
Annexes

Annex A. Input vectors of fire risk indices

Table A.1. Input vectors x_1 , x_2 , and x_3 used to calculate the Gretener's index (Kaiser 1979, Rasbash *et. al.* 2004, SFPE 2002)

Variable	Comp.
Geometry data (vector x_1)	
Height between the floor and the ceiling of the storey (m)	x_{11}
A building height (m)	x_{21}
Height of basement (m)	x_{31}
The theoretical length of the compartment (m)	x_{41}
The equivalent width, expressed in meter (m)	x_{51}
Fire-specific data (vector x_2)	
Immobile fire load (MJ/m ²)	x_{12}
Mobile fire load (MJ/m ²)	x_{22}
The flame propagation class (-)	x_{32}
Destruction temperature (°C)	x_{42}

Table A.1. Continued

Variable	Comp.
Fire-specific data (vector x_2)	
A combination of a low fire load and a low number of ignition sources, such as for residential buildings (-)	x_{52}
A combination of a low fire load and a moderate number of ignition sources, such as in the industry of non-combustible products (-)	x_{62}
A combination of moderate fire load and a moderate number of ignition sources, such as in many industries (-)	x_{72}
A combination of a high fire load and a moderate number of ignition sources, such as in the paper and woodwork industry (-)	x_{82}
A combination of a high fire load and a low number of ignition sources, such as in storage industry (-)	x_{92}
The mobility subfactor considers evacuation time under such conditions as a multiple of the calculated time for healthy mobile and independent persons (-)	$x_{10,2}$
The number of persons that can be present in the compartment (persons/m ²)	$x_{11,2}$
The number of exit units (-)	$x_{12,2}$
Subfactor (the number of separate exit directions or exit paths available) (min.)	$x_{13,2}$
Automatic fire detection (-)	$x_{14,2}$
Improved water supplies (-)	$x_{15,2}$
Sprinkler system and other automatic detection (-)	$x_{16,2}$
Responding fire station (-)	$x_{17,2}$
The average fire resistance of the structural and separating elements (min.)	$x_{18,2}$
The average fire resistance of the outside walls (min.)	$x_{19,2}$
The average fire resistance of the ceiling or the roof (min.)	$x_{20,2}$
The average fire resistance of interior walls (min.)	$x_{21,2}$
Method-specific data (vector x_3)	
The number of cardinal points (north, east, south, west) (-)	x_{13}
The average dimension of the content and reflects the ratio between the total volume of the content and the total surface (m)	x_{23}
Level number of the building (the main access level has number $E = 0$; levels above: 1, 2, 3, etc., levels below: -1, -2, -3, etc.) (-)	x_{33}

Table A.1. Continued

Variable	Comp.
Method-specific data (vector $\mathbf{x}_3$)	
Will evaluate the possibility to replace the building and its content (-)	x_{43}
Will reflect the monetary value of the goods (€)	x_{53}
Depending on the individual activity (-)	x_{63}
Discovery of a fire and warning (-)	x_{73}
Manual extinguishers and hose stations to permit a rapid intervention of the occupants on a starting fire (-)	x_{83}
Fire brigade time factor (-)	x_{93}
Occupants training level (-)	$x_{10,3}$

Table A.2. Input variables used to calculate the FSES index I_{FSES} (the variables x_{11i} , x_{21i} , ..., $x_{13,1i}$ are used also to calculate the hierarchical approach index I_H) (Rasbash *et al.* 2004, SFPE 2002)

Variable	Value	Min.	Max.
Fire safety variables $S_k(\mathbf{x}_{1i})$			
Construction	x_{11i}	-13	4
Interior finish (corridors, exits)	x_{21i}	-5	3
Interior finish (rooms)	x_{31i}	-3	3
Corridor partitions/walls	x_{41i}	-10	2
Doors to corridor	x_{51i}	-10	2
Zone dimensions	x_{61i}	-6	1
Vertical openings	x_{71i}	-14	3
Hazards area	x_{81i}	-11	0
Smoke control	x_{91i}	-5	4
Emergency movement routes	$x_{10,1i}$	-8	5
Manual fire alarm	$x_{11,1i}$	-4	2
Smoke detection and alarm	$x_{12,1i}$	0	5
Automatic sprinklers	$x_{13,1i}$	0	10

