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Research Article

Solving the Problem of Multiple-Criteria Building Design Decisions with respect to the Fire Safety of Occupants: An Approach Based on Probabilistic Modelling

Egidijus Rytas Vaidogas and Jurgita Šakėnaitė

Vilnius Gediminas Technical University, 11 Sauletekio Avenue, LT-10223 Vilnius, Lithuania

Correspondence should be addressed to Egidijus Rytas Vaidogas; egidijus.vaidogas@vgtu.lt

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The design of buildings may include a comparison of alternative architectural and structural solutions. They can be developed at different levels of design process. The alternative design solutions are compared and ranked by applying methods of multiple-criteria decision-making (MCDM). Each design is characterised by a number of criteria used in a MCDM problem. The paper discusses how to choose MCDM criteria expressing fire safety related to alternative designs. Probability of a successful evacuation of occupants from a building fire and difference between evacuation time and time to untenable conditions are suggested as the most important criteria related to fire safety. These two criteria are treated as uncertain quantities expressed by probability distributions. Monte Carlo simulation of fire and evacuation processes is natural means for an estimation of these distributions. The presence of uncertain criteria requires applying stochastic MCDM methods for ranking alternative designs. An application of the safety-related criteria is illustrated by an example which analyses three alternative architectural floor plans prepared for a reconstruction of a medical building. A MCDM method based on stochastic simulation is used to solve the example problem.

1. Introduction

Architectural and structural design of buildings face many problems and these problems include a selection among alternative plans of houses, individual floors, alternative use of floors in one building, alternative structural solutions, and structural materials. The selection problem is highly important in the early design stage. In the literature, attempts are described to provide some theoretical base for the selection among alternative architectural and structural solutions [1–3].

The presence of several alternative floor plans or similar alternative architectural solutions generates a problem of a multiple-criteria selection with respect to economic and architectural/structural characteristics (criteria) of each alternative. As fire prevails among hazards present in buildings, criteria related to fire safety should be included in the selection problem.

If considered from the standpoint of fire safety, alternative architectural and structural solutions mean different possibilities of fire spread, evacuation, and firefighting. A choice of a specific solution among a number of alternatives should take into account a number of economic, functional, technical, aesthetical criteria. Methods of multiple-criteria decision-making (MCDM) can be used for such a choice [4]. Until now, a building-related MCDM did not use criteria expressing fire safety [5–7]. Therefore, it makes sense to include criteria expressing fire safety into building-related MCDM problems.

In the field of fire safety, MCDM was applied to ranking fire safety criteria [8, 9]. MCDM was also used for the choice among alternative buildings with respect to fire safety and selection of fire safety systems [10, 11].

The present study proposes a building-related MCDM which takes into account fire risk to occupants. The conventional application of MCDM to build property is expanded

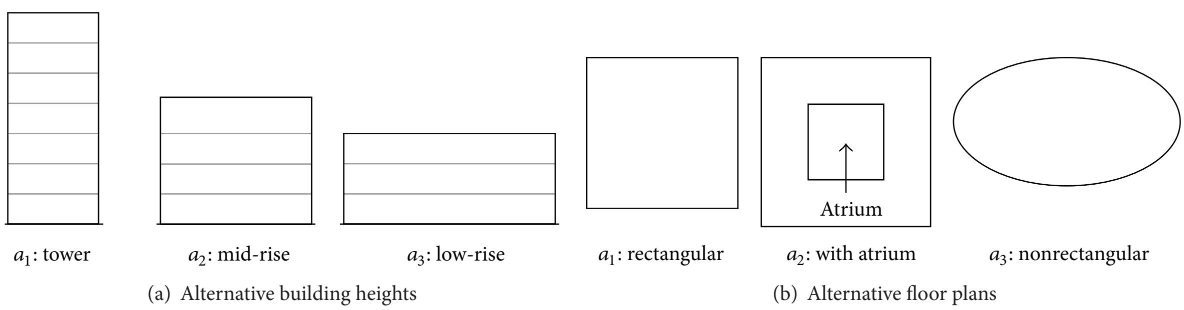


Figure 1: Alternative shapes and floor plans of a building specified on the conceptual level of design process.

by applying estimates of the fire risk as MCDM criteria. They are expressed in terms of probabilities that occupants will be exposed to untenable conditions which can build up on escape routes. Criteria expressed through time to untenable conditions and rescue time are applied to ranking alternative building design solutions. The proposed procedure allows solving MCDM problems when some elements of a decision-matrix are random. An application of the procedure is illustrated by a choice among different architectural solutions of a medical building.

2. The Problem of Choosing among Alternative Design Solutions of a Building

2.1. Development of Alternative Designs. A generation of alternative architectural and structural designs (or, briefly, alternatives) is one of the main tasks arising in the early stage of a building creation. The process of developing different alternatives is to a large margin intuitive and is not easily amenable to a mathematical formalisation. This process will be highly influenced and sometimes constrained by regulations and client wishes. However, the designer (architect or structural engineer) will always have certain freedom in specifying alternatives and choosing among them, especially, in the early stage of building design. At the same time, an improper rating of alternatives and an erroneous choice of one as seemingly the best solution can protract the entire process of design and construction and encumber exploitation. Consequently, an application of mathematical means that facilitating selection of the best alternative among a set of developed alternatives will allow reducing probability of a wrong choice.

A generation of alternatives can be interpreted as a discretisation of a continuous process. In principle, small changes in the design will allow generating an almost endless set of alternatives. However, in many cases the designer will face the problem of a selection among a limited set of alternatives which represent principal or fairly different design solutions.

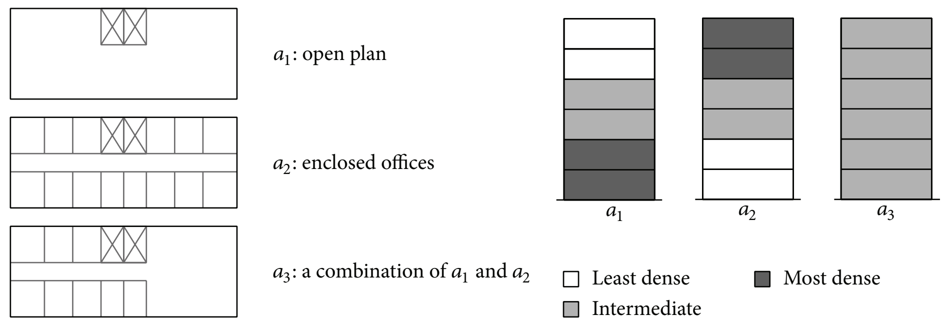
The set of n alternatives denoted, say, by $a_1, a_2, \ldots, a_i, \ldots, a_n$ can be generated at different levels of development (LODs) in the process of building design. Five LODs range from "conceptual" to "as-built" and offer different possibilities for specifying, comparing and rating the alternatives a_i (Table 1). On the conceptual level, a_i can represent different shapes or floor plans of a building under design (Figure 1). On the lower levels of schematic and detailed design, the alternatives a_i can be developed within a given shape or floor plan of a building (Figure 2). Finally, the alternatives a_i can be generated for a building with a specific configuration and floor plans. These alternatives can represent different structural systems and materials of the main structure and nonload bearing elements, alternative internal and external finishes, and different solutions of building utilities.

Table 1: Definition of levels of development (LOD) in a building design process [12, 13].

Level	Brief description	Definition
LOD 100	Conceptual design	Vague information consisting of nongeometric data or line work, areas, volumes, zones, and so forth
LOD 200	Schematic design	Generic elements shown in three dimensions
LOD 300	Detailed design	Specific elements with object geometry (dimensions, capacities, and connections)
LOD 400	Construction	Shop drawing/fabrication
LOD 500	As-built (actual)	The project as it has been constructed. The model and associated data is suitable for maintenance and operations of the facility

A formal framework for comparison and ranking of the alternatives a_i is the methodology of MCDM. It allows interalternative comparisons of a_i by applying a set of criteria $c_1, c_2, \ldots, c_j, \ldots, c_m$. A problem statement of MCDM is n-by-m decision-making matrix $\mathbf{C}$. Its element c_{ij} represents a value of the criterion c_j related to the alternative a_i. A wide variety of MCDM methods allows ranking the alternatives a_i by applying both quantitative and qualitative criteria c_j. MCDM can accommodate subjective and objective, fixed, fuzzy, and random criteria c_j [14].

