide span. It is clear that construction of such an opening and lintel will increase the duration and cost of reconstruction works required by the floor plan A with respect to the plans B and C. On the other hand, the floor plans B and C will require to construct a larger number of partitions to form new rooms than the floor plan A.

The differences in the floor plans will lead to differences in the risk posed by potential fire to patients, medical staff and visitors of the canteen. A selection among the alternatives A to C must include an MCDM attribute which reflects the risk to lives of these three categories of occupants.

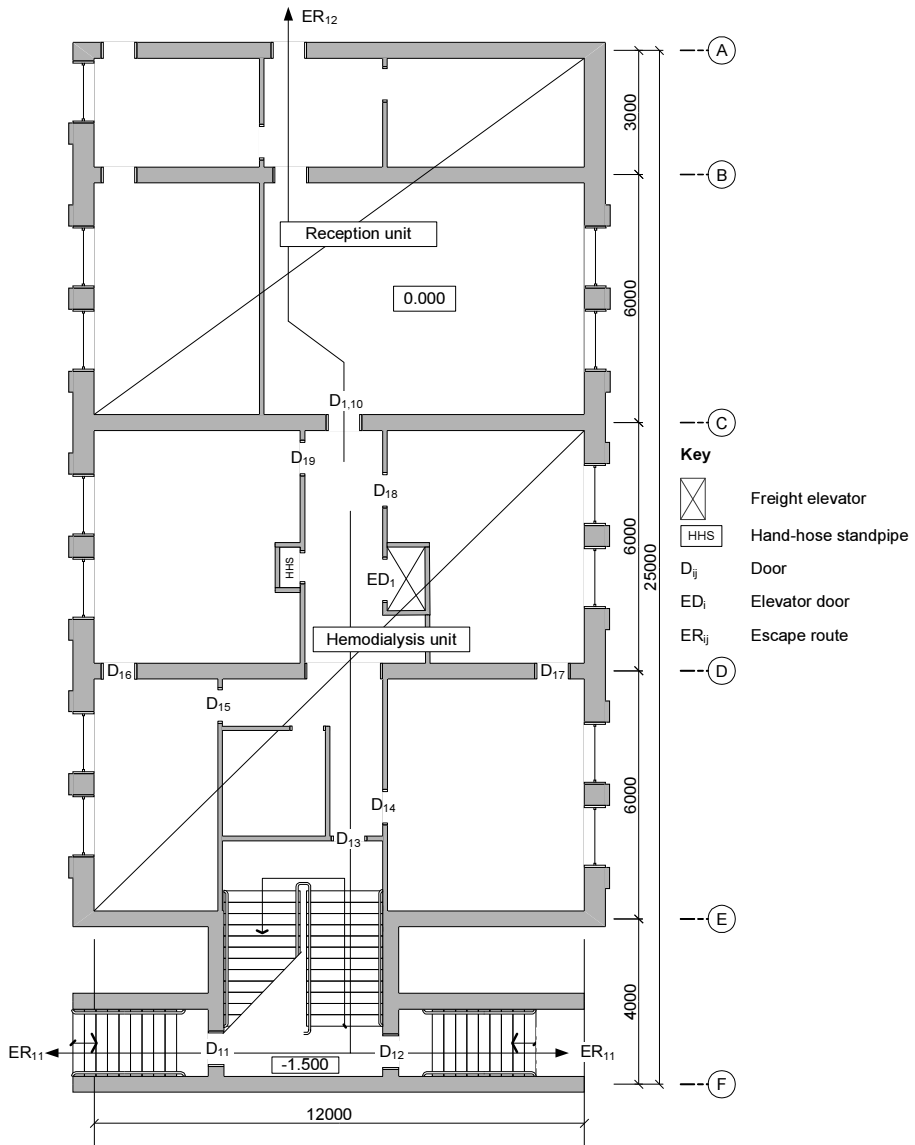


Fig. 3.9. Plan of the hemodialysis unit in the first floor of the building

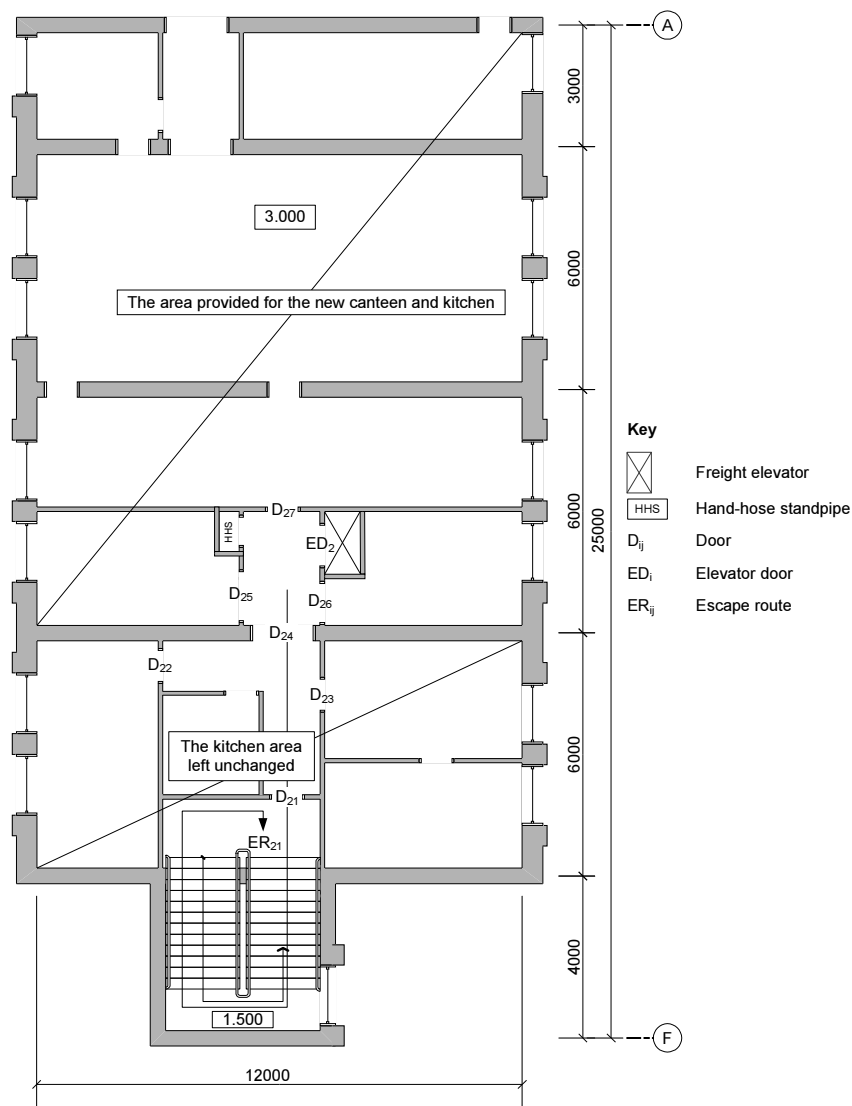


Fig. 3.10. Existing wall plan of the catering department in the second floor of the building

