LEIDYKLA TECHNIKA

PROTECTING BUILT PROPERTY AGAINST FIRE DISASTERS: MULTI-ATTRIBUTE DECISION MAKING WITH RESPECT TO FIRE RISK

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Received 4 May 2010; accepted 12 July 2010

ABSTRACT. The protection of buildings against fire disasters may require a comparison of alternative fire safety designs. The fire safety solutions can be compared by means of a general methodology known as multi-attribute selection or multi-criteria decision making. The alternative fire designs can be described by a number of attributes which characterise each of the alternatives. Fire risk expressed in the general form used for the quantitative risk assessment is applied to compose the set of attributes of a multi-attribute selection problem. It is shown how to accomplish the multi-attribute selection in the presence of epistemic uncertainties in the elements of fire risk estimate. Epistemic probability distributions assigned to elements of fire risk are specified and propagated though models of the multi-attribute selection by means of Monte Carlo simulation. An example presented in the paper considers the choice among alternative systems of automatic fire sprinklers.

KEYWORDS: Multiattribute decision making (MCDM); Fire; Sprinklers; Risk; Risk index

1. INTRODUCTION

It is needless to say that fire is the main physical hazard threatening life and property in non-industrial and many industrial buildings. Although some buildings involve the potentiality of other disastrous accidents, for instance, explosions of domestic gas, failure of structural and mechanical components (e.g., due to earthquake actions or component faults in elevators) or stampedes during a crown panic, fire remains the dominating cause of disasters in buildings. Fire in an individual building is a low-probability event; however, fires occur frequently and destroy life and property in a population of buildings in any country. A review of general statistics on fire damage in different countries is provided, among others, by Ramachandran (1998) and Yung (2008).

Fires in non-industrial buildings exhibit the same feature as many industrial accidents if we look at their consequences. A fire with minor, limited consequences is much more likely to happen in a particular building than a major fire disaster. A common feature in a number of disasters in buildings is a sudden spread of fire from apparently small fire to one which is highly threatening and disastrous.

International Journal of Strategic Property Management
ISSN 1648-715X print / ISSN 1648-9179 online
http://www.ijspm.vgtu.lt
DOI: 10.3846/ijspm.2010.29

A review of fire disasters in public and office buildings is provided by Rasbash et al. (2004). Craighead (2009) describes major fires in high-rise office buildings. Taking a look at these accidents allows to notice that a major fire is an uncertain and complex phenomenon influenced by many random processes and factors and capable to happen under various scenarios with different consequences. This turns building fires to an ideal subject of quantitative risk assessment (QRA) (Yung, 2008; Hasofer et al., 2007; Meacham, 2002; Hoła, 2006, 2007, 2009, 2010). However, the management of fire risk on the basis of QRA results remains an exception in dwellings, offices and public buildings. In Europe, QRA and QRA-based managerial decisions are mandatory only in nuclear power plants and industrial facilities regulated by the Seveso II directive (e.g., Kirchsteiger et al., 1998). In the US, the national fire protection organisations produced guidelines for fire risk assessment; however, the assessment itself is not mandatory practice in this country, to the best of our knowledge (SFPE, 2006; NFPA, 2009).

The present paper considers how to apply the results of fire risk estimation by means of QRA to a decision-making in the field of fire safety. The main idea is to incorporate results of QRA into the framework of the formal decision-making methodology known as multi-attribute selection (MAS) or multi-criteria decision making (MCDM). It is shown that MAS will allow to compare alternative fire safety design by taking into account the fire risk associated with each of them.

2. METHODOLOGICAL BACKGROUND

2.1. Performance-based fire codes and fire risk

Although an 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 is conforming to building regulations 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 to an application of risk assessment for fire safety provision.

The prescriptive codes are still widely used in many countries, including the authors' country 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 brigade 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). The latter is widely denoted by the acronym QRA intro-

duced above. In other words, the performance-based approach is a risk-based one.

2.2. Optimisation tasks in fire safety design

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 possibilities to apply formal methods of optimisation to decision-making concerning 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).

The optimisation problems related to fire-safety design can be classified into two general types:

1. Determination of an optimum level of fire safety.
2. Search for an optimum combination of fire safety measures.

The determination of the optimum level of fire safety is expressed as a search for a fire protection strategy which yields the minimisation of total cost (Ramachandran, 2002). This task is based on classical problem of total cost minimisation (benefit maximisation) which is well known in the fields of reliability and risk management (e.g., Smith, 2005). The expression of the total cost includes the annual probability of fire occurrence; however, this problem is too "crude" because it doest not account for different fire scenarios which can end up in a variety consequences, direct and indirect ones.

The search for an optimum combination of fire safety measures can be formally expressed in the form of several problems of different generality:

a) The choice among alternative fire protection measures and their combinations using logical trees (e.g., a decision tree analysis) (e.g., Donegan, 2002);
b) The search for an optimal package of fire protection and insurance (Ramachandran, 1998);
c) Cost-benefit evaluation of fire safety measures (Brown, 2005; Butry et al., 2007);
d) Search for a best configuration of an individual fire safety system (e.g., Lai et al., 2010).

The problems just listed are amenable to mathematical formalisation in the form of tasks of single- and multi-objective optimisation as well as the tasks of MAS. The distinction between the multi-objective optimisation and MAS can be viewed as a distinction between decision problems with continuous and discrete decision space (e.g., Sakalauskas and Zavadskas 2009; Zavadskas and Vaidogas, 2009).