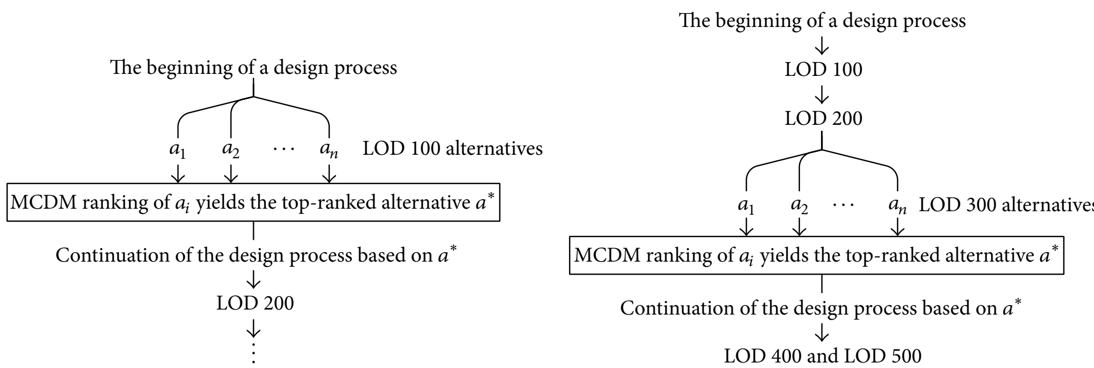
In the context of building design organised as a successive passing of LODs, a comparison of the alternatives a_i will make sense if a_i will represent the same LOD. In principle, branching of the design process into the alternatives a_i is possible on the conceptual level LOD 100, as long as it is possible to characterise the vague information expressed by



(a) Alternative interior floor plan designs

(b) Alternative allocations of occupants in a building

FIGURE 2: Alternative design solutions of a building within a given geometrical configuration.



(a) Comparison of conceptual designs

(b) Comparison of designs on higher level of detail

FIGURE 3: A generation of the alternative building designs a_i at different levels of development.

conceptual designs by some qualitative or quantitative criteria c_j (Figure 3(a)). Most of them will express subjective opinions of architect and client, because very little can be measured quantitatively and objectively at this stage of design.

Higher levels of detail represented by LODs from 200 to 400 give better opportunity to formulate and solve a MCDM problem. Branching of the design process into the alternatives a_i can be done on each of these levels (Figure 3(b)). At the same time, a development of a large number n of the alternatives a_i and characterisation of each of them by the criteria c_j can encumber the design process. In essence, a solution of a MCDM problem will require preparing n different designs of building related to the LOD reached in the design process. On the other hand, a successful choice of the best alternative design (top-ranked alternative, say, a^*) may allow compensating for that extra effort, due to the effect of a multiple-criteria optimisation.

2.2. Inclusion of Criteria Related to Building Fire Safety. The prevailing hazard in most of nonindustrial occupations and many industrial buildings is the fire hazard. Its converse, a fire safety, is usually decomposed into safety of occupants, safety of fire-fighting operations, and safety of structures subjected to fire effects. A certain number m_s of quantitative or qualitative measures expressing the three aforementioned aspects of safety can be included into an m-dimensional vector of MCDM criteria, $\mathbf{c}$. For instance, the vector $\mathbf{c}$ can be composed of two subvectors:

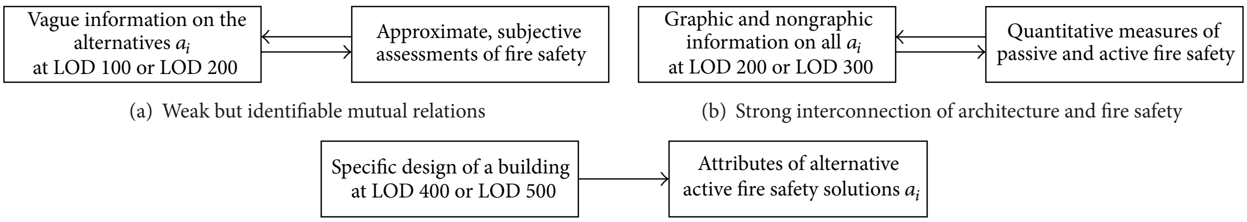
$$\begin{aligned}\mathbf{c} &= \left(\mathbf{c}' \mid \mathbf{c}''\right) \\ &= \left(c_1, c_2, \ldots, c_{m-m_s} \mid c_{m-m_s+1}, c_{m-m_s+2}, \ldots, c_m\right),\end{aligned} \tag{1}$$

where $\mathbf{c}'$ and $\mathbf{c}''$ are vectors including criteria of general nature and safety-related criteria, respectively. To compose the decision-making matrix $\mathbf{C}$, it is necessary to specify values of $\mathbf{c}'$ and $\mathbf{c}''$ for each alternative a_i.

The fire safety can be influenced by decisions made on all LODs. For instance, early decisions at LOD 100 or LOD 200 may pose the following selection problems related to the fire safety:

(1) An inclusion of a large volume space like an atrium into the building will generate the need to deal with increased risk to the life of occupants. Atria allow smoke and heat to travel throughout all floors of a building (e.g., [15, 16]). The opposite alternative of a solid floor plan will not pose this problem.

(2) A decision to erect a high-rise tower instead of a low-rise, longitudinal building will automatically pose



(a) Weak but identifiable mutual relations

(b) Strong interconnection of architecture and fire safety

(c) One-way relation between architecture and fire safety

FIGURE 4: Three levels of an interconnection of building design and assurance of fire safety.

the problems related to fire safety of tall buildings (e.g., [17]).

(3) An allocation of people predominantly in the lower floors of an office tower will increase the chance of a successful evacuation in comparison to other occupant distributions (Figure 2(b)). Occupant loads depend on human behaviour which is sometimes difficult to control. However, alternative allocations can be assessed and compared by means of probabilistic measures [18].

Although LOD 100 and LOD 200 designs present a vague information, some criteria c_j belonging to the subvector $\mathbf{c}''$ can be specified and used for solving a MCDM problem. Let us compare a building with an atrium (design concept a_1) and a solid plan building (design concept a_2) (Figure 1(b)). The criterion c_j can be a number of scores subjectively assigned by an expert to fire safety level of a_1 and a_2 (e.g., a_1 earns 6 and a_2 earns 8 in a 10-point scale). A component of $\mathbf{c}''$ can also be an average cost (in €/m^2, say) of fire safety systems which can or must be installed in a_1 and a_2. The concept a_1 presupposes a provision of smoke and heat control equipment in the atrium. Therefore, fire safety system of a_1 may cost in average more than fire safety system of a_2. Even if a_1 is preferable from the architectural standpoint, higher average fire safety costs of a_1 and possibly higher risk to occupants can make a_1 less appealing than a_2. The cost of build-in fire protection is high (e.g., [19]). A trade-off between cost of fire safety and fire risk to occupants may be necessary in many design situations [20]. The need of such a trade-off is capable of creating a mutual relation between architectural design and fire protection at LOD 100 or LOD 200 (Figure 4(a)).

The best platform for a comparison of the alternatives a_i by means of formal MCDM methods is LOD 200 and LOD 300 designs (Figure 4(b)). The knowledge of at least approximate geometry and building materials specified at these development levels will allow applying a computer simulation of fire and evacuation processes. Many computer codes used for such a simulation require transferring geometry and material data between a CAD system and often coupled systems of fire and evacuation simulation (e.g., FDS and Evac codes [22, 23]). The computer simulation allows obtaining estimates of fire and evacuation processes. These estimates can be used as fire-related criteria c_j belonging to the subvector $\mathbf{c}''$. The criteria c_j will be able to reflect both passive and active fire safety measures. For instance, different compartmentation and internal lining can be used to develop the alternatives a_i.

The alternatives a_i can also be developed for a unique architectural and structural solution of the building at LOD 400 or LOD 500, in which passive fire protection measures are unchangeable. However, alternative technical measures can be provided as an active fire protection [11, 12]. The components c_j of the subvector $\mathbf{c}''$ will have to reflect a fire safety level achieved by a combined provision of passive and active measures.

MCDM methods allow ranking the alternatives a_i with deterministic, random, and fuzzy criteria c_j. Despite the fact that the praxis of fire and evacuation assessment is predominantly deterministic, all key characteristics related to a building fire safety are random [24, 25]. For instance, random quantities are

(1) evacuation times related to the paths that will be available during a certain time after a fire outbreak,

(2) times to untenable conditions in available evacuation paths,

(3) times to structural failures which can endanger fire fighting operations,

(4) potential numbers of victims among occupants and fire fighters.

This randomness should be taken into account in specifying the components c_j of the subvector $\mathbf{c}''$. The criteria c_j can be uncertain quantities or quantities expressing uncertainties (e.g., probabilities).