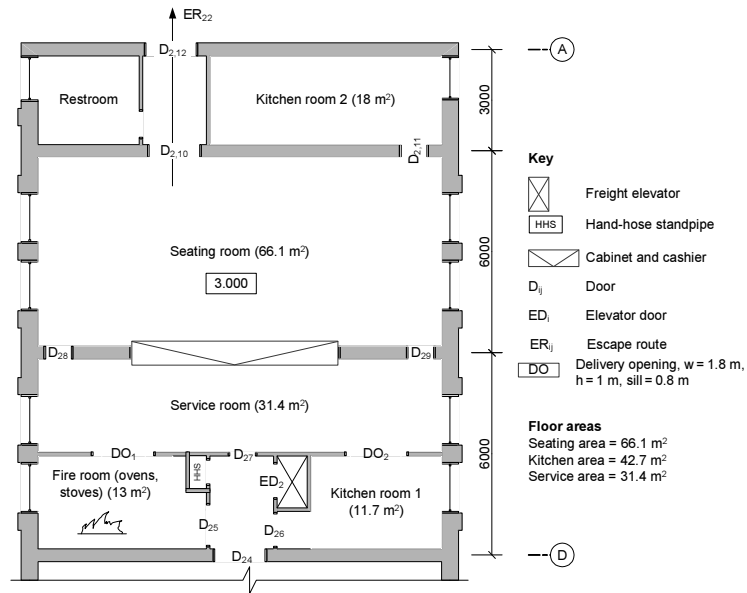


Fig. 3.11. New wall plan A for opening a canteen in the second floor of the hospital building (alternative A)

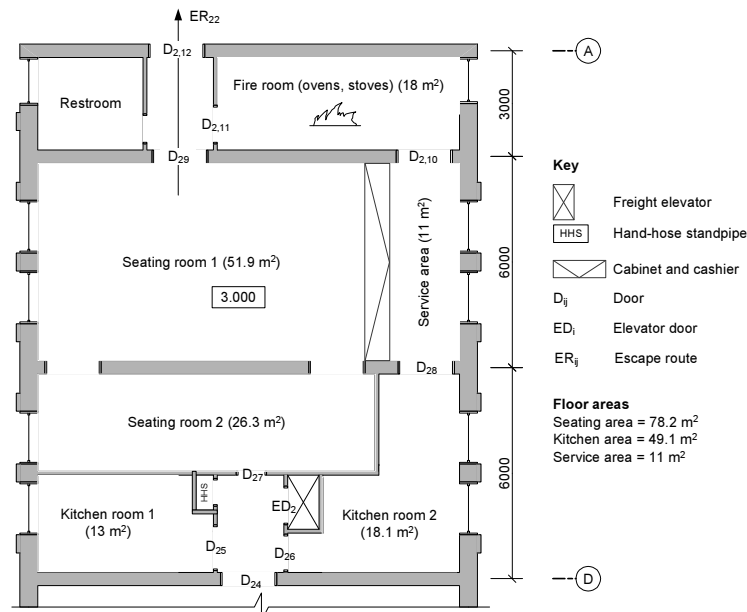


Fig. 3.12. New wall plan B for the canteen (alternative B)

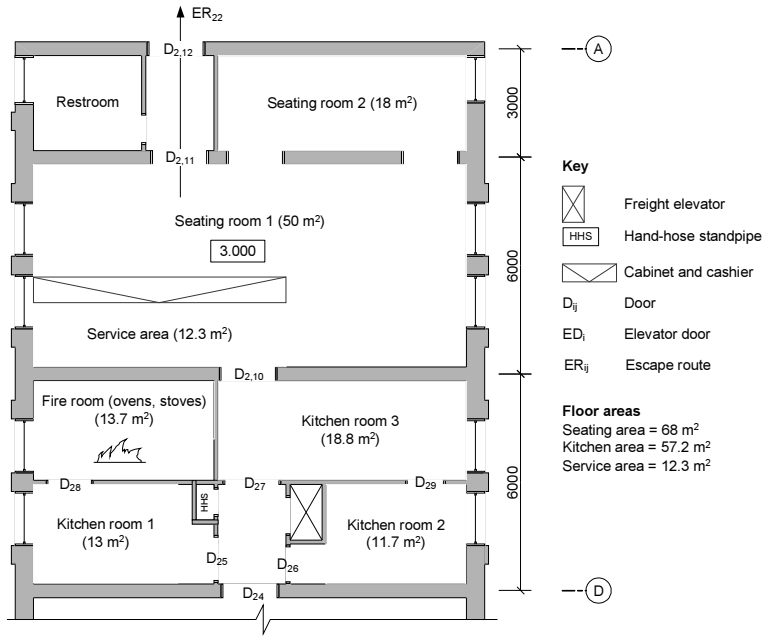


Fig. 3.13. New wall plan C for the canteen (alternative C)

3.5.2. Specification of attributes related to life safety

Candidate attributes

A probability of a successful evacuation from a building fire (P_{se} , say) can serve as the most informative MCDM attribute c_{ij} expressing the life safety. According to Rasbash *et al.* (2004: 184), this probability is given by

$$P_{se} = P(T_u \geq T_e) = P(T_u \geq T_d + T_r + T_{tr}) \quad (3.2)$$

where T_u is the time to untenable conditions (the time gaseous combustion products take to travel from the fire room and produce untenable conditions on an escape route); T_e is the total evacuation time (time to egress (SFPE 2002: 5-59)); T_d is the discovery time (the time period from ignition to discovery of a fire, known also as the perception time); T_r is the reaction time (the time period from fire discovery to the start of escape action, known also as action or recognition time or gathering phase); T_{tr} is the travel time (the time taken to move to the place of safety). Needless to say, the times in Eq. (3.2) are always subject to uncertainties and must be modelled as random variables. The chance

of fire injuries will increase with the increasing duration of exposure to untenable conditions, expressed by the difference $T_e - T_u$.

The alternative floor plans A, B and C can be compared in terms of the probability P_{se} . However, this probability is relatively difficult to estimate and the estimation will involve information common to all three alternatives:

- The discovery time T_d may be considered equal for all three alternatives (the existing part of the building is and new part will be equipped with automatic detectors and alarm which reduce T_d to approximately one minute in the whole building, see Rasbash *et al.* (2004: 185) and Ramachandran (1998: 71)).
- The reaction time T_r may also be assumed to be equal for all three alternatives because the types and numbers of occupants (hemodialysis patients, medical staff, kitchen staff as well as visitors of canteen and reception unit) will not depend on the wall plans in individual alternatives.
- The time needed to egress the hemodialysis unit, T_{irs} , may be considered equal for all three alternatives because different floor plans in the second floor will not influence possibilities of escape from this unit.

The alternative floor plans will create different possibilities for gaseous combustion products to travel horizontally through the second floor and to leak into the hemodialysis unit. This may cause differences in the time to untenable conditions on potential escape routes, T_u in both floors. The different wall plans and position of fire room will also provide different routes of evacuation and so differences in the travel times T_{ir} related to the individual alternatives. The idea was to compare the alternative floor plans by using the times T_u and T_{ir} and not the probabilities of a successful evacuation, P_{se} .

The time to the production of untenable conditions in the hemodialysis unit (T_{u1} , say) can be taken as a candidate MCDM attribute related to the live safety of hemodialysis patients because the total time of evacuation from this unit, T_e , may be considered the same for all three alternatives:

$$c_{ij} = T_{u,i1} \quad (i = 1, 2, 3) \quad (3.3)$$

where the values of the subscript i refer to the alternatives A, B and C and the subscript "1" denotes the first floor.

The life safety of kitchen staff and visitor of the canteen will depend on times to untenable conditions (T_{u2} , say) and travel times (T_{ir2} , say) related to available escape routes. A candidate MCDM attribute expressing the life safety of occupants in the second floor can be expressed by the difference of T_{u2} and T_{ir2} :

$$c_{i,j+1} = T_{u,i2} - T_{tr,i2} \quad (i = 1, 2, 3) \quad (3.4)$$

where the subscript “2” refers to the second floor.