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 a MAS problem with relative ease. We think that the "marriage" of QRA and MAS can allow to make fire safety related decisions which implements the goals of performance-based and are based on formal tools of MAS.

3. MULTI-ATTRIBUTE SELECTION IN RISK-BASED FIRE SAFETY DESIGN

3.1. MAS problem and fire safety aspects

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

Data for solving a MAS problem is formulated as a $m \times n$ decision matrix:

$$\mathbf{C} = [\boldsymbol{c}_1, \dots, \boldsymbol{c}_i, \dots, \boldsymbol{c}_m]^{\mathrm{T}} \quad (1)$$

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 matrix $\bar{\mathbf{C}}$ is obtained from $\mathbf{C}$. The structure of $\bar{\mathbf{C}}$ is:

$$\bar{\mathbf{C}} = [\bar{\boldsymbol{c}}_1, \dots, \bar{\boldsymbol{c}}_i, \dots, \bar{\boldsymbol{c}}_m]^{\mathrm{T}} \quad (2)$$

where: $\bar{\boldsymbol{c}}_i = (\bar{c}_{i1}, \bar{c}_{i2}, \dots, \bar{c}_{ij}, \dots, \bar{c}_{in})$ (i = 1, 2, … , m) is the row-vector calculated by normalizing components of the corresponding $\boldsymbol{c}_i$. Most methods of MAS select a^* with the normalised $\bar{\mathbf{C}}$ and not the initial $\mathbf{C}$ (Triantaphyllou, 2000; Hwang and Yoon, 1981). Examples of normalization formulas used to obtain $\bar{c}_{ij}$ from c_{ij} are given by Vaidogas (2007), Vaidogas and Hayashi (2007), Liu (2009), Peldschus (2009), Urbanavičienė et al. (2009), Zavadskas et al. (2008).

The difference in significance of the attributes c_{ij} (i = 1, 2, … , m) is expressed by the vector of weights, $\boldsymbol{w} = (w_1, w_2, \dots, w_j, \dots, w_n)^{\mathrm{T}}$. Usually, the weights w_j are between 0 and 1 and add up to 1. If $\boldsymbol{w}$ 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 the literature for specifying w_j, both crisp and fuzzy (Hwang and Yoon, 1981; Triantaphyllou, 2000). These methods can be as informal as Delphi method or as formal as the eigenvector technique of the analytical hierarchy process (e.g., Donegan, 2002). An example of specifying w_j used for fire related decisions in the Edinburgh method developed for ranking fire safety attributes of buildings (Watts, 2002; Rasbash et al., 2004).

The key element of each MAS method is the criterion, according to which a_i are ranked and the best one, a^*, is selected (MAS criterion, in short). In this paper, criteria of several, say, n_k methods applied to selecting a^* will be denoted by the letters K_1, K_2, … , K_k, … , K_{n_k}. 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 MAS 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; Hoła and Schabowicz, 2010; Schabowicz and Hola, 2007).

The specification of $\boldsymbol{w}$, and the choice of K_k, together with the calculation of $\bar{\mathbf{C}}$ require to make subjective decisions. For instance, different MAS methods should be chosen for different decision-making situations by answering subjective questions (Hwang and Yoon, 1981). The subjectivity of MAS is a natural background for applying uncertain attributes c_{ij}. Uncertainty distributions widely used in QRA and expressing, in essence, a subjective degree of belief naturally match the subjective setting of MAS.

3.2. Alternative fire designs

In context of the fire design, the alternatives a_i can be alternative fire safety designs:

1. To install some fire protection measure(s) in a building or to retain it without any protection;
2. To install only one specific protection measure or a combination of 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).

The alternative fire safety designs listed above are related to active fire protection measures. However, alternative solutions can also be generated by considering also passive fire protection, such as alternative compartmentalisation or choosing among alternative walls, doors, structural members.

Alternative solutions of active and passive fire protection are amenable to a formal comparison within an MAS problem. Economic attributes and attributes expressing standard technical characteristics of fire protection measures can be a natural part of this problem. However, the MAS 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.

3.3. MAS attributes related to fire safety

The alternative solutions of active and passive fire protection can be compared within the decision tree analysis, in which they are called "safety strategies" or "courses of action" (Rasbash et al., 2004; Donegan, 2002; Ramachandran, 1998). The decision tree is the appropriate approach to use if the object is to identify the alternative a_i optimising a single attribute, say, c_{i1} (e.g., the most cost effective fire protection strategy identified by searching for minimum total annual cost). Thus the decision tree analysis can be considered a special, simplified case of MAS. However, 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}.

In our opinion, the attributes c_{ij} evaluating the alternatives a_i can be grouped into four categories:

I. Attributes expressing technical characteristics of fire safety measures (performance, effectiveness, reliability (availability), e.g., see the 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 accident, the attribute "reliability" mentioned in the first group can be included in this category.

Attributes of the 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 shouldn't 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 the 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 MAS 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 (see, e.g. Watts, 2002) for fire risk indices used by insurers). 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 MAS problem.

Attributes of the 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.

The following two approaches to quantifying fire risk of entire building are well-known in the field of fire safety:

- Fire risk indexing (e.g., Rasbash et al., 2004; Watts, 2002);
- Fire risk assessment carried out in line with QRA (see the references given in Introduction).