3. Mathematical Specification of Decision Criteria

The criteria c_j related to fire protection of a building can be very diverse and reflect economic and technical characteristics of build-in fire safety [11, 12]. It is reasonable to state that the most important criteria c_j should measure the life safety of building occupants in a preflashover period of fire development.

In previous decades, the fire safety of buildings was quantified by means of nonprobabilistic fire risk indices [26]. They reflect in certain way the life safety and, technically speaking, can be used as c_j. However, the indices are relatively insensible to architectural and structural changes and so are not very useful for interalternative comparisons [27].

The most informative and integral criterion c_j expressing the life safety is the probability of a successful evacuation from a building fire:

$$P_{\text{se}} = P\left(T_u \geq T_e\right) = P\left(T_u \geq T_d + T_r + T_{\text{tr}}\right), \qquad (2)$$

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; 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 (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 information behind the random times T_e and T_u can be utilised for a MCDM at least in two ways.

If it is possible to obtain accurate and "cheap" estimates of the probabilities $P(T_u \geq T_e)$, they can be used as MCDM criteria

$$c_{ij} = P\left(T_{uij} \geq T_{eij}\right), \qquad (3)$$

where T_{uij} and T_{eij} are random times related to the alternative a_i and available evacuation path j. The criteria defined by (3) are in essence deterministic and can be easily included into the decision-making matrix **C**. However, scarcity of hard data on the times T_{uij} and T_{eij} may generate uncertainty related to the "true" values of the probabilities $P(T_{uij} \geq T_{eij})$. In terms of the theory known as the quantitative risk assessment such uncertainty is called epistemic (state-of-knowledge) uncertainty and quantified by applying methods of Bayesian statistical theory (e.g., [28]). A result of a Bayesian estimation of $P(T_{uij} \geq T_{eij})$ will be an epistemic random variable $\tilde{c}_{ij}$. It can be used as an element of the decision-making matrix. However, in the latter case a MCDM problem will be formulated as a decision-making matrix $\widetilde{\mathbf{C}}$, some elements of which are uncertain in the epistemic sense. Simply stated, the decision problem will be expressed by a random matrix $\widetilde{\mathbf{C}}$.

The second way of utilising information behind T_e and T_u is to use the random criteria

$$\tilde{c}_{ij} = T_{uij} - T_{eij}. \qquad (4)$$

They will allow carrying out interalternative comparisons without estimating the probabilities $P(T_{uij} \geq T_{eij})$. At the same time, information used to assess probability distributions of T_{uij} and T_{eij} will be in the main part the same as information used to estimate $P(T_{uij} \geq T_{eij})$. With the criteria $\tilde{c}_{ij}$ defined by (4), a MCDM problem will be formulated through a random decision-making matrix $\widetilde{\mathbf{C}}$.

The direct data allowing us to fit the probability distributions of T_{uij} and T_{eij} will hardly be available in most design situations. However, distributions of T_{uij} and T_{eij} and so the probabilities $P(T_{uij} \geq T_{eij})$ can be estimated by means of a stochastic (Monte Carlo) simulation of fire and evacuation processes. Such a simulation became an intensive field of fire safety investigation in recent years [29–31]. In context of MCDM, the simulation can yield generated samples of T_{uij} and T_{eij}. These samples can be used for either choosing the probability distributions of T_{uij} and T_{eij} or estimating $P(T_{uij} \geq T_{eij})$.

A specification of probabilistic input information for a computer-aided fire simulation can be gained from various sources. There exist large collections of data on fires in general [8]. Databases related to fires are collected and maintained in such particular areas as safety of nuclear power plants [32]. Unfortunately, the data situation in some specific areas of fire safety (e.g., sprinklers and fire alarms) is not very encouraging [33]. Consequently, specification of input information for assessing such values as T_{uij} and T_{eij} will have to rely on Bayesian analysis widely used for a probabilistic risk assessment.

The distributions (estimates) of the times T_{uij} and T_{eij} can be applied to solving a MCDM problem with either deterministic or stochastic decision-making matrix, **C** or $\widetilde{\mathbf{C}}$. Several MCDM methods were proposed to solve the selection problem with the random matrix $\widetilde{\mathbf{C}}$ [34–36]. The following case study illustrates dealing with $\widetilde{\mathbf{C}}$ by means of a MCDM method based on stochastic simulation.

4. An Application to a Reconstruction of a Medical Building

4.1. Alternatives under Comparison and Safety-Related MCDM Criteria. The present case study considers an existing two-storey wing of a hospital building in Lithuania. The first floor of the wing accommodates a haemodialysis unit and the second floor is used for a catering department (Figures 5 and 6). Smoke detectors in all rooms of the building will activate an alarm system in case of fire. Fresh air supply fans installed in the building are supposed to automatically shut down when the fire alarm is activated.

A hospital administration is going to reconstruct the catering department and to open a canteen in the second floor. 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.

Three new floor plans are considered in the design (Figures 7 to 9). 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 a MCDM problem:

(i) a_1 is a floor plan with single-room seating area ($66.1\,\text{m}^2$) and large service area ($31.4\,\text{m}^2$) (Figure 7), 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 2).

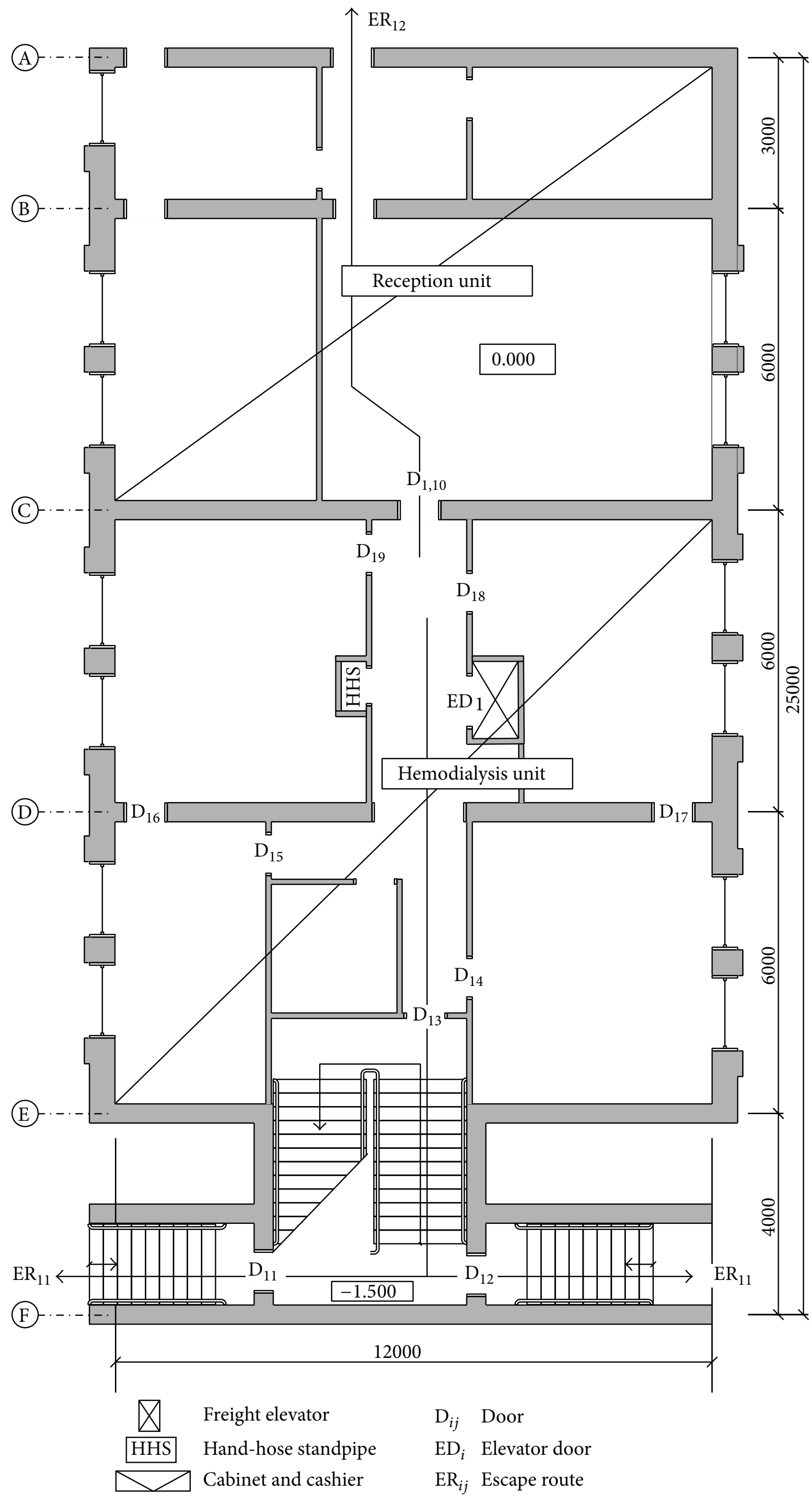


Figure 5: Plan of the haemodialysis unit in the first floor of the building.