The times $T_{u,i1}$, $T_{u,i2}$ and $T_{tr,i2}$ depend on the development of fire and movement of occupants on the second floor. An estimation of probability distributions of these times will require to model a development of fire in the building under analysis. Consequently, a specification of an MCDM decision making matrix used in the present case study will include a computer fire simulation.

Initiation of fire

The fire is assumed to be initiated in the room used to operate stoves and ovens or, briefly, the fire room (Figs. 3.11 to 3.13). The fire will be initiated by an ignition of an electrical kitchen stove and a subsequent ignition of flue above the stove. The fire will be caused by a malfunction of a thermostat in the stove and ignition of a mixture of oil and grease in a tray.

The heat release rate (HRR) of the oil and grease pool fire may be assumed constant over the fire duration $(0, t_o)$, where the subscript “o” stands for “oil” (Karlson and Quintiere 2000: 34; Babrauskas 2002: 3-25). The constant HRR of this fire, $\dot{q}_o$, will be modelled by the expression

$$\dot{q}_o = \bar{q}_o + \xi_o \quad (3.5)$$

where $\bar{q}_o$ is the average value of $\dot{q}_o$ estimated with the data given in Fig. 3.14 and ξ_o is the random variable expressing stochastic uncertainty in values of $\dot{q}_o$. This uncertainty results from uncertainties in the variables mentioned in Fig. 3.14. For the purpose of fire simulation, the value of $\bar{q}_o$ was estimated to be equal to 605 kW and the probability distribution of ξ_o was assumed to be normal with the mean of 0 kW and variance of 1200 (kW)^2 . The duration of the pool fire, t_o , is assumed to be uncertain and modelled by the normal random variable T_o with the distribution $N(433 \text{ s}, 900 \text{ s}^2)$. Densities of the random variables ξ_o and T_o are illustrated in Fig 3.14.

The HRR of flue fire, which will be initiated by the pool fire of oil and grease at the time t_{f0} , will be simulated as a time history $\dot{q}_f(t)$ expressed by

$$\dot{q}_f(t) = \bar{q}_f(t) + \xi_f(t) \quad \text{with } t \in (t_{f0}, t_f) \quad (3.6)$$

where $\bar{q}_f(t)$ is the average value of $\dot{q}_f(t)$ and $\xi_f(t)$ is the random, “fluctuating part” of $\dot{q}_f(t)$ at the time t ; and $t_f - t_{f0}$ is the duration of the flue fire. For the purpose of a computer fire simulation, the continuous process $\dot{q}_f(t)$ was replaced by the set of random variables

$$\Xi_f = \{(\bar{q}_f(t_l) + \xi_f(t_l)), l = 1, 2, \dots, 17\} \quad (3.7)$$

where t_l are time moments obtained by assuming that the flue fire will last 400 s and dividing the fire duration $t_f - t_{f0}$ into 16 intervals, each lasting 25 seconds (Fig. 3.15); $\bar{q}_f(t_l)$ is the average HRR at the moment t_l ; and $\xi_f(t_l)$ is a normally distributed random variable with the mean 0 kW and standard deviation equal to $0.07 \times \bar{q}_f(t_l)$. The random variables $\xi_f(t_l)$ were assumed to be correlated and the correlation coefficients were calculated by means of the following model (Bottenbruch *et al.* 1989):

$$\rho_{lk} \equiv \rho(\xi_f(t_l), \xi_f(t_k)) = \exp\{-\kappa |t_l - t_k|\} \text{ with } \kappa = 0.02 \quad (3.8)$$

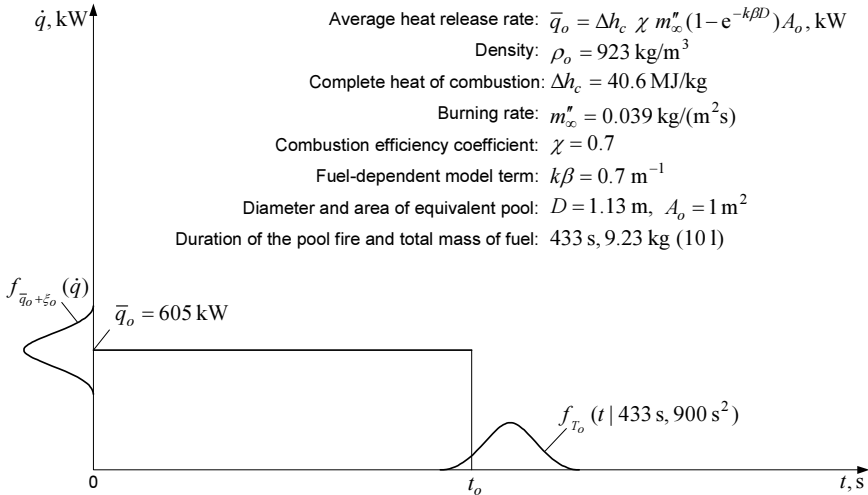


Fig. 3.14. Mathematical model of the heat release rate for the pool fire of oil and grease (the model of $\bar{q}_o$ was adopted from Karlson and Quintiere (2000: 34) and Babrauskas (2002: 3-25))

The discretisation of the fire duration (t_{f0} , t_f) follows from the measurement techniques of the so-called free burn experiments used to determination of the HRR values at given time moments t_l (e.g., Babrauskas 2002: 3-10). A certain number of individual time histories (signals) measured in repeated experiments allows to estimate the mean values $\bar{q}_f(t_l)$ at given t_l and to fit probability distributions of the random variables $\xi_f(t_l)$. Unfortunately, many authors carry out experiments which yield only one signal (realisation of $\dot{q}_f(t)$) and try to represent the time history $\dot{q}_f(t)$ by a deterministic model known also as a design

fire (e.g., Karlson and Quintiere 2000: 39; Kim and Lilley 2000; Mouritz *et al.* 2006).

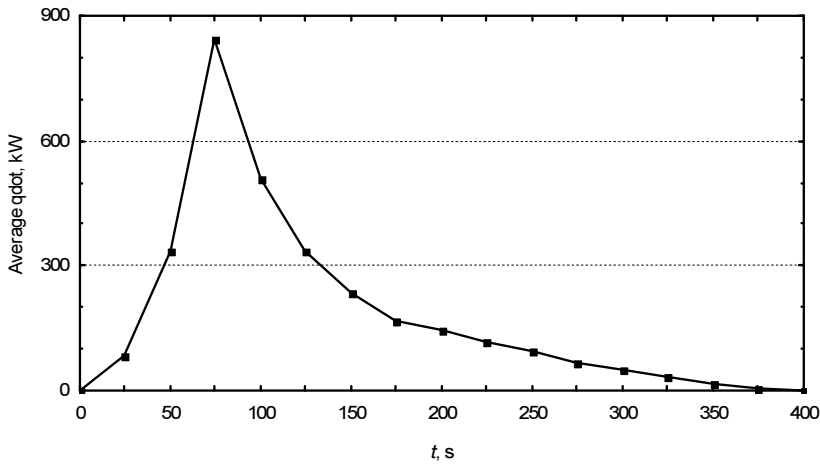


Fig. 3.15. Time history of the average heat release rate of the flue fire, $\bar{q}_f(t_l)$, drawn for $t_{f0} = 0$ s and $t_f = 400$ s