The two approaches can be viewed as methodological tools of the performance-based fire design. The difference between fire risk indexing and fire risk assessment resembles difference between traditional deterministic structural analysis and reliability-based one (Šakėnaitė and Vaidogas, 2010).

A fire risk index, say, $I(\boldsymbol{x}_i)$ fits naturally for a MAS attribute c_{ij}, that is, $c_{ij} \equiv I(\boldsymbol{x}_i)$. 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 (components of the vector $\boldsymbol{x}_i$). The characteristics are called "fire safety parameters or attributes", albeit the term "attribute" is not used in the sense of MAS (Rasbash et al., 2004; Watts and Solomon, 2002; Watts and Kaplan, 2001).

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, $I_1(\boldsymbol{x}_i)$, $I_2(\boldsymbol{x}_i)$ and $I_3(\boldsymbol{x}_i)$ which express fire risk to building and its content, occupants and business activities, respectively (FRAME, 2010). 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 MAS problem in the form of three separate attributes, for instance, $c_{ij} \equiv I_1(\boldsymbol{x}_i)$, $c_{i,j+1} \equiv I_2(\boldsymbol{x}_i)$) and $c_{i,j+2} \equiv I_3(\boldsymbol{x}_i)$.

Although fire risk indices $I(\boldsymbol{x}_i)$ are natural candidates to be used as MAS attributes c_{ij}, their use in the framework of MAS 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 $\boldsymbol{x}_i$) 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.

A systematic investigation of the indices $I(\boldsymbol{x}_i)$ differences in fire safety measures expressed in our case by the alternatives a_i is not known to us. Our finding is that the widely-known indices are either incapable or too rough to express subtle differences among fire safety measures represented by a_i (Šakėnaitė and Vaidogas, 2010).

Other problems with the use of indices are not MAS specific ones; however, these problems may reduce attractiveness of the indices $I(\boldsymbol{x}_i)$ to the use within MAS:

a) The indices $I(\boldsymbol{x}_i)$ 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 $I(\boldsymbol{x}_i)$ and input information possess high degree subjectivity; a specification of this information is not well documented;

e) The indices $I(\boldsymbol{x}_i)$ are generally "rigid" systems; they do not allow to take account of new developments in fire risk assessment.

We think that the listed shortcomings of the fire risk indices $I(\boldsymbol{x}_i)$ may limit their application to MAS. An alternative approach to fire risk indexing is a fire risk assessment in line with QRA. Results of QRA can be serve as MAS attributes related to fire safety.

4. INCORPORATING FIRE RISK MEASURES INTO MAS

4.1. Fire risk in decision 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 paper, 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). 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:

$$\boldsymbol{s}_{ir} = (s_{ir1}, s_{ir2}, \ldots, s_{irj}, \ldots, s_{irn}) \tag{3}$$

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

Fire risk related to $a_i \equiv$

$$\{(l_{ir}, o_{ir}, \boldsymbol{s}_{ir}), r = 1, 2, \ldots, n_i\} \tag{4}$$

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 an estimation are considered, among others, by Hall (2010), Hauptmanns et al. (2008), Nyyssönen et al. (2005), Rönty et al. (2004), Vaidogas (2003, 2006). In many cases the estimation of the failure probabilities will be a non-trivial task. Potential points of introduction of the alternative fire designs with different failure probabilities are shown in Figure 1.

The total number of the outcomes, n_i, may vary from alternative to alternative. The risk (4) may express fairly diverse information, especially when the severity of each o_{ir} is represented by more than one significance measure. The vectors $\boldsymbol{s}_{ir}$ ($r = 1, 2, \ldots, n_i$) can be grouped in the $n_i \times n$ matrix:

$$[\boldsymbol{s}_{i1}, \boldsymbol{s}_{i2}, \ldots, \boldsymbol{s}_{ir}, \ldots, \boldsymbol{s}_{in_i}]^{\mathrm{T}} \tag{5}$$

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 that are associated with ith alternative and apply this vector within MAS, namely,

$$\boldsymbol{c}_i = \left(\sum_{r=1}^{n_i} l_{ir} s_{ir1}, \sum_{r=1}^{n_i} l_{r_i} s_{ir2}, \ldots \right.$$
$$\left. \ldots, \sum_{r=1}^{n_i} l_{ir} s_{irj}, \ldots, \sum_{r=1}^{n_i} l_{ir} s_{irn} \right) \tag{6}$$