Table A.2. Continued

Variable	Value	Min.	Max.
Occupancy risk variables $R_k(x_{2i})$			
Patient mobility	x_{12i}	1.0	4.5
Patient density	x_{22i}	1.0	2.0
Zone location	x_{32i}	1.1	1.6
Ratio of patients to attendants	x_{42i}	1.0	4.0
Patient average age	x_{52i}	1.0	1.2

Table A.3. Input variables used to calculate the Dow's index I_D (Dow 1994)

Variable	Value
Dimensionless variables representing general process hazards	$x_{11}, x_{21}, \dots, x_{61}$
Dimensionless variables representing special process hazards	$x_{12}, x_{22}, \dots, x_{12,2}$
Dimensionless variable representing the intrinsic rate of potential energy release from fire or explosion	x_0

Table A.4. Input vectors x_1 , x_2 and x_3 used to calculate the FRAME index related to building and occupants, respectively $I_{FRAME,1}$ and $I_{FRAME,2}$

Notation of variable in the FRAME manual	Comp.	Value	Notation of variable in the FRAME manual	Comp.	Value
Geometry data (vector x_1)			k	$x_{18,2}$	0.008
h	x_{11}	5	f_s	$x_{19,2}$	90
H^+	x_{21}	15	f_f	$x_{20,2}$	0
l	x_{31}	70	f_d	$x_{21,2}$	15
b	x_{41}	40	f_w	$x_{22,2}$	0
Fire-specific data (vector x_2)			u_l	$x_{23,2}$	0
Q_i	x_{12}	100	u_2	$x_{24,2}$	0
Q_m	x_{22}	400	u_3	$x_{25,2}$	8
M	x_{32}	1	w_l	$x_{26,2}$	0
T	x_{42}	150	w_2	$x_{27,2}$	0
a_l	x_{52}	0	w_3	$x_{28,2}$	0

Table A.4. Continued

Notation of variable in the FRAME manual	Comp.	Value	Notation of variable in the FRAME manual	Comp.	Value
a_2	x_{62}	0.1	w_4	$x_{29,2}$	1
a_3	x_{72}	0	w_5	$x_{30,2}$	0
a_4	x_{82}	0.1	Method-specific data (vector $\mathbf{x}_3$)		
a_5	x_{92}	0	Z	x_{13}	3
p	$x_{10,2}$	1	m	x_{23}	0.3
X	$x_{11,2}$	0.1	E	x_{33}	3
x	$x_{12,2}$	4	c_1	x_{43}	0
K	$x_{13,2}$	4	c_2	x_{53}	$12 \cdot 10^6$
s_1	$x_{14,2}$	0	n_1	x_{63}	0
s_2	$x_{15,2}$	3	n_2	x_{73}	0
s_3	$x_{16,2}$	0	n_3	x_{83}	2
s_4	$x_{17,2}$	14	n_4	x_{93}	0

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

B.1. Introduction

Sprinkler systems can substantially contribute to the prevention of heavy fires and mitigation of fire consequences. When applied in combination with another protective systems, (e.g. fire alarm), the sprinklers can considerably reduce the risk posed by fires (e.g. Melinek 1993ab; Rasbash *et al.* 2004; Guanquan and Jinhua 2008; Chow and Chow 2009). Unfortunately, another obvious fact is that sprinkler systems are not fail-safe technical objects. The percentage of fires, in which sprinkler systems do not carry out their extinguishing function, is relatively large. The data on failures of sprinklers and other active fire protection measures collected over the past 50 years indicate that in some cases the chance of failure is unacceptably high (Rasbash *et al.* 2004; Rönty *et al.* 2004; Nyyssönen *et al.* 2005; Hall 2006, 2010; Koffel 2006).

The problem of sprinkler reliability was addressed by many authors who applied various approaches to dealing with the potential sprinkler failure. The approaches range from a simple calculation of country-specific failure rates to an estimation of reliability by applying methodological means of quantitative risk assessment (QRA) based on Bayesian reasoning (e.g., Siu and Apostolakis 1986, 1988; Hauptmans *et al.* 2008; Malm and Pettersson 2008). However, the issue of failure data and other information necessary for reliability assessment was not addressed in a more or less systematic way.