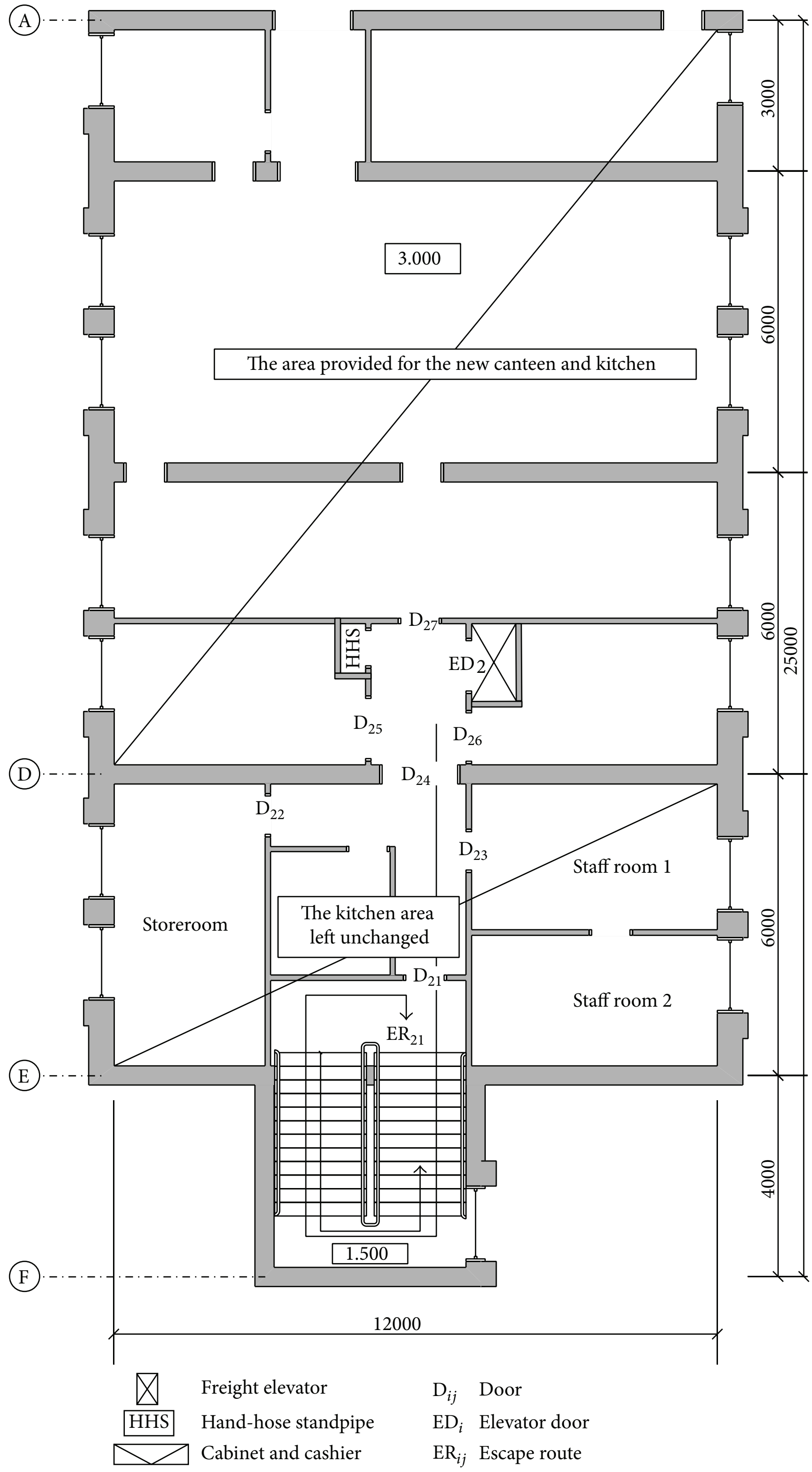


Figure 6: Existing wall plan of the catering department in the second floor of the building.

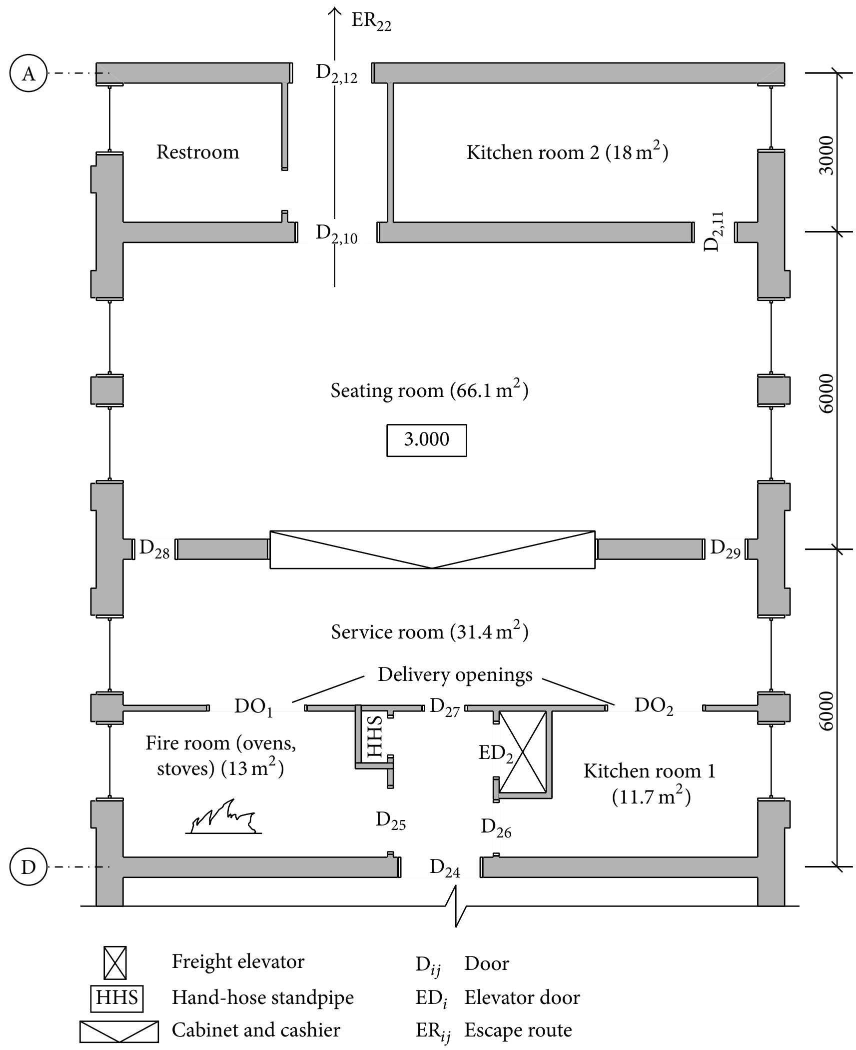


FIGURE 7: New wall plan a_1 for the canteen.

(ii) a_2 is a two-room seating area (51.9 m^2 and 26.3 m^2), relatively small service area (11 m^2) (Figure 8); among the three alternative plans, the room of potential fire initiation in the plan a_2 is at the largest distance from freight elevator, stairwell, and hospital units in the first floor.

(iii) a_3 is a two-room seating area (50 m^2 and 18 m^2), relatively small service area (12.3 m^2) (Figure 9); 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 2).

In terms of fire safety, the alternatives a_1, a_2, and a_3 can be characterised as follows:

(i) a_1 is the floor plan with the least effective compartmentation; the room of potential fire initiation is in front of the freight elevator and is 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, Figure 7); in case of fire, the combustion products will first affect kitchen staff and then visitors of

TABLE 2: Characteristics of the floor plans a_1, a_2, and a_3 shown in respective Figures 7, 8, and 9 (the bold rows indicate characteristics of the alternatives which will be used as MCDM criteria).