The stove and flue fire will spread to a set of cupboards in the surrounding of the stove. The cupboards will ignite when the upper gas layer reaches the temperature of 200°C. The HRR history of the cupboards was modelled similarly to the one of the flue fire, that is, by a set of random variables

$$\Xi_c = \{(\bar{q}_c(t_l) + \xi_c(t_l)), l = 1, 2, \dots, 17\} \quad (3.9)$$

where the subscript “c” stands for “cupboard”, $\bar{q}_c(t_l)$ is a mean values of HRR at the moment t_l and $\xi_c(t_l)$ is the “fluctuating” part of HRR at t_l . The sequence of the mean values $\bar{q}_c(t_l)$ was adopted from Peacock *et al.* (2005) and is shown in Fig. (3.16). The duration of the cupboard fire is assumed to be equal to 800 s and thus $t_1 = 0$ s, $t_{17} = 800$ s and $t_{i+1} - t_i = 50$ s (Fig. 3.16). The fluctuating parts $\xi_c(t_l)$ were modelled as correlated random variables with mean values equal to 0 kW and standard deviations equal to $0.05 \times \bar{q}_c(t_l)$. The coefficients of correlation $\rho(\xi_c(t_l), \xi_c(t_k))$ were calculated with the model given by Eq. (3.8) with $\kappa = 0.01$.

The window in the kitchen room is assumed to break when the temperature reaches a sufficiently high temperature. Previous fire simulations used deterministic values to express this temperature as well as the percentage of broken window area (Frantzich 1997: 30; Olsson 1999: 35; Hietaniemi 2007). In the present study, the breaking temperature and fraction of broken glass area will

be modelled by two respective random variables ξ_{wt} and ξ_{wa} . The following probability distributions were assumed for these variables:

$$\xi_{wt} \sim N(250^{\circ}\text{C}, 155(^{\circ}\text{C})^2) \text{ (normal distribution)} \quad (3.10a)$$

$$\xi_{wa} \sim \text{Be}(6, 21) \text{ (a beta distribution with the mode of 0.2)} \quad (3.10b)$$

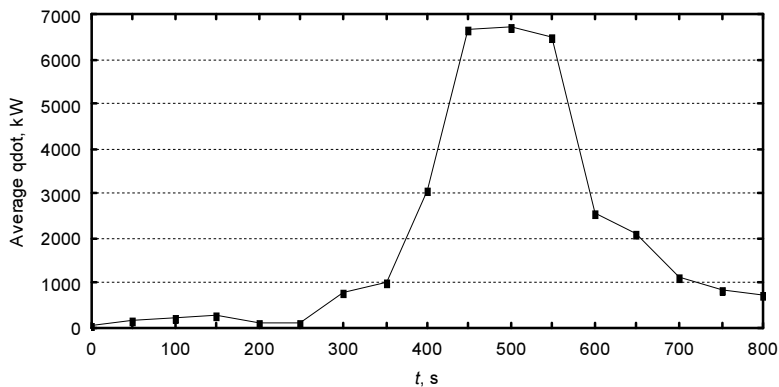


Fig. 3.16. A sequence of average heat release rates of the cupboard fire, $\bar{q}_c(t_i)$

The variables ξ_{wt} and ξ_{wa} are assumed to be uncorrelated because any data, which can substantiate presence or absence of a stochastic dependence between ξ_{wt} and ξ_{wa} is not known to us. Characteristics of the random variables ξ_{wt} and ξ_{wa} , along with ones of other random variables used in the problem, are summarised in Table 3.11.

The scenario of fire initiation is the same in all three alternatives. The position of stove and cupboards with respect to the window in the fire room is also assumed the same in all alternative floor plans.

Fire development and scenarios

Hemodialysis unit and catering department are operated only in the daytime and so lives of patients and staff can not be threatened if the fire will break out in the night time. If the fire breaks out, the people staying in the second floor will be threatened by

- Heat radiation,
- Toxic gases in the smoke and
- Impaired visibility which can complicate the evacuation.

Table 3.11. Probability distributions of the random variables used for the computer fire simulation in the hospital building considered in an MCDM problem

Variable	Symbol	Mean	Coeff. of var.	Distribution
The fluctuation of the oil fire HRR ⁽¹⁾ around the mean value $\bar{q}_o$ (Fig. 3.14)	ξ_o	605 kW	0.05	Normal
The random duration of oil fire (Fig. 3.14)	T_o	433 s	0.07	Normal
The fluctuation of the flue fire HRR ⁽¹⁾ around the mean value $\bar{q}_f(t_l)$ at t_l (Fig. 3.15)	$\xi_f(t_l)^{(3)}$	0 kW	0.07	Lognormal
The fluctuation of the cupboard fire HRR around the mean value $\bar{q}_c(t_l)$ at t_o (Fig. 3.16)	$\xi_c(t_o)^{(2)}$	0 kW	0.05	Lognormal
The temperature of wind glass breaking	ξ_{wt}	250°C	0.05	Normal
The fraction of the broken glass area	ξ_{wa}	0.222	0.354	Beta ⁽³⁾

⁽¹⁾ HRR = heat release rate

⁽²⁾ The variables $\xi_f(t_l)$ and $\xi_c(t_l)$ ($l = 1, 2, \dots, 17$) are assumed to be correlated with the correlation coefficients calculated by Eq. (3.8)

⁽³⁾ Beta distribution with the parameters 6 and 21 and the mode of 0.2

People staying in the first floor will be endangered by toxic combustion gasses, which can penetrate from the floor of fire origin into the rooms where patients and staff stay. The most relevant criterion of reaching untenable conditions is the smoke interface height (Olsson 1999: 35). In the present case study, this height is assumed to be equal to 2 m above the floor in all rooms of the building.

The combustion gasses can spread from the second floor to the first floor by two ways:

- Through the vertical shaft of the elevator if the elevator doors ED₁ and ED₂ are left open due to negligence or when the fire outbreaks during loading and unloading operations (Figs. 3.9 and 3.11 to 3.13), and
- Through the stairwell in the case that doors to the stairwell, D₂₁ and D₁₃, are open in both first and second floor (Figs. 3.9 and 3.10).

Leakage of combustion products between the second and first floors through other paths is considered to be negligible. The ventilation located in the first and second floors are not interconnected. In case of fire, these systems will be shut down by fire alarm.

Occupants in hemodialysis unit, kitchen and canteen have four escape routes:

1. Escape route ER_{11} (first floor, horizontal evacuation): from the hemodialysis unit to the stairwell through the door D_{13} and then to the outside through D_{11} and D_{12} (Fig. 3.9);
2. Escape route ER_{12} (first floor, horizontal evacuation): from the hemodialysis unit to the reception unit and then to the main building of the hospital (Fig. 3.9);
3. Escape route ER_{21} (second floor, horizontal and vertical evacuation): from the kitchen and canteen to the stairwell through the door D_{21} and then to the outside through D_{11} and D_{12} (Fig. 3.10);
4. Escape route ER_{22} (second floor, horizontal evacuation): from the kitchen and canteen to the main building of the hospital through the door $D_{2,12}$ (Figs. 3.11 to 3.13).