This annex takes a look at the available and accessible data on sprinkler reliability. Several aspects related to the collection of this data are reviewed as well. An effort was made to distinguish between failure data collected in conventional buildings and data accumulated in installations of nuclear, offshore and process industries as well as military facilities. The attention was focussed on the wide category of sprinklered conventional buildings which make up the largest part of sprinklered environment. The main purpose was to assess the data situation in terms of the possibility to form data sets and gain other information for the estimation of sprinkler reliability.

B.2. Sprinkler failure modes and collection of failure data

A sprinkler system (or sprinklers, in brief) is a relatively complicated technical object which can fail in variety of ways (modes). Specific failure modes are also related to a specific type of sprinklers which can have four principal arrangements (Table B.1). These four basic types of sprinklers differ in terms of

how water is put into the area of the fire and, of course, how they fail on component and system level. The lists of components and subsystems given in Table B.1 should be supplemented with critical human “components” (system owner, designer, installer, inspector, maintenance person). A human factor plays a major role in failures of sprinklers installed in conventional buildings, the safety culture of which is not necessarily very strict (e.g., Hall 2006, 2010).

Table B.1. Four basic types of sprinkler systems (compiled from SFPE 2002)

Type	Principal components/subsystems	No of components/subsystems
Wet pipe system	Water supply from the main (water tank); gate valve to control water supply to system; alarm valve; piping network; sprinkler heads	5
Dry pipe system	Water supply from the main (water tank); gate valve to control water supply to system; dry pipe valve; piping network; sprinkler heads	5
Deluge system	Water supply from the main (water tank); main control valve; electric sprinkler alarm; deluge valve; release valve; smoke detector; thermal detector; control panel; piping network; battery cabinet	10
Preaction system	Water supply from the main (water tank); main control valve; electric sprinkler alarm; deluge valve; check valve; air supply; smoke detector; thermal detector; control panel; piping network; battery cabinet; closed sprinkler head; system maintaining small fire pressure in the fire network	10

Contribution of failures on the component level to the sprinkler system failure is represented by means of fault tree diagrams (Rönty *et al.* 2004; Hauptmans *et al.* 2008). Both identification of system failure modes and development of fault tree diagrams for them will reveal what data is necessary for the estimation of system reliability. A unified and, ideally, world-wide classification of causes and modes of sprinkler failures could improve the collection and exchange of failure data and probably the quality of the data. Unfortunately, a simple look at the literature devoted to sprinkler reliability shows that in the past years different authors/countries applied different classifications of modes and causes of system failure (Tables B.2 and B.3). Some authors mix modes, causes and circumstances of failures together in one list. Differences between some definitions of failure modes may be only semantic; however, the lack of a unified failure terminology does not facilitate the collection and exchange of data.

Table B.2. Lists of modes and causes of sprinkler failures used by different authors

Author(s)	Failure modes and causes
Linder (1993)	Installation errors, design mistakes, manufacturing/equipment defects, lack of maintenance, exceeding design limits, and environmental factors
Rönty <i>et al.</i> (2004)	Usage failure, maintenance failure, installation failure, device failure, instruction failure
Malm and Pettersson (2008)	No activation of sprinkler system, fire in a non-sprinklered area with deficient fire compartmentation, extinguishing agent does not reach the fire (insufficient amount of water, inadequate design), sprinkler system shut off
Siu and Apostolakis (1986, 1988)	Failure to actuate given a demand (demand unavailability), failure to put out the fire given an actuation, suppression of fire after a critical set of components has been damaged
Koffel (2006), Hall (2010)	Operational failure/reliability, performance failure/reliability

Table B.3. A brief summary of data on sprinkler failure probabilities (Moelling *et al.* 1980, reproduced also by Rönty *et al.* 2004)