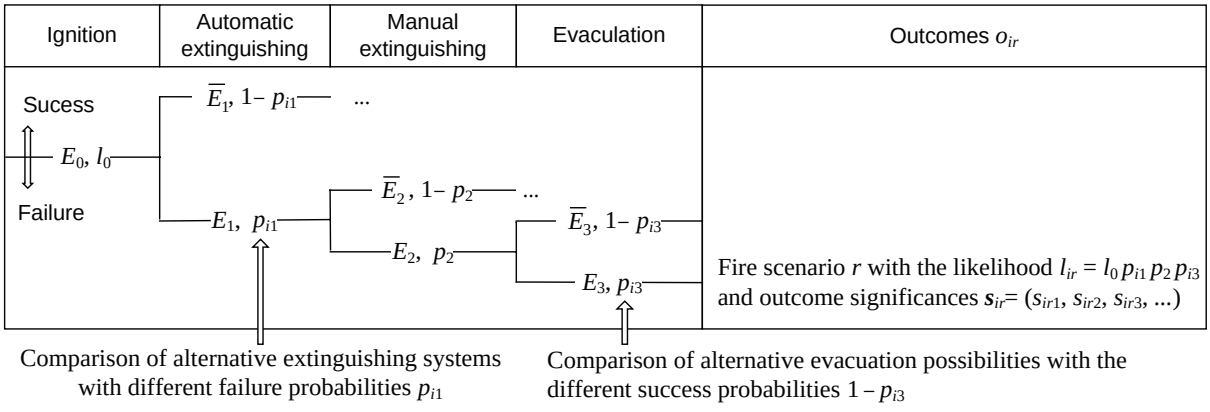

Figure 1. A fragment of an event tree diagram with the event tree path expressing the fire scenario *r*; the diagram shows also potential points of consideration of alternative fire design solutions within a QRA problem

In the case that the severity of each o_{ir} is represented by a single significance s_{ir} (vectors $\boldsymbol{s}_{ir}$ 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 MAS problem.

The expected significances in Eq. (6) contain the likelihoods l_{ir}, which in many cases can be estimated independently of the significances s_{irj} (e.g., Kumamoto and Henley, 1996). 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 $\overline{E}_b$, respectively (e.g., the event tree diagram in Figure 1 shows that $l_{ir} = l_0 p'_1 p'_2 p'_3$ and n_{br} = 3).

4.2. 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., Vaidogas 2009; Vaidogas and Juocevičius, 2008a, 2009; 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 MAS requires selecting a^* in the presence of uncertain components c_{ij} of **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 and fault trees (e.g., Figure 3) (Aven and Pörn, 1998; Vaurio and Jänkälä, 2006; Vaidogas and Juocevičius 2007, 2008b). 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 a MAS problem with stochastic attribute vectors:

$$\tilde{\boldsymbol{c}}_i = (\tilde{c}_{i1}, \tilde{c}_{i2}, \dots, \tilde{c}_{ij}, \dots, \tilde{c}_{in}) \tag{7}$$

Replacing $\boldsymbol{c}_i$ in the initial deterministic decision matrix $\mathbf{C}$ by $\tilde{\mathrm{c}}_i$ defined by either Eq. (1) will yield a stochastic decision matrix:

$$\tilde{\mathbf{C}} = [\tilde{\mathrm{c}}_1, \dots, \tilde{\mathrm{c}}_i, \dots, \tilde{\mathrm{c}}_m]^{\mathrm{T}} \tag{8}$$

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 MAS problem formulated in the form of $\tilde{\mathbf{C}}$ can be solved by applying the propagation of epistemic and, if necessary, aleatory uncertainties (Zavadskas and Vaidogas; 2009). The solution will consists in sampling values $\tilde{\mathbf{C}}_l$ of $\tilde{\mathbf{C}}$ by means of Monte Carlo simulation ($l = 1, 2, \dots, N_l$). The MAS problem can be solved and the best alternative can be chosen for each $\tilde{\mathbf{C}}_l$. The simulation will yield the frequencies of the selection of individual alternatives a_i as the best ones in N_l trials. Then the alternative with the highest frequency of selection can be chosen as a^*.

5. APPLICATION EXAMPLE

A sprinkler system among three alternative systems a_1, a_2, and a_3 is to be chosen. The alternatives a_1, a_2, and a_3 denote dry pipe, deluge and pre-action sprinklers, respectively (Table 1). The most appropriate one, a^*, will serve along with automatic fire detectors and alarm system as 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 Figure 2.

Table 1. 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 ~ 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	$\tilde{p}_1$ ~ Be(4, 58) with the mode of 0,05
	Sprinkler failure probability p_{fi2}
Dry pipe a_1	$\tilde{p}_{12}$ ~ Be(4; 55) (beta distribution)
Deluge a_2	$\tilde{p}_{22}$ ~ Be(4; 60)
Pre-action a_3	$\tilde{p}_{32}$ ~ Be(3; 30)
	Mode of the distribution of p_{fi2}
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	$c_{35} = 0.27$

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:

$$\mathrm{Risk}_i \equiv \{(l_{ir}, o_{ir}, \boldsymbol{s}_{ir}),\ r = 1, 2, 3, 4\} \tag{9}$$

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 $\boldsymbol{s}_{ir}$ is the vector of significances of o_{ir}.

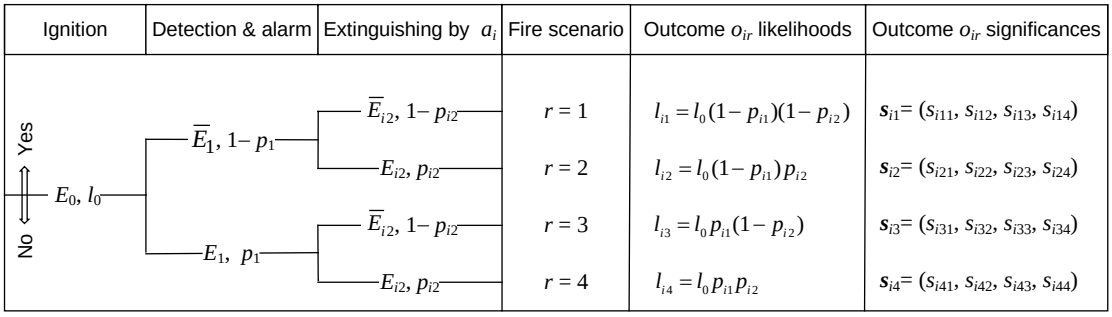

Figure 2. Simplified event tree diagram for a fire in a sprinklered building with a fire detection and alarm system