The evacuation process and spread of gaseous combustion products will be influenced by the status of doors and windows during the fire development. The consideration of whether individual doors and windows will be partially or fully open or closed, and, if closed, locked or unlocked will generate a relatively large number scenarios of spread of combustion products and certain number of scenarios of escape from fire. These scenarios are usually represented by event tree diagrams (Frantzich 1997: 46; Olson 1999: B-1). An event tree path ends with outcomes (consequences) denoted in this work by o_{ir} , where r is the number of the fire scenario and i relates o_{ir} to the alternative a_i (Sec. 1.1.2). The event o_{ir} can mean any damage to occupants or property caused by fire. In the context of the present case study, the event o_{ir} means an unsuccessful evacuation and therefore the probability o_{ir} can be expressed as

$$P(o_{ir} | \text{fire}) = P(T_{uir} < T_{eir}) \quad (3.11)$$

where T_{uir} and T_{eir} is the random time to untenable conditions and evacuation time in the fire r occurring in the building a_i , respectively. In the logic of an event tree modelling, the events o_{ir} ($r = 1, 2, \dots, n_i$) are mutually exclusive and the probabilities $P(o_{ir} | \text{fire})$ are usually the lower the higher is the number of fire victims (severities s_{ir} of o_{ir}).

A comparison of the probabilities $P(o_{ir} | \text{fire})$ and corresponding severities s_{ir} within an MCDM problem is possible in the way described in Sec. 2.4.2. However, the inter-alternative comparison can be based only on the worst-case scenarios related to a_i , in which the spread of combustion products poses the highest risk to occupants. Such scenarios can be characterised by the attributes defined by Eqs. (3.3) and (3.4).

The fire scenarios will be specified by making the following assumptions concerning possible routes of travel of combustion products:

- i. The seepage of gaseous combustion products through closed doors and windows is negligible.
- ii. The windows will be closed during the fire unless the temperature in the rooms will be sufficiently high to break the windows.
- iii. The staff rooms 1 and 2 as well as the storeroom in the second floor are normally locked up during most of the daytime (Fig. 3.10). Personnel stay in the rooms 1 and 2 only a relatively short time at the beginning and end of the shift time. The storeroom is visited periodically; however, the duration of visits is short.
- iv. The doors D_{24} , D_{25} , D_{26} and D_{27} in the kitchen are normally fully open during the daytime (Figs. 3.11 to 3.13).
- v. In the plan A, the doors D_{28} , D_{29} and $D_{2,11}$ are kept close during the normal operation of the canteen (Fig. 3.11). However, they will be left fully open in the course of evacuation.
- vi. In the plan B, the doors D_{28} and $D_{2,10}$ are kept open during the daytime and the door $D_{2,11}$ is normally kept locked up due to security reasons (Fig. 3.12). It is very probable that this door will be locked up also in the course of fire.
- vii. In the plan C, the doors D_{28} , D_{29} and $D_{2,10}$ are normally kept open during the operation of kitchen and canteen (Fig. 3.13).
- viii. The pairs of the doors at the end of the escape route ER_{22} are spring doors ($D_{2,11}$ and $D_{2,12}$ in Figs. 3.11 and 3.13, D_{29} and $D_{2,12}$ in Fig. 3.12). They will automatically close after evacuees pass them.
- ix. The doors to the stairwell, D_{13} and D_{21} , as well as the doors to the outside, D_{11} and D_{12} , are spring doors (Figs. 3.9 and 3.10). It is highly probable that they will automatically close after evacuees pass them and nobody will fix them open.

Two fire scenarios leading to a maximum growth in combustion product concentration (toxicity and limitation of visibility) in the first and second floor will be considered. In both scenarios it is conservatively assumed that the door to fire room will be left open after kitchen staff escapes the room or, alternatively, this door will not be closed from outside when the fire breaks out and nobody is inside the fire room. Such a situation will contribute to a decrease of the times to untenable conditions, $T_{u,i1}$ and $T_{u,i2}$, and, possibly, to an increase of the travel times $T_{tr,i2}$ related to the aforementioned escape routes ER_{11} to ER_{22} .

In the first scenario the fire is confined to the second floor because the elevator door ED_2 and the door to the stairwell, D_{21} , are closed (Fig. 3.10). This fire scenario involves different event sequences for the alternative floor plans A, B and C:

- Alternative A: the staff rooms 1 and 2 and the storeroom are unoccupied when the fire outbreaks (Fig. 3.10); the combustion products will block the escape route ER_{21} in a relatively short time and the evacuation will occur through the escape route ER_{22} (Fig. 3.11); the untenable conditions on ER_{22} will first be reached in the service room at the time $T_{u,12}$.
- Alternative B: untenable conditions on the escape route ER_{22} will be first reached in the room including service area and seating room at the time $T_{u,22}$ (Fig. 3.12). Evacuation of staff and visitors of the canteen will be possible through the escape route ER_{21} (Fig. 3.10).
- Alternative C: untenable conditions will be reached first in the fire room and kitchen room 1 (Fig. 3.13); however, the kitchen staff will leave these rooms relatively quickly; the kitchen room 2 can be evacuated through the kitchen room 3; consequently, the escape route ER_{22} will be blocked for kitchen staff staying in room 2 when the untenable conditions will occur in the kitchen room 3 at the time $T_{u,32}$; the evacuation of kitchen staff in the service area and visitors in the seating areas will be possible through the escape route ER_{22} .

In the second scenario, the combustion products will spread to the haemodialysis unit in the first floor through the shaft of the freight elevator. This scenario will take place when the elevator doors in the first and second floors, ED_1 and ED_2 , are left open in the course of fire (Figs. 3.9 and 3.10). The travel of the combustion products from the first to the second floor through the stairwell is considered to be small because the spring doors D_{13} and D_{21} close automatically after evacuees pass them. In the second scenario, the times to untenable conditions in the second floor will not be considered because the leakage through elevator shaft will decrease the concentrations of combustion products with respect to concentrations reached in the first scenario. The differences between the position of fire room in the alternatives A, B and C as well as in the wall plans of these alternatives will lead to different times to untenable conditions in the first floor, $T_{u,i1}$ ($i = 1, 2, 3$).

The times to untenable conditions $T_{u,i1}$ and $T_{u,i2}$ can be estimated by means of a computer fire simulation, the input information for which is generated by means of a stochastic simulation.

Developing probability distributions of the attributes

A specification of the MCDM attributes defined by Eqs (3.3) and (3.4) requires to estimate probability distributions of the random times to untenable conditions, $T_{u,i1}$ and $T_{u,i2}$, as well as probability distributions of the travel times $T_{lr,i2}$. Such estimation can be done by applying a computer simulation of fire and evacuation

processes. The input information for this computer simulation can be specified by means of a stochastic simulation.

The simulation of fire was carried out by means of the computer model CFAST for each of the alternatives A, B and C. CFAST implements the so-called two-zone fire model used to calculate gas temperatures in rooms, smoke interface height, heat transfer to potential victims and much more (Walton 2002: 3-189; Peacock *et al.* 2005). A visualisation of the CFAST model developed for the alternative A is given in Fig. 3.17. Further visualisations can be found in Annex F.