Floor plan characteristic	Plan a_1	Plan a_2	Plan a_3
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 €	**458.0**	**298.5**	**315.6**
Estimated reconstruction time, months	**3.5**	**2.1**	**2.0**

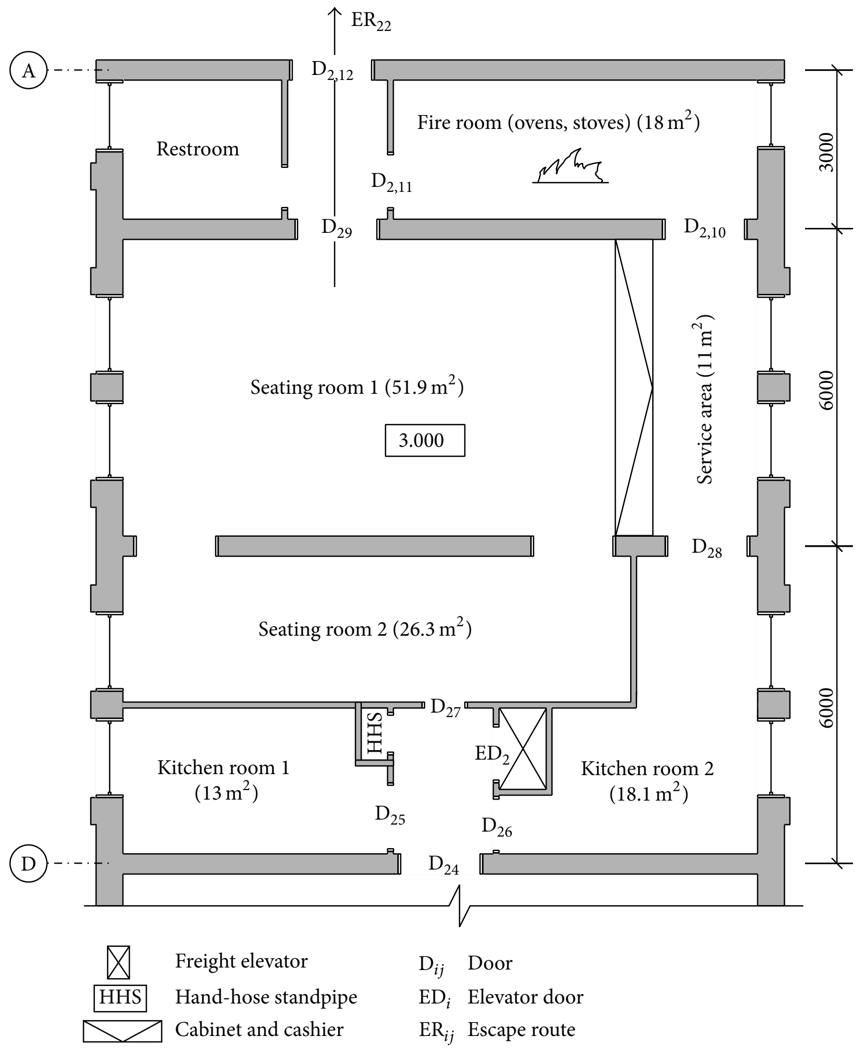


Figure 8: New wall plan a_2 for the canteen.

the canteen; the horizontal evacuation is possible through the escape routes ending with doors D_{21} and $D_{2,12}$ (Figures 6 and 7).

(ii) a_2 is the floor plan with the most remote position of the fire room with respect to the freight elevator and stairwell, an average compartmentation in comparison to plans a_1 and a_3; there are two horizontal vents for the flow of gaseous combustion products to the inside (doors $D_{2,10}$ and $D_{2,11}$, Figure 8); 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 door D_{21}, whereas the evacuation through $D_{2,12}$ can be problematic (Figures 6 and 8).

(iii) a_3 is 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 door D_{28} (Figure 9); the possible paths of horizontal evacuation ending with doors D_{21} and $D_{2,12}$ are similar to those in the plan a_1 (Figures 6 and 9).

The alternatives a_1 to a_3 will differ in the economic sense and, to a certain degree, in the necessary operations of reconstruction. For instance, the floor plan a_1 requires providing a large opening in the load-bearing masonry wall for cabinet and cashier (Figure 7). 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_1 with respect to the plans a_2 and a_3. On the other hand, the floor plans a_2 and a_3 will require constructing a larger number of partitions to form new rooms than the floor plan a_1.

The differences in the floor plans will lead to differences in the risk posed by a potential fire to patients, medical staff, and visitors of the canteen. A selection among the alternatives a_1 to a_3 must include a MCDM criterion which reflects the risk to lives of these three categories of occupants.

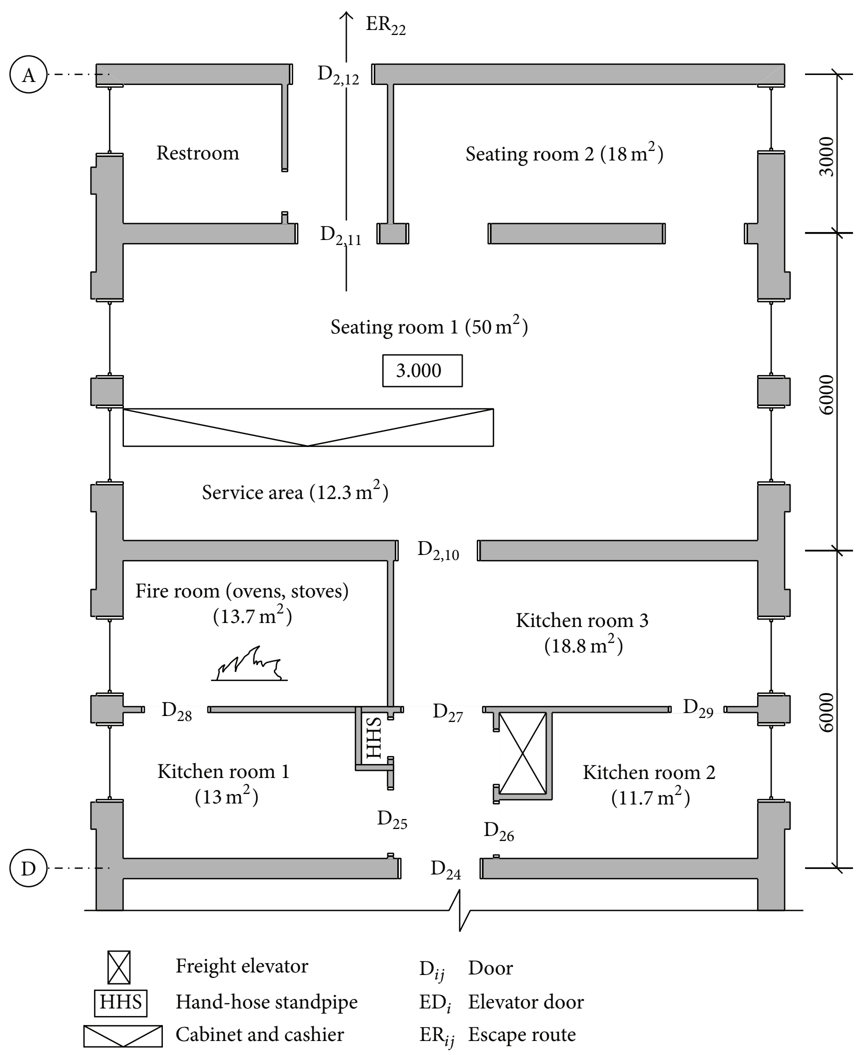


FIGURE 9: New wall plan a_3 for the canteen.

The alternative floor plans a_1, a_2, and a_3 can be compared in terms of the probability P_{se}. However, this probability is relatively difficult to be estimated and the estimation will involve information common to all three alternatives:

(1) 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 (e.g., [8]).

(2) The reaction time T_r may also be assumed to be equal for all three alternatives because the types and numbers of occupants (haemodialysis patients, medical staff, and kitchen staff as well as visitors of canteen and reception unit) will not depend on the wall plans in individual alternatives.

(3) The time needed for evacuation of the haemodialysis unit, T_{tr}, 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 haemodialysis 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_{tr} related to the individual alternatives. The idea was to compare the alternative floor plans by using the times T_u and T_{tr} and not the probabilities of a successful evacuation, P_{se}.

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

$$c_{ij} = T_{u,i1} \quad (i = 1, 2, 3), \tag{5}$$

where the values of the subscript i refer to a_1, a_2, and a_3 and subscript "1" denotes the first floor.

The life safety of kitchen staff and visitors of the canteen will depend on times to untenable conditions (say T_{u2}) and travel times (say $T_{\mathrm{tr}2}$) related to available escape routes. A candidate MCDM criterion expressing the life safety of occupants in the second floor can be expressed by the difference of T_{u2} and $T_{\mathrm{tr}2}$:

$$c_{i,j+1} = T_{u,i2} - T_{\mathrm{tr},i2} \quad (i = 1, 2, 3), \tag{6}$$

where subscript "2" refers to the second floor.