As shown in Figure 2, the vectors s_{ir} are expressed as $\boldsymbol{s}_{ir} = (s_{ir1}, s_{ir2}, s_{ir3}, s_{ir4})$, 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, $p_1 = P(E_1 \mid E_0)$; and
- The conditional probabilities that sprinklers a_i will fail given $E_0 \cap E_1$ or $E_0 \cap \overline{E}_1$, namely, $p_{i2} = P(E_{i2} \mid E_0 \cap E_1)$ (Figure 2).

The expression of the risk given by Eq. (9) will be used to form the attribute vector $\boldsymbol{c}_i = (c_{i1}, c_{i2}, c_{i3}, c_{i4}, c_{i5})$, 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 1).

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 1 (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 1:

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

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

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

$$L_{i4} = L_0\tilde{p}_1\,\tilde{p}_{i2} \tag{10}$$

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 $\tilde{\boldsymbol{s}}_{ir} = (\tilde{s}_{ir1}, \tilde{s}_{ir2}, \tilde{s}_{ir3}, \tilde{s}_{ir4})$. The property loss due to fire, $\tilde{s}_{ir1}$, obeys a lognormal distribution (Rasbash et al., 2004). 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. 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).

Table 2. Components of the random significance vectors $\tilde{s}_{ir}$ *

Dry pipe system a_1	
Vectors $\tilde{\boldsymbol{s}}_{1r}$ ($i = 1$; $r = 1, 2, 3, 4$)	The mean μ_{ir} and std. dev. σ_{ir} of $\tilde{s}_{ir1}$ (€th)
$\begin{bmatrix} \tilde{\boldsymbol{s}}_{11} \\ \tilde{\boldsymbol{s}}_{12} \\ \tilde{\boldsymbol{s}}_{13} \\ \tilde{\boldsymbol{s}}_{14} \end{bmatrix} = \begin{bmatrix} L(0.348, 0.198) & 0 & B(20, 0.01) & P(2.0) \\ L(1.637, 0.246) & B(20,0.10) & B(20,0.30) & P(17.0) \\ L(0.348, 0.198) & B(20,0.05) & B(20,0.15) & P(2.0) \\ L(1.778, 0.246) & B(20,0.25) & B(20,0.45) & P(19.0) \end{bmatrix}$	$\tilde{s}_{111}: \mu_{11} = 1.5, \sigma_{11} = 0.3$ $\tilde{s}_{121}: \mu_{12} = 5.3, \sigma_{12} = 1.325$ $\tilde{s}_{131}: \mu_{13} = 1.5, \sigma_{13} = 0.3$ $\tilde{s}_{141}: \mu_{14} = 6.1, \sigma_{14} = 1.525$
Deluge system a_2	
Vectors $\tilde{\boldsymbol{s}}_{2r}$ ($i = 2$; $r = 1, 2, 3, 4$)	The mean μ_{ir} and std. dev. σ_{ir} of $\tilde{s}_{ir1}$ (€th)
$\begin{bmatrix} \tilde{\boldsymbol{s}}_{21} \\ \tilde{\boldsymbol{s}}_{22} \\ \tilde{\boldsymbol{s}}_{23} \\ \tilde{\boldsymbol{s}}_{24} \end{bmatrix} = \begin{bmatrix} L(1.013, 0.601) & 0 & B(20, 0.01) & P(4.0) \\ L(1.637, 0.246) & B(20,0.10) & B(20,0.30) & P(17.0) \\ L(1.013, 0.601) & 0 & B(20,0.05) & P(4.0) \\ L(1.778, 0.246) & B(20,0.25) & B(20,0.45) & P(19.0) \end{bmatrix}$	$\tilde{s}_{211}: \mu_{21} = 3.3, \sigma_{21} = 0.66$ $\tilde{s}_{221}: \mu_{22} = 5.3, \sigma_{22} = 1.325$ $\tilde{s}_{231}: \mu_{23} = 3.3, \sigma_{23} = 0.66$ $\tilde{s}_{241}: \mu_{24} = 6.1, \sigma_{24} = 1.525$
Pre-action system a_3	
Vectors $\tilde{\boldsymbol{s}}_{3r}$ ($i = 3$; $r = 1, 2, 3, 4$)	The mean μ_{ir} and std. dev. σ_{ir} of $\tilde{s}_{ir1}$ (€th)
$\begin{bmatrix} \tilde{\boldsymbol{s}}_{31} \\ \tilde{\boldsymbol{s}}_{32} \\ \tilde{\boldsymbol{s}}_{33} \\ \tilde{\boldsymbol{s}}_{34} \end{bmatrix} = \begin{bmatrix} L(0.475, 0.331) & 0 & B(20, 0.01) & P(2.0) \\ L(1.637, 0.246) & B(20,0.10) & B(20,0.30) & P(17.0) \\ L(0.475, 0.331) & B(20,0.05) & B(20,0.15) & P(2.0) \\ L(1.778, 0.246) & B(20,0.25) & B(20,0.45) & P(19.0) \end{bmatrix}$	$\tilde{s}_{311}: \mu_{31} = 1.7, \sigma_{31} = 0.34$ $\tilde{s}_{321}: \mu_{32} = 5.3, \sigma_{32} = 1.325$ $\tilde{s}_{331}: \mu_{33} = 1.7, \sigma_{33} = 0.34$ $\tilde{s}_{341}: \mu_{34} = 6.1, \sigma_{34} = 1.525$

*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

Values of standard deviations of $\tilde{s}_{ir1}$ given in Table 2 were assumed hypothetically.