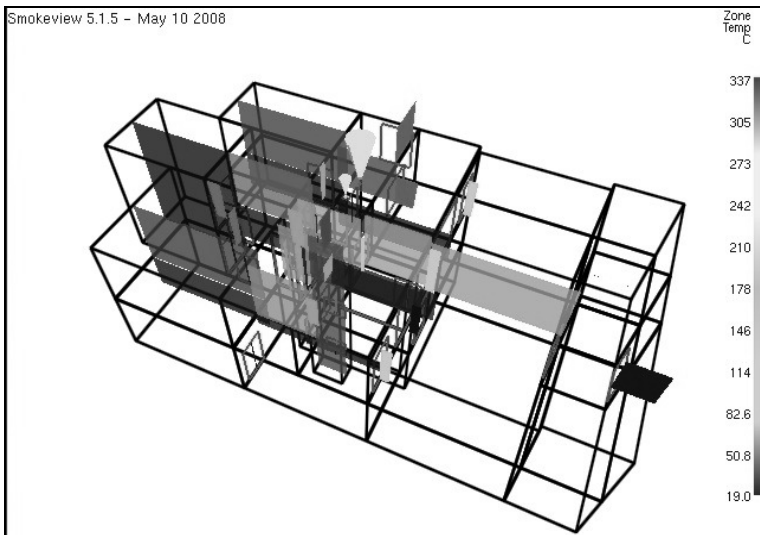


Fig. 3.17. A visualisation of the CFAST model developed for the second fire scenario and the alternative floor plan A (Fig. 3.11)

For each MCDM alternative, the fire simulation was carried out by embedding the CFAST algorithm in the loop of a stochastic simulation. The loop was repeated 100 times. The number of repetitions will be denoted by N_k (i.e., $N_k = 100$). The following four-step procedure was repeated each time (the k th time):

1. The values ξ_{ok} to $\xi_{wa,k}$ of the random variables ξ_o to ξ_{wa} summarised in Table 3.11 were generated by means of a stochastic simulation.

2. The k th value of the heat release rate of the pool fire, $\dot{q}_{ok} = \bar{q}_o + \xi_{ok}$, was calculated and the pool fire with constant HRR $\dot{q}_{ok}$ and duration t_{ok} was uploaded into the CFAST model.
3. The k th values Ξ_{fk} and Ξ_{ck} of the HRR histories Ξ_f and Ξ_c defined by Eqs. (3.7) and (3.9) were computed and uploaded into the CFAST model. These values were composed of the respective sums $\bar{q}_f(t_l) + \xi_{fk}(t_l)$ and $\bar{q}_c(t_l) + \xi_{ck}(t_l)$ ($l = 1, 2, \dots, 17$). The flue fire succeeded the pool fire after the time $t_{f0} = 50$ s.
4. The computer fire simulation was carried out with the input information specified as indicated above and the k th values of the times to untenable conditions, $T_{u,i1}$ or $T_{u,i2}$, were obtained from the output information of CFAST. These times will be denoted by $t_{u,i1k}$ or $t_{u,i2k}$.

The fire simulation was repeated 100 times for the first fire scenario, in which the fire is initiated in the second floor and can spread to the first floor. This simulation produced three samples of the random times to untenable conditions, $T_{u,i1}$ ($i = 1, 2, 3$). The samples are denoted by the symbols τ_{11} , τ_{21} and τ_{31} given in Table 3.12 and presented in Table G.1 given in Annex G. These samples were used to fit the probability distributions of the respective random variables $T_{u,i1}$ ($i = 1, 2, 3$) used as MCDM attributes and expressed by Eq. (3.3). Results of the distribution fitting are given in Table 3.13.

Table 3.12. Simulated samples of the times to untenable conditions

Random time	Simulated sample*	Escape route blocked by smoke	Available escape route
Alternative A, Fig. 3.11 ($i = 1$)			
$T_{u,11}$	$\tau_{11} = \{t_{u,11k}, k = 1, 2, \dots, N_k\}^{**}$	ER ₁₂ , Fig. 3.9	ER ₁₁ , Fig. 3.9
$T_{u,12}$	$\tau_{12} = \{t_{u,12k}, k = 1, 2, \dots, N_k\}$	ER ₂₁ , Fig. 3.10	ER ₂₂ , Fig. 3.11
Alternative B, Fig. 3.12 ($i = 2$)			
$T_{u,21}$	$\tau_{21} = \{t_{u,21k}, k = 1, 2, \dots, N_k\}$	ER ₁₂ , Fig. 3.9	ER ₁₁ , Fig. 3.9
$T_{u,22}$	$\tau_{22} = \{t_{u,22k}, k = 1, 2, \dots, N_k\}$	ER ₂₂ , Fig. 3.12	ER ₂₁ , Fig. 3.10
Alternative C, Fig. 3.13 ($i = 3$)			
$T_{u,31}$	$\tau_{31} = \{t_{u,31k}, k = 1, 2, \dots, N_k\}$	ER ₁₂ , Fig. 3.9	ER ₁₁ , Fig. 3.9
$T_{u,32}$	$\tau_{32} = \{t_{u,32k}, k = 1, 2, \dots, N_k\}$	ER ₂₁ , Fig. 3.10	ER ₂₂ , Fig. 3.13

* Sample elements $t_{u,i2k}$ ($i = 1, 2, 3$) are values of the respective random times $T_{u,i2}$
 ** $N_k = 100$ in all computer fire simulations

Then the fire simulation was repeated again 100 times for the second fire scenario, in which the fire is confined to the second floor. The three samples of the random times to untenable conditions, $T_{u,i2}$ ($i = 1, 2, 3$), are denoted by the

respective symbols τ_{11} , τ_{21} and τ_{31} , given in Table 3.12. These samples are presented in Table G.2 given in Annex G. The samples τ_{11} , τ_{21} and τ_{31} were used to fit probability distributions for the random variables $T_{u,i2}$ ($i = 1, 2, 3$). The fitted distributions are described in Table 3.14. These variables appear in the MCDM attribute expressed by Eq. (3.4).

Table 3.13. Descriptive measures of the samples of the times to untenable $T_{u,i1}$ related to the first fire scenario and the three alternative floor plans in the hospital building under reconstruction ($i = 1, 2, 3$)

Sample statistic/distribution fitting results	Sample of $t_{u,11k}$	Sample of $t_{u,21k}$	Sample of $t_{u,31k}$
Sample size	100	100	100
Mean, s	126.3	236.1	57.5
Median, s	126.0	236.0	57.25
Coeff. of variation, %	2.02	1.66	4.26
Standardised skewness	3.66	1.17	2.34
Standardised kurtosis	2.19	0.37	1.75
Minimum, s	14.7	223.0	51.75
Maximum, s	29.0	245.0	65.75
KS-DN for normal distribution/ p-value	0.1015/0.2555	0.071/0.6938	0.0912/0.3805
KS-DN for lognormal distribution/p-value	0.1039/0.2306	0.0738/0.6471	0.0826/0.5156
KS-DN for Gumbel distribution/p-value	0.1584/0.0132	0.1179/0.1242	0.0886/0.4175
Fitted distribution	Normal	Normal	Lognormal
Estimate of the 1 st parameter*	123.33 (mean)	236.1 (mean)	4.05 (scale)
Estimate of the 2 nd parameter*	2.56 (std.dev.)	3.91 (std.dev.)	0.04 (shape)

* Parameter of the fitted distribution

The travel times $T_{ir,i2}$ were estimated by means of the computer model SIMULEX (e.g., Kuligowski and Peacock 2005). The computer simulation was repeated 100 times and produced three samples of $T_{ir,i2}$ values $\{t_{ir,i2k}, k = 1, 2, \dots, 100\}$ ($i = 1, 2, 3$). Elements of these samples, $t_{ir,i2k}$, were obtained with different simulated number of visitors in the canteen, ζ_{vk} . In addition, locations of visitors and kitchen staff were randomly distributed for each k and i . The random numbers of the visitors, ζ_{vk} , were sampled from a binomial distribution by assuming that the maximum number of seats in the canteen is equal to 30:

$$\zeta_v \sim B(0.3, 30) \text{ (binomial distribution with the mean of 9)} \quad (3.12)$$