Failure mode	Point estimates and 90 % confidence estimates of probability per demand		
	Lower bound	Point estimate	Upper bound
Sprinkler heads fail to open	Not reported	$<1 \times 10^{-6}$ (0.0001 %)	Not reported
Fire detectors fail to function	1.89×10^{-3} (0.189 %)	2.97×10^{-3} (0.297 %)	4.45×10^{-3} (0.445 %)
Deluge valves fail to open	8.9×10^{-4} (0.089 %)	1.90×10^{-3} (0.19 %)	3.58×10^{-3} (0.358 %)
Fire pumps fail to start	4.47×10^{-3} (0.447 %)	1.40×10^{-2} (1.4 %)	2.39×10^{-2} (2.39 %)
Check valves fail to open	3×10^{-5} (0.003 %)	1×10^{-4} (0.01 %)	3×10^{-4} (0.03 %)
Alarms fail to function	2.681×10^{-2} (2.681 %)	3.62×10^{-2} (3.62 %)	4.81×10^{-2} (4.81 %)
Personnel fail to trip manual release	Not reported	0.2	Not reported
Frequency of the event “valves closed inadvertently”	5.47×10^{-3} year ⁻¹ (0.547 %)	5.475×10^{-2} year ⁻¹ (5.475 %)	0.5479 year ⁻¹

Reasons for the variation of failure causes and modes are analysed by Malm and Pettersson (2008). They also detected and addressed an obvious variation of reliability estimates among different sources. An illustration of such a variation

is shown in Table 2.6. The variation among reliability estimates as well as the lack of unification in naming causes and modes of sprinkler failures is among four factors which complicate the estimation of sprinkler reliability (Fig. 2.1, corners 1 and 2).

One can expect that sprinkler failure terminology is unified in some industries and military environments with high safety culture and well-developed system of reliability and accident data collection, first of all, nuclear and offshore industries (e.g., see Cadwallader and Eide 2010 and the references therein, NTNU 2010). However, the industrial and military installations are only a small fraction of sprinklered built environment.

The dominance of human factor among causes of sprinkler failures is another issue which complicates reliability estimation (Fig. 2.1, corner 3). Human errors can be the cause of all types of sprinkler system failures (Fig. B.1). Hall (2006, 2010) states that, according to US data collected after fires in conventional buildings, almost all sprinkler failures to operate (demand failures) were caused by human errors. Only 2 to 3 % of such failures were due to damaged components. It is obvious that, at least in buildings with relatively lax safety culture, the problem of sprinkler reliability is largely the problem of human reliability. In this respect, sprinklers are similar to building structures, the failures of which are caused predominantly by human errors (e.g., Melchers 1999). The prediction of improper human behaviour in the design, installation and use of sprinklers requires specific data.

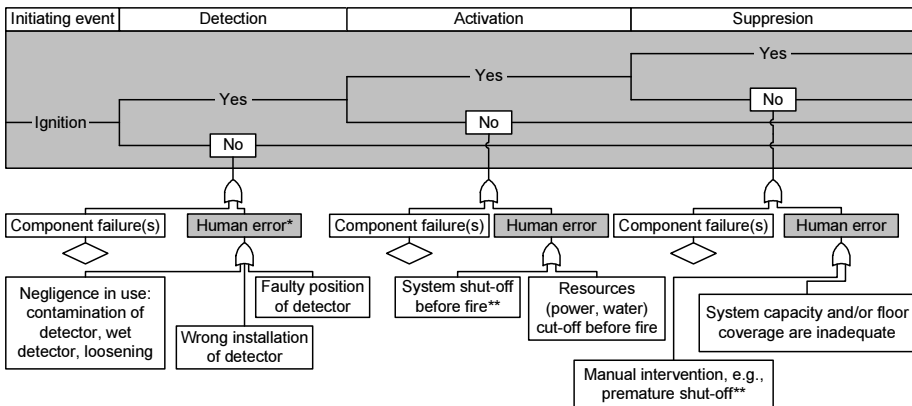


Fig. B.1. Schematic event tree shown with the fault trees developed for the illustration of the influence of human error on the sprinkler system failure (*according to Nyysönen *et al.* (2005); **according to Hall (2006))

The generic data on human errors is available in the form of human reliability databases, such as, THERP, HEART, HRC and INTENT (e.g.,

Vaidogas 2007a; Vlasenko and Kozlov 2009). However, such data was collected mainly in industrial environments. At present it is not clear to what degree information from such databases is suitable to the estimation of reliability of sprinklers used in conventional buildings. Any sprinkler-specific database of human reliability is not known to us.