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

4.2. Probabilistic Simulation of Burning Objects. The fire is assumed to be initiated in the room used to operate stoves and ovens or, briefly, the fire room (Figures 7 to 9). 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 to be constant over the fire duration $(0, t_o)$, where the subscript "o" stands for "oil" [37, 38]. The constant HRR of this fire, $\dot{q}_o$, will be modelled by the expression

$$\dot{q}_o = \overline{q}_o + \xi_o, \tag{7}$$

where $\overline{q}_o$ is the average value of $\dot{q}_o$ estimated with the data given in Figure 10 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 Figure 10.

For the purpose of fire simulation, the value of $\overline{q}_o$ 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 s, 900 s^2). Densities of the random variables ξ_o and T_o are illustrated in Figure 10.

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 as

$$\dot{q}_f(t) = \overline{q}_f(t) + \xi_f(t) \quad \text{with } t \in \left(t_{f0}, t_f\right), \tag{8}$$

where $\overline{q}_f(t)$ 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 $t_{f0} - t_f$ 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

$$\Xi_f = \left\{\left(\overline{q}_f(t_l) + \xi_f(t_l)\right),\ l = 1, 2, \ldots, 17\right\}, \tag{9}$$

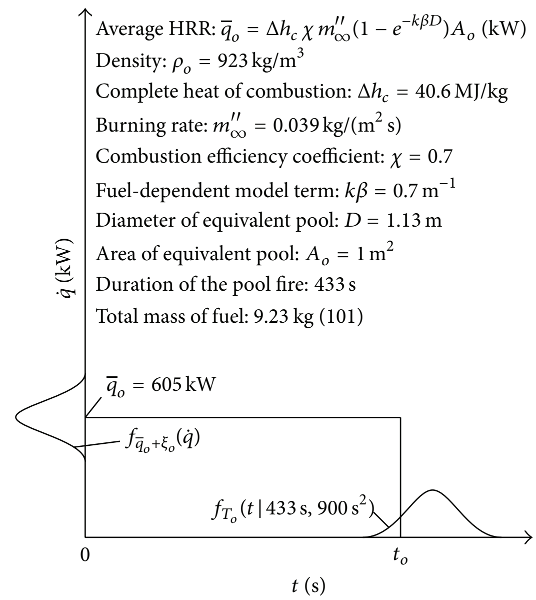


Figure 10: Mathematical model of the heat release rate (HRR) for the pool fire of oil and grease (the model of $\overline{q}_o$ was adopted from Karlsson and Quintiere [21]).

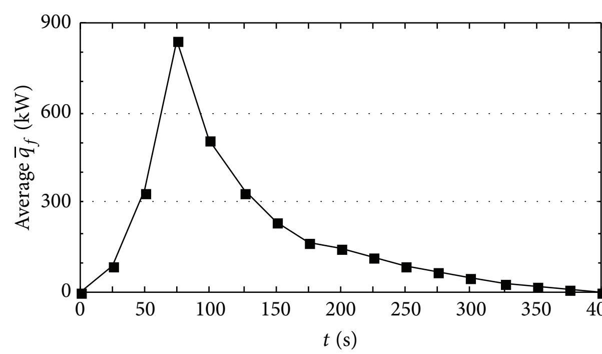


Figure 11: Time history of the average heat release rate of the flue fire, $\overline{q}_f(t_l)$, drawn for t_{f0} = 0 s and t_f = 400 s.

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 (Figure 11); $\overline{q}_f(t_l)$ 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 $0.07 \times \overline{q}_f(t_l)$. The random variables $\xi_f(t_l)$ were assumed to be correlated and the correlation coefficients were calculated by means of the following model [39]:

$$\rho_{lk} \equiv \rho\left(\xi_f(t_l), \xi_f(t_k)\right) = \exp\left\{-\kappa\left|t_l - t_k\right|\right\} \tag{10}$$

with $\kappa = 0.02$.

The discretisation of the fire duration (t_{f0}, t_f) follows from the measurement techniques of the so-called free burn experiments used for determining HRR values at given time moments t_l (e.g., [40]). A certain number of individual time histories (signals) measured in repeated experiments allow

TABLE 3: Probability distributions of the random variables used for the computer fire simulation in the hospital building considered in a MCDM problem.

Variable	Symbol	Mean	Coeff. of var.	Distribution
The fluctuation of the oil fire HRR(1) around the mean value $\overline{q}_o$ (Figure 10)	ξ_o	605 kW	0.05	Normal
The random duration of oil fire (Figure 10)	T_o	433 s	0.07	Normal
The fluctuation of the flue fire HRR(1) around the mean value $\overline{q}_f(t_l)$ at t_l (Figure 11)	$\xi_f(t_l)^{(3)}$	0 kW	0.07	Lognormal
The fluctuation of the cupboard fire HRR around the mean value $\overline{q}_c(t_l)$ at t_o (Figure 12)	$\xi_c(t_o)^{(2)}$	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 $\xi_c(t_l)$ ($l = 1, 2, \ldots, 17$) are assumed to be correlated with the correlation coefficients calculated by (10).
(3) Beta distribution with the parameters 6 and 21 and the mode of 0.2.

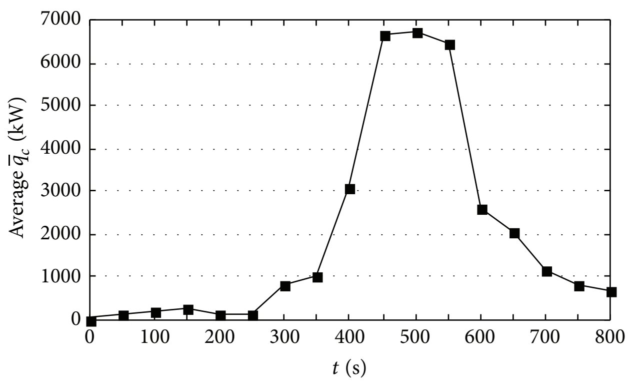


FIGURE 12: A sequence of average heat release rates of the cupboard fire, $\overline{q}_c(t_l)$.

estimating the mean values $\overline{q}_f(t_l)$ at given t_l and fitting probability distributions of the random variables $\xi_f(t_l)$.

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

$$\Xi_c = \{(\overline{q}_c(t_l) + \xi_c(t_l)),\ l = 1, 2, \ldots, 17\}, \qquad (11)$$

where the subscript "c" stands for "cupboard," $\overline{q}_c(t_l)$ is 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 $\overline{q}_c(t_l)$ was adopted from Babrauskas [40] and is shown in Figure 12. 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 (Figure 12). 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 $0.05\times\overline{q}_c(t_l)$. The coefficients of correlation $\rho(\xi_c(t_l), \xi_c(t_k))$ were calculated with the model given by (10) with $\kappa = 0.01$.

The window in the kitchen room is assumed to break when the temperature reaches a sufficiently high temperature. 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°C, $155(°\text{C})^2$) (normal distribution) and $\xi_{wa} \sim$ Be(6, 21) (a beta distribution with the mode of 0.2).

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.

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 to be the same in all alternative floor plans.

4.3. Fire Development and Scenarios. Haemodialysis unit and catering department are operated only in the daytime and so lives of patients and staff cannot 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.

People staying in the first floor will be endangered by toxic combustion gasses. They 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. 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:

(1) through the vertical shaft of the freight elevator if the elevator doors ED_1 and ED_2 are left open due to negligence or when the fire outbreaks during loading and unloading operations (Figures 5 and 7 to 9);

(2) through the stairwell in the case that doors to the stairwell, D_{21} and D_{13}, are open in both first and second floor (Figures 5 and 6).

Leakage of combustion products between the second and first floors through other paths is considered to be negligible. The ventilations 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 haemodialysis unit, kitchen, and canteen have four escape routes:

(1) Escape route ER_{11} (first floor, horizontal evacuation): from the haemodialysis unit to the stairwell through the door D_{13} and then to the outside through D_{11} and D_{12} (Figure 5).

(2) Escape route ER_{12} (first floor, horizontal evacuation): from the haemodialysis unit to the reception unit and then to the main building of the hospital (Figure 5).

(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} (Figures 5 and 6).

(4) Escape route ER_{22} (second floor, horizontal evacuation): from the kitchen and canteen to the main building of the hospital through the door $D_{2,12}$ (Figures 7 to 9).

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 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 (Figure 6). This fire scenario involves different event sequences for the alternative floor plans a_1, a_2, and a_3:

(i) a_1: the staff rooms 1 and 2 and the storeroom are unoccupied when the fire outbreaks (Figure 6); 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} (Figure 7); the untenable conditions on ER_{22} will first be reached in the service room at the time $T_{u,12}$.