Table 3.14. Descriptive measures of the samples of the times to untenable $T_{u,i2}$ related to the second fire scenario and the three alternative floor plans ($i=1, 2, 3$)

Sample statistic/distribution fitting results	Sample of $t_{u,12k}$	Sample of $t_{u,22k}$	Sample of $t_{u,32k}$
Sample size	100	100	100
Mean, s	143.09	123.63	74.03
Median, s	144	123	74
Coeff. of variation, %	3.98	4.33	3.51
Standardised skewness	0.19	2.03	1.01
Standardised kurtosis	-1.05	0.9	-0.55
Minimum, s	132.0	110.0	68.5
Maximum, s	156.0	139.0	80.5
KS-DN/p-value (normal distr.)	0.0914/0.3771	0.1125/0.1594	0.1075/0.1981
KS-DN/p-value (lognormal d.)	0.0979/0.2944	0.1038/0.2322	0.1008/0.2629
KS-DN/p-value (Gumbel distr.)	0.1294/0.0702	0.0868/0.4456	0.1314/0.0632
Fitted distribution	Normal	Gumbel	Lognormal
Estimate of the 1 st parameter*	143.09 (mean)	121.09 (mode)	4.30 (scale)
Estimate of the 2 nd parameter*	5.69 (std.dev.)	4.89 (scale)	0.04 (shape)

* Parameter of the fitted distribution

Table 3.15. Descriptive measures of the samples of travel times $T_{ir,i2}$ elapsed during the evacuation from the second floor ($i=1, 2, 3$)

Sample statistic/distribution fitting results	Sample of $t_{ir,12k}$	Sample of $t_{ir,22k}$	Sample of $t_{ir,32k}$
Sample size	100	100	100
Mean, s	19.72	18.47	22.0
Median, s	19.5	18.35	21.6
Coeff. of variation, %	0.134	0.18	0.14
Standardised skewness	3.6553	1.0029	0.6941
Standardised kurtosis	2.189	-1.721	-1.0195
Minimum, s	14.7	12.6	15.8
Maximum, s	29.0	25.7	28.9
KS-DN/p-value (normal distr.)	0.1118/0.1646	0.0631/0.8213	0.0658/0.7790
KS-DN/p-value (lognormal d.)	0.0890/0.4118	0.0650/0.7925	0.0516/0.9529
KS-DN/p-value (Gumbel distr.)	0.0687/0.7335	0.0744/0.6379	0.0723/0.6728
Fitted distribution	Gumbel	Normal	Lognormal
Estimate of the 1 st parameter*	18.51 (mode)	18.47 (mean)	3.08 (scale)
Estimate of the 2 nd parameter*	2.148 (scale)	3.32 (std.dev.)	0.14 (shape)

* Parameter of the fitted distribution

The probability mass function of the above distribution is shown in Fig. 3.18. In this simulation, the number of kitchen staff remained constant and equal to six persons in all simulations. The sample $\{\xi_{vk}, k = 1, 2, \dots, 100\}$ is

presented in Table H.1 given in Annex H. Fig. 3.19 shows the distribution of nine visitors ($\zeta_{vk} = 9$) in the canteen and six kitchen staff at the commencement of evacuation. Further visualisations of SIMULEX model are presented in Annex H.

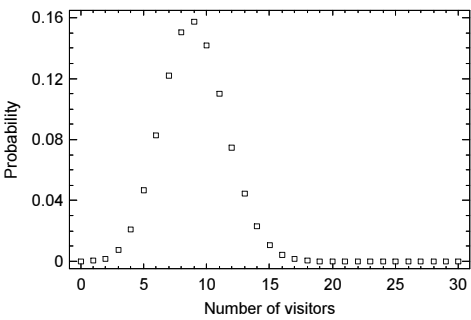


Fig. 3.18. Probability mass function of the binomial distribution $B(0.3, 30)$ used to model the number of visitors in the canteen, ζ_{vk} , at the start of fire

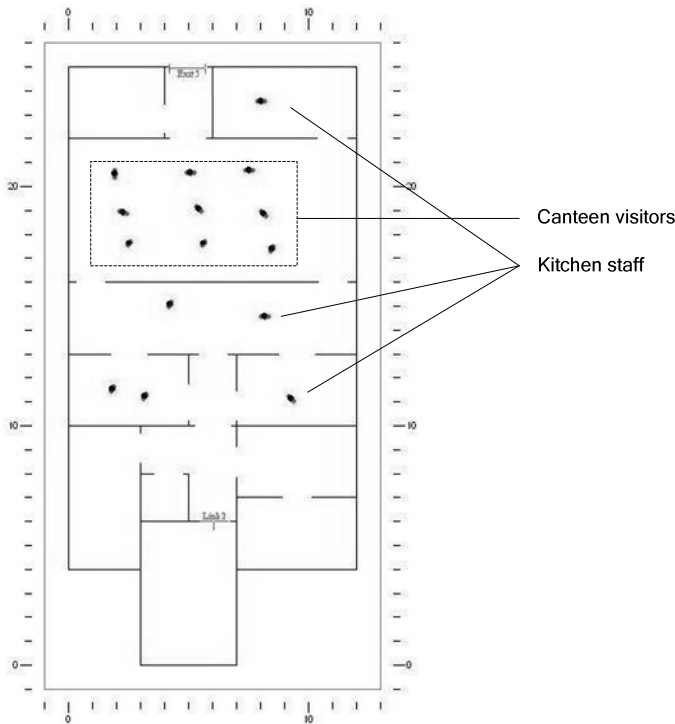


Fig. 3.19. Distribution of the kitchen staff and nine visitors of the canteen before commencement of evacuation in the floor A shown in Fig. 3.11 (SIMULEX model)

Descriptive measures of the samples $\{t_{ir,ik}, k = 1, 2, \dots, 100\}$ ($i = 1, 2, 3$) as well as probability distributions fitted to these samples are presented in Table 3.15.

3.5.3. The random decision making matrix used in the problem

An MCDM analysis was carried out by taking into account five attributes c_1 to c_5 explained in Table 3.16. The attributes related to the fire safety, c_1 and c_2 , were the respective random times $T_{u,i1}$ and $T_{ir,i2} - T_{u,i2}$, selected as MCDM attributes at the beginning of Sec. 3.5.2 (see Eqs. (3.3) and (3.4)). Hereby, the Table 3.16 contains random and non-random components of the decision making matrix $\tilde{C}$. The kitchen area c_3 was included among the attributes because the kitchen will still perform the catering function in the hospital even after the reconstruction of the second floor. The larger is the kitchen area the better conditions will be to perform this function. Floor reconstruction cost c_4 and estimated reconstruction time c_5 are natural attributes of a building-related MCDM and they do not need further explanation. The weights w_j given in Table 3.16 mean that the greatest significance was assigned to the attributes associated with the life safety ($w_1 + w_2 = 0.6$). The floor reconstruction cost is also among the significant attributes ($w_4 = 0.25$).