The influence of human factor now can be approximately assessed from the general studies of sprinkler reliability (e.g., Rönty *et al.* 2004; Malm and Pettersson 2008; Hall 2006, 2010). The incorporation of human errors into the fault tree analysis (FTA) aimed to estimate sprinkler reliability can reveal what specific human reliability data may be necessary for the estimation (Hauptmans *et al.* 2008). However, FTA as such does not generate data.

The changes during a long-lasting life of sprinkler systems are the fourth factor which makes difficult the collection of failure data suitable to adequate reliability estimation (Fig. 2.1, corner 4). In conventional buildings, sprinklers are used over several decades and are subjected to a gradual ageing. It is natural to expect that the ageing along with modifications and repairs “invisibly” influence the reliability of sprinklers. In addition, changes in building ownership or tenancy during the life-time of sprinklers can lead to changes in the safety culture and so the influence of human factor on possible failures.

A collection of data, which would allow a full-scale time-dependent reliability analysis, will require observation of sprinkler populations lasting many years and, possibly, carrying out accelerated degradation (ageing) tests. Any data collected in such a way is not known to us. We can only notice again that the problem of time-dependence of sprinkler reliability is similar to the time-dependence of reliability of building structures (e.g., Melchers 1999). Knowledge gained in the latter field can be applied in the former one.

The failure modes of sprinklers include also an accidental activation (discharge of water in the absence of fire). The non-fire activation is mainly due to a manufacturing defect, an improper installation or user error. The data on accidental system activations are presented, among others, by Jensen *et al.* (2006), Butry *et al.* (2007), Hall (2010). In principle, both probability of sprinkler failure in fire and in the absence of fire can be estimated by means of FTA. In either case FTA will require component failure data and human reliability data. At the present time, we are not aware of any open data source which would contain component level data related to non-fire activations.

B.3. Data related to sprinkler reliability

The potential sources of information which can be used for the assessment of sprinkler system reliability can be classified as follows:

1. Direct post-mortem data on sprinkler system failures during fires;
2. Input data on system component failures for fault tree models developed for specific sprinkler systems;
3. Specific information which may influence results of sprinkler reliability assessment (e.g., the percentage of the fires in which sprinklers operate and which are not reported to the fire brigade, see Rogers 1977; Rasbash *et al.* 2004);
4. Subjective knowledge allowing expert judgment used in QRA models which can be developed for a sprinkler system (e.g., Siu and Apostolakis 1986, 1988).

The hard historic data on sprinkler failures on system and component level is yielded by the first two information sources. Data of the third data source can, in essence, be attributed to one of the first two sources. The subjective information classified as the fourth data source can be combined with the hard data within the Bayesian approach to QRA (Siu and Kelly 1998; Kelly and Smith 2009).

B.3.1. Potential populations for retrieval of data on system failures

The number of sprinkler installations in large countries and regions is in millions. The number of fires in sprinklered buildings can be in thousands of events from the population of millions and the number of sprinkler failures in fires can reach hundreds of events (e.g., Rohr 2001; Rohr and Hall 2005; Hall 2010). Thus, at first glance, the possibly large amount of direct data on sprinkler failures might allow to assess the sprinkler failure probability by means of the classical (Fisherian) approach. However, the variety of environments, in which sprinklers are installed, and differences within the population of sprinklers may constrain the possibility to estimate the reliability directly from the failure data.

The size of the population of sprinkler installations and failure data retrieved from this population may be limited by several factors shown in Fig. 2.2. These factors include:

- The culture of data collection and exchange;
- The relevance of data from different environments;
- Possible concealment of failure data.

The collection and exchange of sprinkler reliability data has different level of organisation in different environments. Data is systematically accumulated

and shared in nuclear power plants through a voluntary collaboration of a number of installations worldwide (e.g., Berg *et al.* 2006; Atwood *et al.* 2003; Cadawallader 2007). Some other industries, for instance, oil and gas production, have also a well-organised collection of data on reliability of fire detection and suppression measures (e.g., OGP 2010). However, nuclear power plants as well as some industrial and military installations are a relatively small fraction of sprinklered build environment. An international collaboration in collection of failure data seems not to be available in the case of sprinkler installations in conventional buildings (e.g., residential, institutional and public ones).