(ii) a_2: untenable conditions on the escape route ER_{22} will be first reached in the room including service area and seating room at the time $T_{u,22}$ (Figure 8). Evacuation of staff and visitors of the canteen will be possible through the escape route ER_{21} (Figure 6).

(iii) a_3: untenable conditions will be reached first in the fire room and kitchen room 1 (Figure 9); 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 (Figures 5 and 6). 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.

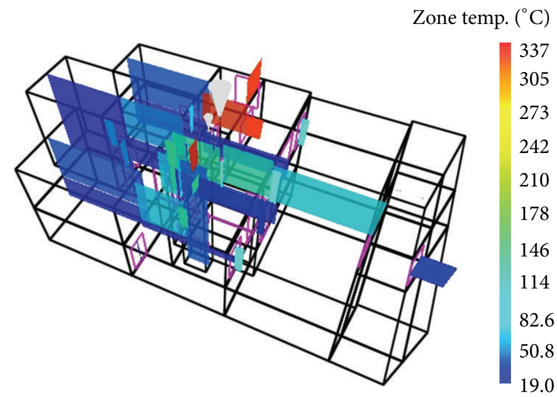


Figure 13: A visualisation of the CFAST model developed for the second fire scenario and the alternative floor plan a_1 (Figure 7).

The differences between the position of the fire room in a_1, a_2, and a_3 as well as in the wall plans of these alternatives will lead to different times to untenable conditions in the first floor, $T_{u,i1}$ $(i = 1, 2, 3)$.

4.4. Fitting Probability Distributions of the Criteria. The times to untenable conditions $T_{u,i1}$ and $T_{u,i2}$ can be estimated by means of a computer fire simulation. Input information for this simulation can be generated by means of a stochastic simulation. In the present study, the fire was simulated by means of the computer model CFAST for each of a_1, a_2, and a_3. A visualisation of the CFAST model developed for the alternative a_1 is given in Figure 13.

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 time k):

(1) The values ξ_{ok} to $\xi_{wa,k}$ of the random variables ξ_o to ξ_{wa} summarised in Table 3 were generated by means of a stochastic simulation.

(2) The kth value of the heat release rate of the pool fire, $\dot{q}_{ok} = \overline{q}_o + \xi_{ok}$, was calculated and the pool fire with constant HRR $\dot{q}_{ok}$ and duration t_{ok} was uploaded into the CFAST model.

(3) The kth values Ξ_{fk} and Ξ_{ck} of the HRR histories Ξ_f and Ξ_c defined by (9) and (11) were computed and uploaded into the CFAST model. These values were composed of the respective sums $\overline{q}_f(t_l) + \xi_{fk}(t_l)$ and $\overline{q}_c(t_l)+\xi_{ck}(t_l)$ $(l = 1, 2, \ldots, 17)$. 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

TABLE 4: Simulated samples of the times to untenable conditions.

Random time	Simulated sample*	Escape route blocked by smoke	Available escape route
	Alternative a_1, Figure 7 ($i = 1$)		
$T_{u,11}$	$\boldsymbol{\tau}_{11} = \{t_{u,11k},\ k = 1, 2, \ldots, N_k\}^{**}$	ER_{12}, Figure 5	ER_{11}, Figure 5
$T_{u,12}$	$\boldsymbol{\tau}_{12} = \{t_{u,12k},\ k = 1, 2, \ldots, N_k\}$	ER_{21}, Figure 6	ER_{22}, Figure 7
	Alternative a_2, Figure 8 ($i = 2$)		
$T_{u,21}$	$\boldsymbol{\tau}_{21} = \{t_{u,21k},\ k = 1, 2, \ldots, N_k\}$	ER_{12}, Figure 5	ER_{11}, Figure 5
$T_{u,22}$	$\boldsymbol{\tau}_{22} = \{t_{u,22k},\ k = 1, 2, \ldots, N_k\}$	ER_{22}, Figure 8	ER_{21}, Figure 6
	Alternative a_3, Figure 9 ($i = 3$)		
$T_{u,31}$	$\boldsymbol{\tau}_{31} = \{t_{u,31k},\ k = 1, 2, \ldots, N_k\}$	ER_{12}, Figure 5	ER_{11}, Figure 5
$T_{u,32}$	$\boldsymbol{\tau}_{32} = \{t_{u,32k},\ k = 1, 2, \ldots, N_k\}$	ER_{21}, Figure 6	ER_{22}, Figure 9

*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.

TABLE 5: 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 1st parameter*	123.33 (mean)	236.1 (mean)	4.05 (scale)
Estimate of the 2nd parameter*	2.56 (std. dev.)	3.91 (std. dev.)	0.04 (shape)

*Parameter of the fitted distribution.

the kth 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 simulation of the first fire scenario, in which the fire is initiated in the second floor and can spread to the first floor, produced three samples of the random times to untenable conditions, $T_{u,i1}$ ($i = 1, 2, 3$). The samples are denoted by the symbols $\boldsymbol{\tau}_{11}$, $\boldsymbol{\tau}_{21}$, and $\boldsymbol{\tau}_{31}$ and explained in Table 4. These samples were used to fit the probability distributions of the respective random variables $T_{u,i1}$ ($i = 1, 2, 3$) used as MCDM criteria and expressed by (5). Results of the distribution fitting are given in Table 5.

The simulation of the second fire scenario, in which the fire is confined to the second floor, yielded three samples of the random times to untenable conditions, $T_{u,i2}$ ($i = 1, 2, 3$). These samples are denoted by the respective symbols $\boldsymbol{\tau}_{12}$, $\boldsymbol{\tau}_{22}$, and $\boldsymbol{\tau}_{32}$, (Table 4). The samples $\boldsymbol{\tau}_{12}$, $\boldsymbol{\tau}_{22}$, and $\boldsymbol{\tau}_{32}$ were used to fit probability distributions for the random variables $T_{u,i2}$ ($i = 1, 2, 3$). The fitted distributions are described in Table 6. These variables appear in the MCDM criterion expressed by (6).

The travel times $T_{tr,i2}$ were estimated by means of the computer model SIMULEX. The computer simulation was repeated 100 times and produced three samples of $T_{tr,i2}$ values $\{t_{tr,i2k},\ k = 1, 2, \ldots, 100\}$ ($i = 1, 2, 3$). Elements of these samples, $t_{tr,i2k}$, were obtained with different simulated numbers of visitors in the canteen, ξ_{vk}. In addition, locations of visitors and kitchen staff were randomly distributed for each k and i. The random numbers of the visitors, ξ_{vk}, were sampled from a binomial distribution by assuming that the maximum number of seats in the canteen is equal to 30: $\xi_v \sim B(0.3, 30)$ (binomial distribution with the mean of 9).

In the simulation of evacuation, the number of kitchen staff members remained constant and equal to six persons in all simulations. Figure 14 shows the distribution of nine visitors ($\xi_{vk} = 9$) in the canteen and six kitchen staff members at the commencement of evacuation.

Descriptive measures of the samples $\{t_{tr,i2k},\ k = 1, 2, \ldots, 100\}$ ($i = 1, 2, 3$) as well as probability distributions fitted to these samples are presented in Table 7.

TABLE 6: 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 1st parameter*	143.09 (mean)	121.09 (mode)	4.30 (scale)
Estimate of the 2nd parameter*	5.69 (std. dev.)	4.89 (scale)	0.04 (shape)

*Parameter of the fitted distribution.

TABLE 7: Descriptive measures of the samples of travel times $T_{tr,i2}$ elapsed during the evacuation from the second floor ($i = 1, 2, 3$).

Sample statistic/distribution fitting results	Sample of $t_{tr,12k}$	Sample of $t_{tr,22k}$	Sample of $t_{tr,32k}$
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 1st parameter*	18.51 (mode)	18.47 (mean)	3.08 (scale)
Estimate of the 2nd parameter*	2.148 (scale)	3.32 (std. dev.)	0.14 (shape)

*Parameter of the fitted distribution.

4.5. The Random Decision-Making Matrix and Selection of the Best Alternative. A MCDM analysis was carried out by taking into account five criteria c_1 to c_5 explained in Table 8. The criteria related to the fire safety, c_1 and c_2, were the respective random times $T_{u,i1}$ and $T_{tr,i2}-T_{u,i2}$, selected as MCDM criteria in Section 4.1 (see (5) and (6)). Hereby, Table 8 contains random and nonrandom components of the decision-making matrix $\widetilde{\mathbf{C}}$. The kitchen area c_3 was included among the criteria because the kitchen will still perform the catering function in the hospital even after the reconstruction of the second floor. The larger the kitchen area is, the better the conditions will be to perform this function. Floor reconstruction cost c_4 and estimated reconstruction time c_5 are natural criteria of a building-related MCDM and they do not need further explanation. The weights w_j given in Table 8 mean that the greatest significance was assigned to the criteria associated with the life safety ($w_1 + w_2 = 0.6$). The floor reconstruction cost is also among the significant criteria ($w_4 = 0.25$).