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), to 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. Figure 3 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. Figure 4 shows the probability mass function for the uncertain outage $\tilde{s}_{114} \sim P(\lambda_{14})$.

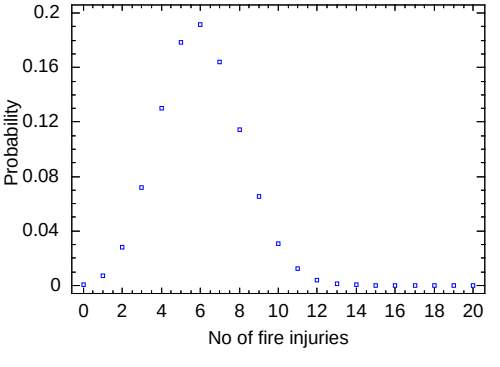

Figure 3. Probability mass function of the random number of injured persons, $\tilde{s}_{123}$ (sprinkler system a_1, fire scenario $r = 2$); $\tilde{s}_{123} \sim$B(20, 0.3)

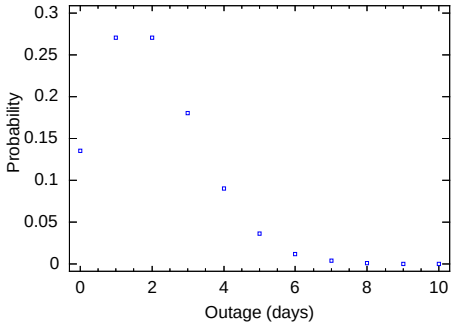

Figure 4. Probability mass function of the random duration of outage, $\tilde{s}_{114}$ (sprinkler system a_1, fire scenario $r = 1$); $\tilde{s}_{114} \sim P(2.0)$

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

$$\tilde{\boldsymbol{c}}_i = (\tilde{c}_{i1}, \tilde{c}_{i2}, \tilde{c}_{i3}, \tilde{c}_{i4}, c_{i5}) = \\ = \left(\sum_{r=1}^{4} L_{ir}\tilde{s}_{ir1}, \sum_{r=1}^{4} L_{ir}\tilde{s}_{ir2}, \sum_{r=1}^{4} L_{ir}\tilde{s}_{ir3}, \sum_{r=1}^{4} L_{ir}\tilde{s}_{ir4}, c_{i5} \right) \tag{11}$$