The availability and quality of failure data may be positively influenced by legislation and/or practice of data collection and reporting in specific countries (Malm and Pettersson 2008). Rasbash *et al.* (2004) praise Australia and New Zealand for establishing a thorough compilation and reporting of data on performance of sprinklers. In these two countries all sprinkler systems are by law directly connected to fire stations and so activation is automatically accompanied by attendance of the brigade. Hall (2006, 2010) describes the American fire accident reporting system NFRIS which allows to calculate sprinkler failure rates using US data on fires. Unfortunately, it is difficult to say how much the failure data from these three countries is relevant to sprinklered environments in other regions.

Different environments are characterised by different safety culture and, possibly, different dominant causes of failures and quality of reliability data. One might expect that the safety culture in nuclear and military installations is higher than that in conventional buildings. Thus failure data from nuclear industry can hardly be automatically applied to, say, domestic sprinklers. Any attempts to measure formally, more or less, the degree of relevance of system failure data to different environments are not known to us.

The relevance of failure data can be considered on the much more detailed level. It is probable that different manufacturers and installers of a specific sprinkler system achieve different level of reliability. Thus failure data on system and component levels collected by specific manufacturer may not be applicable to products of other manufacturers.

The relevance of sprinkler failure data can also be influenced by the period in which the data was collected. It is natural to expect that data on failures accumulated in, say, 1960s and 1970s may not be fully relevant to sprinkler systems manufactured after 30 or 40 years. The general problem and causes of data ageing is mentioned in the reliability literature, for instance, by Cadwallader and Eide (2010). However, any study on “ageing” of data on sprinkler system failures doesn’t seem to be available.

The availability of the data on sprinkler failures can also depend on the possible negative influence of these events on the business of system

manufacturers and insurance companies. One can expect that, at least in some countries, data on sprinkler failures in some specific built environments are kept secret by insurers and manufacturers for commercial reasons. This may be the cause of scarceness of such data for those who do not have access to the in-house information owned by insurers and manufacturers.

B.3.2. The sources of data on system failures

Data on sprinkler system failures are published in studies reported between at least 1950s and 2000s. A brief review of such studies is presented in Table 2.6. Similar reviews with references to individual studies and “raw” estimates of sprinkler reliability are presented by Bukowski *et al.* (1999), Fleming (2004), Rasbash *et al.* (2004), Koffel (2006) and Malm and Pettersson (2008). The studies on sprinkler reliability present information in the form of raw data (e.g., the size of sprinkler population and number of fires and failures) and data reduced into failure rates and probabilities related to specific failure modes (Rönty *et al.* 2004; Hall 2006, 2010; Koffel 2006). Table B.3 is an example of the latter type of data accumulated in four nuclear power plants.

Many of the published studies into sprinkler reliability cover failure data obtained in the specific environment of nuclear power plants (Moelling *et al.* 1980; Berg and Rowekamp 2000; Rönty *et al.* 2004; USNRC 2005; Berg *et al.* 2006). There are also reports which cover a wide range of data on sprinkler failures in buildings used outside the nuclear industry (Rohr 2001; Rönty *et al.* 2004; Rohr and Hall 2005; Hall 2006; Koffel 2006; Malm and Pettersson 2008). The scope, breadth and reporting periods of the studies cited above vary significantly. A brief look at these studies allows to state that data on system failures is undoubtedly available. However, data accumulated outside nuclear and offshore industries reflects mainly the performance of sprinklers in specific countries within specific periods. Any attempt to develop an international database from such data is not known to us.

It seems that at present one can simply say that a particular set of data (raw data or failure rates) will be suitable to an estimation of reliability of a specific sprinkler system only after it is possible to prove that this system belongs to the sprinkler population which generated the data set. On the other hand, the generic data on sprinkler system failures can be useful for the estimation of system failure probabilities within the Bayesian format, for instance, the development of prior distributions for system failure probabilities (see Sec. B.4). In addition, the hard system failure data can be used for an approximate verification of system reliability estimates obtained by means of FTA.

B.3.3. Component failure data

The estimation of sprinkler system reliability by means of FTA is the opposite to the estimation directly from the system failure data. An FTA requires component failure data and the answers to the question where such data can be found are often OREDA data book (OREDA 2002), IEEE Standard 500 (IEEE 1986ab), or the CCPS Guidelines for process equipment reliability data (CCPS 1989). Cadwallader and Eide (2010) present a review of data sources retrievable in the literature published from 1993 forward. A list and short description of component reliability data sources can be found at the website of the Norwegian University of Science and Technology (NTNU 2010).