The alternatives a_1, a_2, and a_3 were ranked by applying a simulation-based MCDM procedure proposed by Vaidogas and Zavadskas [37]. Six deterministic MCDM methods developed in the game theory and described in the book [38] (criteria K_1 to K_6) were embedded in a simulation loop. All criteria were applied to the matrix of estimates, $\widehat{\mathbf{C}}$, obtained from the matrix of dimensionless criteria, $\overline{\mathbf{C}}$, with the criterion weights w_j given in Table 8. The matrix $\overline{\mathbf{C}}$ was computed with the vector-norm normalisation method (e.g., [37, 41]).

A total of a million simulation steps were applied to propagate the uncertainty modelled by the times $T_{u,i1}$ and $T_{tr,i2} - T_{u,i2}$. In the lth step, the criteria K_1 to K_6 were applied to find a^* by using the sampled decision-making matrix $\widetilde{\mathbf{C}}_l$.

Table 8: The transposed random decision-making matrix $\widetilde{\mathbf{C}}^T$ (bold cells) composed for the choice among the fire alternative floor plans in a hospital building shown in Figures 7 to 9.

Criteria	Unit of c_i	Preference	Weights, w_j	Plan a_1	Plan a_2	Plan a_3
Random time to untenable conditions, c_1	Sec.	Min	0.35	$\mathbf{T}_{\mathbf{u},11}$	$\mathbf{T}_{\mathbf{u},21}$	$\mathbf{T}_{\mathbf{u},31}$
Random time to untenable conditions minus random travel time, c_2	Sec.	Max	0.25	$\mathbf{T}_{\mathbf{u},12} - \mathbf{T}_{\mathbf{tr},12}$	$\mathbf{T}_{\mathbf{u},22} - \mathbf{T}_{\mathbf{tr},22}$	$\mathbf{T}_{\mathbf{u},32} - \mathbf{T}_{\mathbf{tr},32}$
Kitchen area, c_3	m^2	Max	0.1	**42.7**	**49.1**	**52.2**
Floor reconstruction cost, c_4	Thous. of €	Min	0.25	**458.0**	**298.5**	**315.6**
Estimated reconstruction time, c_5	Months	Min	0.05	**3.5**	**2.1**	**2.0**

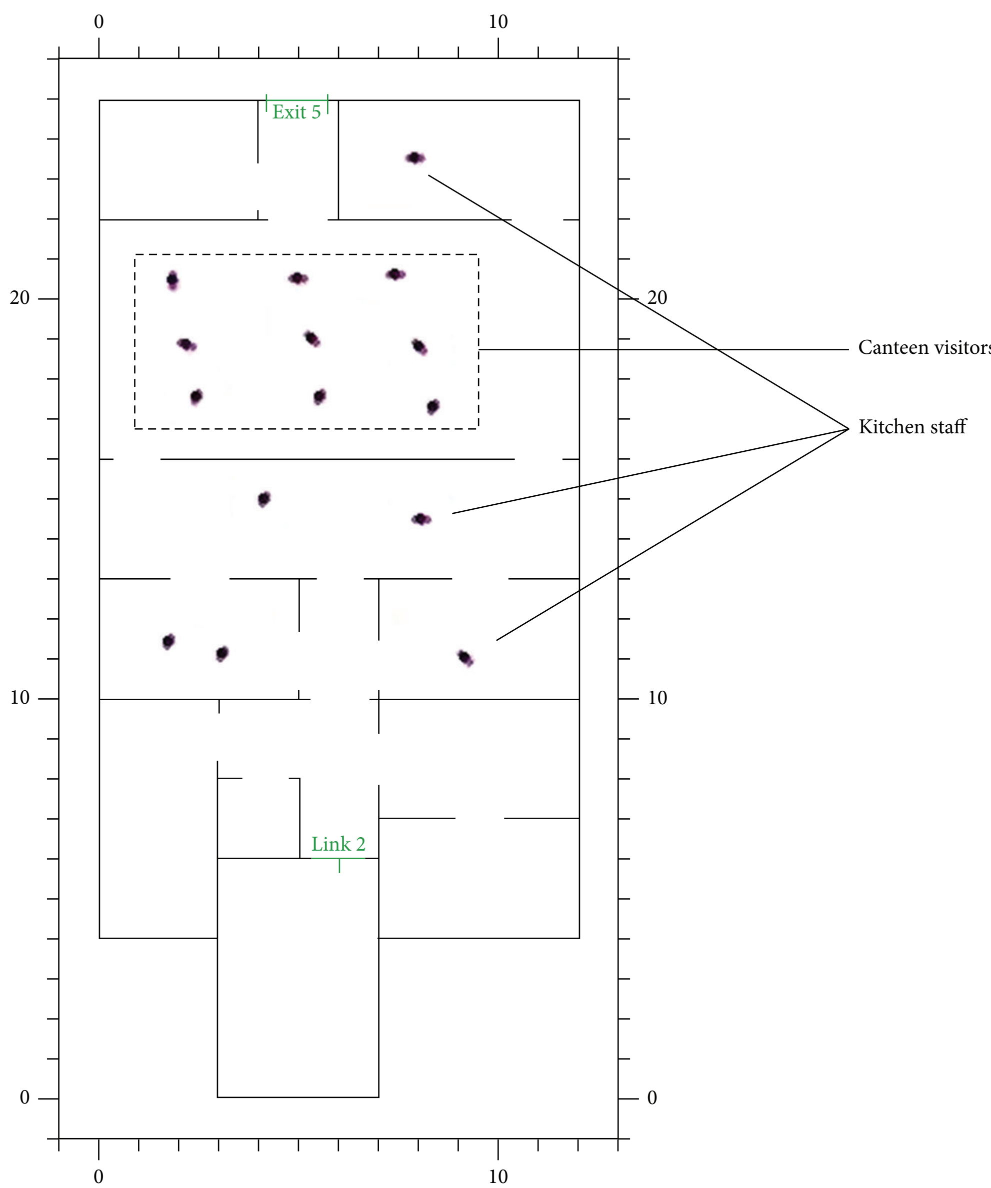


Figure 14: Random distribution of the kitchen staff and nine visitors of the canteen before commencement of evacuation in the floor a_1 shown in Figure 7 (SIMULEX model).

Table 9: Results of the choice among the alternative floor plans a_1, a_2, and a_3 designed for a hospital building and shown in Figures 7 to 9.

MCDM criterion	Frequency$^{(1)}$ of choosing a_i as a^*		
	fr_1	$\mathbf{fr_2}$	fr_3
Wald's K_1	0.4639	**0.5361**	0
Savage's K_2	0	**1**	0
Bernoulli-Laplace K_3	**0.9988**	0.1156×10^{-2}	0
Hurwicz's K_4 ($\lambda = 0.5$)	0	**1**	0
Bayes's criterion K_5	0.331×10^{-3}	**0.9997**	0
Hodges-Lehman's ($\delta = 0.5$)	0.1827×10^{-1}	**0.9817**	0

$^{(1)}$The frequencies fr_1, fr_2, and fr_3 were computed with $N_l = 1 \times 10^6$.

The frequencies of choosing the a_1, a_2, and a_3 as the best ones, fr_1, fr_2, and fr_3, are summarised in Table 9.

5. Conclusions

The building design that takes into account alternative architectural and structural solutions has been considered. A universal methodology known as MCDM can be applied to rank available alternative designs. MCDM can be used at different levels of development of a building project. Each alternative design is characterised by a number of MCDM criteria which are juggled simultaneously.

Fire is prevailing hazard in most buildings and a built-in fire protection is an important part of each building project. Methods of MCDM allow including criteria related to building fire safety. The most important criteria express life safety of occupants. The main finding of this paper is that two criteria can be used for MCDM: (1) probability of a successful evacuation of occupants from a building in fire and (2) difference between evacuation time and time to untenable conditions along available evacuation paths. These criteria are in general uncertain quantities. The probability can be uncertain in the epistemic sense and the difference in times will be uncertain in the aleatory (stochastic) sense. Probability distributions of these criteria can be estimated by a Monte Carlo simulation of fire and evacuation processes.

Problem with uncertain safety-related criteria can be solved by means of stochastic MCDM methods. An application of such a method was illustrated by an example, in which alternative architectural floor plans of a hospital building were compared.

Appendix

See Tables 5, 6, and 7.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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