Table 3.16. The transposed random decision making matrix $\tilde{C}^{-1}$ (shaded cells) composed for the choice among the fire alternative floor plans in a hospital building shown in Figs. 3.11 to 3.13

Attributes	Unit of measur. of c_i	Preference	Attribute weights, w_j	Alternative floor plan		
				A	B	C
Random time to untenable conditions, c_1	sec	Min	0.35	$T_{u,11}$	$T_{u,21}$	$T_{u,31}$
Random travel time minus random time to untenable conditions, c_2	sec	Max	0.25	$T_{u,12} - T_{ir,12}$	$T_{u,22} - T_{ir,22}$	$T_{u,32} - T_{ir,32}$
Kitchen area, c_3	m ²	Max	0.1	42.7	49.1	52.2
Floor reconstruction cost, c_4	thous. LTL	Min	0.25	458.0	298.5	315.6
Estimated reconstruction time, c_5	months	Min	0.05	3.5	2.1	2.0

3.5.4. The result of multi-criteria decision making

The alternatives A, B and C were ranked by applying the simulation-based procedure proposed in Sec. 2.4.2. The deterministic MCDM methods developed in the game theory and described in Sec. 1.2.2 (criteria K_1 to K_6) were embedded in the simulation loop. All criteria were applied to the matrix of estimates, $\hat{C}$, obtained from the matrix of dimensionless attributes, $\bar{C}$, with the attribute weights w_j given in Table 3.16. The matrix $\bar{C}$ was computed with the vector-norm normalisation method expressed by Eq. (1.11a) in Sec. 1.2.1.

A total of a million simulation steps were applied to propagate the stochastic uncertainty modelled by the times $T_{u,i1}$ and $T_{ir,i2} - T_{u,i2}$ ($N_l = 1 \times 10^6$). In the l th step, the criteria K_1 to K_6 were applied to find a^* by using the sampled decision making matrix $\tilde{C}_l$. The frequencies of choosing the alternatives A, B and C as the best ones, fr_A , fr_B and fr_C , are summarised in Table 3.17.

Table 3.17. Results of the choice among the alternative floor plans A, B and C designed for a hospital building and shown in Figs. 3.11 to 3.13

MCDM criterion	Frequency ⁽¹⁾ of choosing a_i as a^*		
	fr_A	fr_B	fr_C
Wald's criterion K_1	0.4639	0.5361	0
Savage's criterion K_2	0	1	0
Bernoulli-Laplace criterion's K_3	0.9988	0.1156×10^{-2}	0
Hurwicz's criterion K_4 ($\lambda = 0.5$)	0	1	0
Bayes's criterion K_5	0.331×10^{-3}	0.9997	0
Hodges-Lehman's criterion's ($\delta = 0.5$)	0.1827×10^{-1}	0.9817	0

⁽¹⁾ The frequencies fr_A , fr_B and fr_C were computed with $N_l = 1 \times 10^6$

The alternative floor plan B was preferred as a^* by the criteria K_1 and K_2 and K_4 to K_6 , whereas the floor plan A was preferred by the criterion K_3 . The alternative B was preferred by the largest number of criteria and therefore B can be considered as a final result a^* .

3.6. Third chapter conclusions

1. Healthcare facilities are prone to an increased fire risk. A management of this risk may require decision making concerning cost-effective fire safety systems to be installed in healthcare occupancies and selection of buildings for such occupancies with respect to quantitative measures of fire safety. An

architectural design of building floors for healthcare facilities may also evoke the problem of making decisions regarding the fire safety.

2. A fire safety system can be selected for a healthcare building in the framework of MCDM by expressing the fire safety level with the FSES fire risk index. This fire safety measure was developed specifically to healthcare occupancies and takes into account a wide range of factors influencing fire safety. In an MCDM problem, the FSES index can serve as a stand-alone attribute and can be juggled simultaneously with more traditional attributes, expressing economic and physical properties of the alternatives under comparison.
3. A selection among several existing buildings with the aim of establish a healthcare occupancy may be also accomplished MCDM which takes into account fire safety. The FRAME fire risk index can be used to quantify fire safety of buildings under comparison and can serve as one of the attributes in corresponding MCDM problem. The FRAME fire risk index is an upgrade of the so-called Gretener's index and reflects well the effectiveness of fire protection measures installed inside buildings.
4. A selection among several alternative architectural designs of a floor in a healthcare buildings can also be accomplished by means of MCDM. The fire safety measures can be introduced into an MCDM problem by assessing the risk to lives of patients and medical staff posed by the spread of combustion products through the rooms of the building. The risk to life can be expressed through the time to a formation of untenable conditions inside the building. This time can be assessed and used as a fire-related MCDM attribute by applying a computer fire simulation. The computer code CFAST implementing the zone model of fire simulation can be used for such an assessment.

General conclusions

1. An analysis of the scientific literature on methods of quantitative fire safety assessment and multi-attribute selection led to the conclusion that it is advisable to combine these methods for making decisions on built property, especially, buildings with increased fire risk. It was found that until now fire safety measures were only sporadically included into building-related multi-attribute decision making.

2. An analysis of possibilities of a quantitative fire safety assessment led to the conclusion that fire safety indices and fire risk profile can be applied as attributes of a building-related multi-attribute selection problem. A decision making matrix of this problem can also include other attributes related to fire safety, namely, the distance from the building to the fire brigade, the response time of fire department, the effectiveness of fire extinguishment by fire units, time to the creation of untenable conditions inside building caught on fire.

3. An investigation of how to expand the building-related multi-attribute selection with attributes quantifying fire safety produced the result that fire risk indices calculated by means of deterministic methods can be incorporated with relative ease into the decision making matrix of the selection problem. However, the fire risk indices can sometimes be insufficiently sensitive to differences between fire safety of buildings compared in the selection problem or differences among alternative fire safety systems of an individual building.

4. An analysis of a possible combination of fire risk assessment and multi-attribute selection led to the result that elements of fire risk profile can be used for specifying attributes of the selection problem. Expected significances of fire consequences can be applied as selection attributes. The expected significances can express monetary losses, number of victims, and the time of business interruption. A calculation of risk profile is relatively complicated and an incorporation of elements of this profile into the multi-attribute selection is advisable for buildings with increased fire risk.

5. An analysis of incorporating fire-related attributes into the multi-attribute selection led to the finding that elements of the decision making matrix containing such attributes can be random variables. They will be expressed by probability distributions quantifying aleatory and epistemic uncertainties in values of the fire-related attributes. The epistemic uncertainties will be characteristic of elements of fire risk profile, directly or indirectly included into the decision making matrix.

6. A method has been developed for solving the problem of multi-attribute selection with the decision making matrix, all or some elements of which are random variables. The main idea of the proposed method is to select the best alternative by applying stochastic simulation. The simulation is carried out by sampling realisations of the decision making matrix and solving the selection problem for each realisation by applying a conventional method of multi-attribute selection. The best alternative among ones considered in the problem is that with the highest frequency of selection in a simulation run.

7. A collection of data on fires in healthcare facilities led to the conclusion that these occupancies are prone to an increased fire risk. It was found that methods of a building-related multi-attribute selection can be applied to the choice among alternative buildings for establishing a specific medical institution, the selection of fire safety system for an individual healthcare building, the architectural decision making concerning the layout of medical buildings.

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ANNEXES

Annexes are given in the enclosed compact disc. They include textual information, computation results and computer code used for the implementation of the simulation-based multi-attribute selection method proposed in this dissertation. Annexes are arranged in eight sections entitled as follows:

Annex A. Input vectors of fire risk indices

Annex B. A brief look at the data on reliability of sprinklers used in conventional buildings

Annex C. Computer code MCS

Annex D. Calculations of the fire risk index for three departments of hospital building

Annex E. Calculations of the fire risk index for three nursing buildings

Annex F. Fire model outputs for alternative floor plans of a hospital building

Annex G. Statistical samples obtained by stochastic simulation and fire code

Annex H. Evacuation model outputs for alternative floor plans of a hospital under reconstruction

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Doctoral Dissertation

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