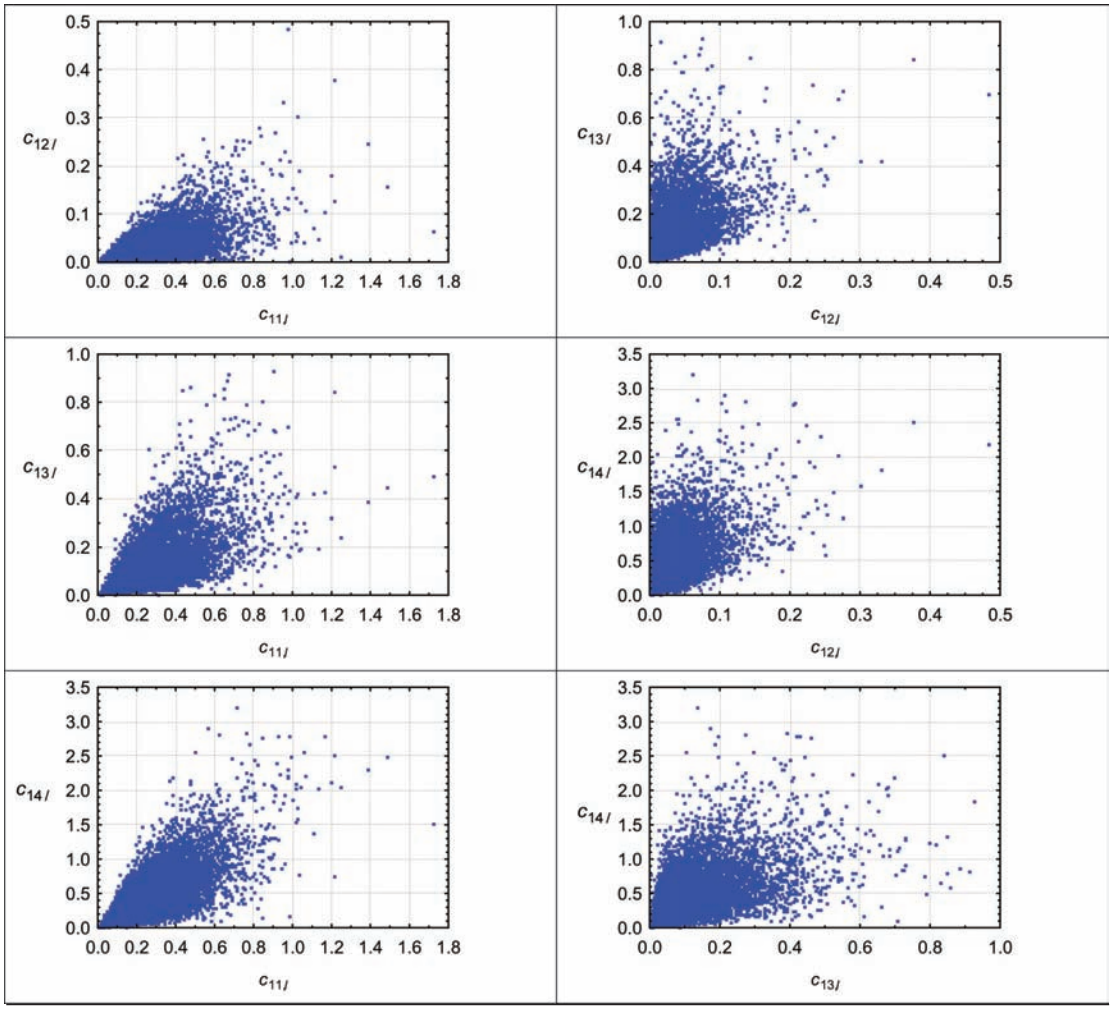

Figure 5. Scatter diagrams drawn for pairs of the simulated values $\tilde{c}_{11,l}$, $\tilde{c}_{12,l}$, $\tilde{c}_{13,l}$, and $\tilde{c}_{14,l}$ of the components of the random decision matrix $\tilde{\mathbf{C}}$ ($l = 1, 2, \ldots, 10\,000$)

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

The vectors $\tilde{c}_i$ defined by Eq. (11) form a 3×5 stochastic decision matrix $\tilde{\mathbf{C}} = [\tilde{\boldsymbol{c}}_1, \tilde{\boldsymbol{c}}_2, \tilde{\boldsymbol{c}}_3]^{\mathrm{T}}$. The selection of a^* with $\tilde{\mathbf{C}}$ is based on sampling the matrices $\tilde{\mathbf{C}}_l$.

Components of $\tilde{\boldsymbol{c}}_i$ are functions of common random variables and so they are stochastically dependent, a practical implementation of sampling of $\tilde{\mathbf{C}}_l$ is problematic. However, the components of $\tilde{\boldsymbol{c}}_i$ are represented by relatively simple Eqs. (10) and (11), in which the random variables L_0, $\tilde{p}_1$ and $\tilde{p}_{i2}$ as well as components of $\tilde{\boldsymbol{s}}_{ir}$ can be assumed to be independent. Therefore the sampling from joint probability distributions of $\tilde{\boldsymbol{c}}_i$ can be replaced by a simpler sampling from epistemic distributions of L_0, $\tilde{p}_1$ and $\tilde{p}_{i2}$ as well as distributions of the components of the vectors $\tilde{\boldsymbol{s}}_{ir}$ and calculating values of $\tilde{\boldsymbol{c}}_i$ by means of Eqs. (10) and (11). Results of such a sampling are illustrated for the vector $\tilde{\boldsymbol{c}}_1$ in Figure. 4 and 5.

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

$$NM: \quad \bar{c}_{ij} = \tilde{c}_{ijl} / \left(\sum_{i=1}^{m} \tilde{c}_{ij}^2 \right)^{-1/2} \tag{12}$$

where: $\tilde{c}_{ijl}$ is the value of the random component $\tilde{c}_{ij}$ of $\tilde{\mathbf{C}}$ sampled in the simulation step l. The MAS criteria K_1 to K_3 presented in Table 3 were applied to $\bar{\mathbf{C}}_l$ with the weights:

$$\boldsymbol{w} = (0.20,\ 0.30,\ 0.25,\ 0.10,\ 0.15)^{\mathrm{T}} \tag{13}$$

The components of $\boldsymbol{w}$ 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.

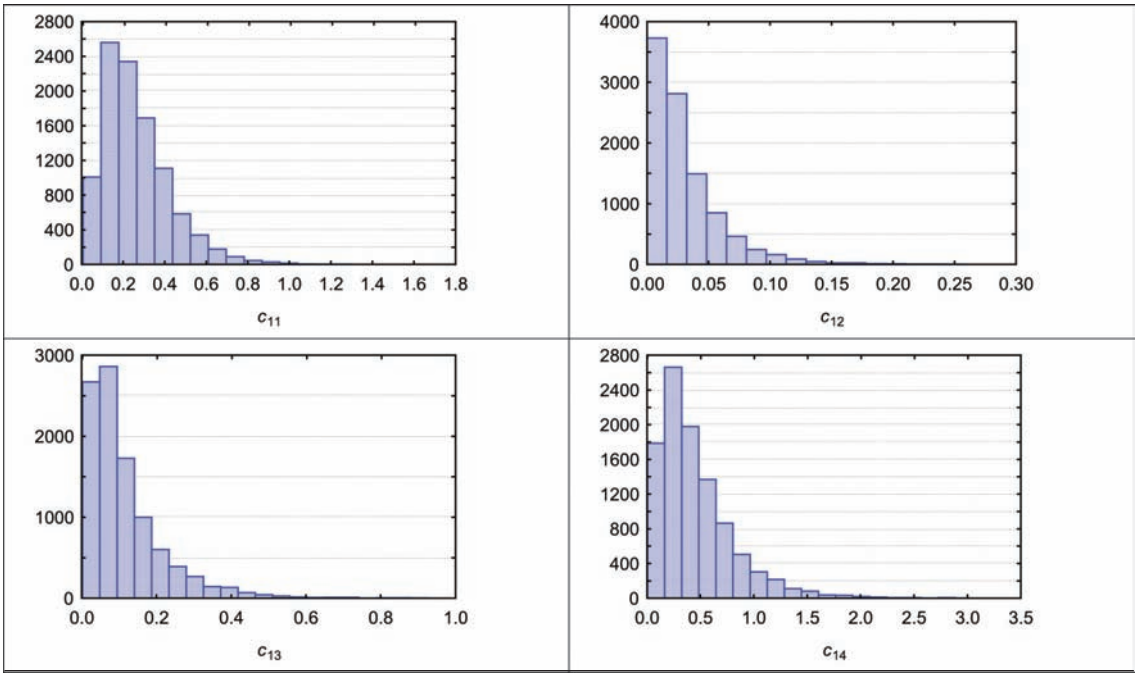

Figure 6. Histograms drawn for the simulated values $\tilde{c}_{11,l}$, $\tilde{c}_{12,l}$, $\tilde{c}_{13,l}$, and $\tilde{c}_{14,l}$ of the components of the random decision matrix $\tilde{\mathbf{C}}$ (l = 1, 2, … , 10 000; the vertical axes in these graphs indicate the number of observations)

A total of 1 $\times 10^4$ simulation steps were carried out to propagate the epistemic uncertainty in l_0, p_1, and p_{i2} and components of $\tilde{\boldsymbol{s}}_{ir}$ through the expressions (10) and (11) and then through the expressions of the criteria K_1 to K_3 given in Table 3 ($N_l = 1\times 10^4$).

In each step, K_1 to K_3 were used to find the best sprinklers a^* on the basis of $\tilde{\mathbf{C}}_l$. The simulation yielded the frequencies fr_i given in Table 3. 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 (12) used together with the criteria K_1 to K_3. An application of other normalization formula may lead to different results of MAS. Therefore, results of MAS are conditioned on the use of specific normalization formula.

6. CONCLUSIONS

The design of fire safety of buildings by applying formal means of multi-attribute selection (MAS) has been considered. Such a design requires to compare alternative solutions of fire safety provisions in a building. In case where the choice of an optimal solution is carried out in line with the performance-based fire design, the attributes of an MAS problem must include measures of fire safety.

The prevailing approaches to fire safety assessment today are fire risk indexing and estimation of fire risk used for quantitative risk assessment (QRA). Fire risk indices are popular and easy to implement systems of fire safety evaluation. However, their use within MAS is problematic, because the indices may be not sufficiently sensitive to differences among alternative fire design solutions, for instance, alternative systems of automatic sprinklers. In addition, there exists large number of indices which are used in different countries and regions and are barely compatible with each other. The development of procedures used for the calculation of fire indices is not sufficiently documented and the calculation itself has a high degree of subjectivity.

An estimation of fire risk in line with QRA is carried out by applying much more rigorous procedures than those used for calculation of fire risk indices. Estimates of fire risk can be incorporated into a MAS 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.

The estimation of failure probabilities of fire protection measures in particular and fire risk in general can be a non-trivial task. The solution of it may require failure rate data and elicitation of expert opinions. However, the fire risk is a very comprehensive measure of fire safety and its estimation is worth of effort, especially if the fire design is carried out in line with the performance-based design codes.

The estimation of fire risk in line with QRA may lead to the result that some or all elements of risk will be uncertain in the epistemic sense. An incorporation of probability distributions expressing the epistemic uncertainty into an MAS problem will lead to a composition of a random decision matrix. The MAS problem with such a matrix can be solved by propagating the uncertainties through MAS models. This can be done by embedding these models into the loop of a Monte Carlo simulation. Such a propagation is illustrated in the text by an example of a choice among alternative systems of fire sprinklers.

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SANTRAUKA

STATYBINIO TURTO GAISRINĖS SAUGOS UŽTIKRINIMAS: DAUGIAKRITERINIS SPRENDIMŲ PRIĖMIMAS ATSIŽVELGIANT Į GAISRO RIZIKĄ

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Norint užtikrinti pastatų gaisrinę saugą, gali prireikti lyginti alternatyvius projektinius saugos sprendimus. Tai atlikti galima pasitelkiant daugiakriterinio vertinimo metodologiją. Alternatyvieji sprendimai gali būti aprašyti keletu charakteristikų (atributų) ir lyginami vienas su kitu. Straipsnyje atributų sąrašas sudaromas naudojant gaisro rizikos išraišką, sudaromą kiekybinio rizikos vertinimo principais. Parodyta, kaip atlikti daugiakriterinį vertinimą, kai rizikos išraiškos elementai yra neapibrėžti epistemine prasme. Episteminio neapibrėžtumo skirstiniai priskiriami uždavinio atributams ir propaguojami matematiniais daugiakriterinio vertinimo modeliais pasitelkiant Monte Karlo modeliavimą. Pateikiamas pavyzdys, nagrinėjantis automatinių sprinklerių sistemos parinkimą iš kelių alternatyvių variantų.