The data sources just mentioned contain a considerable body of generic data which can be useful as a first approximation of the failure rates of sprinkler system components. For instance, Hauptmans *et al.* (2008) refer to data from three different environments (offshore, nuclear and process plant data) to perform an FTA of a wet sprinkler system. The use of data collected in different environments yields an estimate which undoubtedly may be taken as a first approximation to system reliability. However, the “mixture” of input information may cast a natural doubt upon relevance of this estimate to each of these environments taken alone, to say nothing of the sprinklered environment in conventional buildings.

Many of the component failure data sources are specific to the environments of nuclear, offshore and chemical industries as well as military installations. The range of engineering system components covered by these data sources is very wide. However, the specific information on sprinkler system components is not present in them. For instance, the OREDA data book includes information on gas and fire detectors and does not say anything about fire extinguishing systems (OREDA 2002). The IEEE Standard 500 contains information on failures of pumps and valves and this information might be applicable to components of sprinkler systems (IEEE 1986b). However, the direct data on sprinkler system components is not available in this data source. We think that a special study is necessary to determine whether or to what degree the general sources of data on engineering system component failures can be used to perform fault tree analyses of sprinkler systems installed in conventional buildings.

It is natural to assume that manufacturers of sprinkler systems installed in conventional buildings, insurers, and persons/bodies who inspect and maintain such systems may possess in-house collections of data on component-level failures. Unfortunately, it does not seem that somebody took an effort to assemble such data into a component-specific database which would be retrievable from the literature or the internet. We even did not find any reference to such a database. At present it is also not clear how the fire incident reporting

systems, such as NFRIS in US and in a system run by Swedish organisation NCO, are suitable to extract reliability data related to sprinkler system components.

Some data on sprinkler component failures recorded in nuclear and non-nuclear environments are presented in the report prepared by Rönty *et al.* (2004). However, this report can hardly be considered a systematic database.

B.4. Bayesian inference and sprinkler failure data

B.4.1. Data required by usual Bayesian schemes

A large set of failure data allows to calculate an accurate frequentist estimate of sprinkler reliability. The usual estimate is a confidence interval of binomial parameter p or Poisson parameter λ . Rönty *et al.* (2004) and Nyssönen *et al.* (2005) present an interval estimation of λ for sprinklers and fire detection and alarm systems. As sprinklers operate on demand and not over time, the following consideration will focus on the binomial parameter p .

Data on sprinkler failures can be scarce due to various reasons. Some of them were considered in Secs. B.2 and B.3.1. Data scarceness can be faced also during the prediction of human errors and acts of negligence in installation and use of sprinklers and other fire safety systems. The data on sprinkler ageing and the influence of modifications and repairs on the process of ageing may also be scarce from the standpoint of the frequentist estimation.

The Bayesian inference is used to deal with small data sets as well as to combine several sources of information for the estimation of distribution parameters. To our knowledge, the first application of Bayesian inference to scarce sprinkler failure data collected in nuclear installations was done in 1980s by Siu and Apostolakis (1986, 1988). As applied to the estimation of p , the Bayesian inference uses subjective beliefs and/or data from different sources to specify a prior density $\pi(p)$ as well as the so-called plant-specific data E to update $\pi(p)$ to the posterior density $\pi(p | E)$ (e.g., Siu and Kelly 1998).

The widely known schemes of parameter estimation are hierarchical Bayes and empirical Bayes methods (e.g., Atwood *et al.* 2003). The QRA literature describing these methods is, as a rule, semantically oriented to nuclear power plants. However, both methods can be directly applied to the case of sprinklers, as long as failure data is available and can be arranged according to the schemes of these methods. The position of raw data on sprinkler failures in a special case of the hierarchical Bayes method is illustrated by Fig. B.2.

Several points of the Bayesian parameter estimation can be considered problematic:

1. The expression of failure data in the form E and E_k shown in Fig. B.2 requires collection and exchange of raw data as well as a careful characterisation of environment which generated each pair (r_i, n_i) . Unfortunately, we do not know any reports about an attempt to form the data E for at least most typical sprinklered environments.

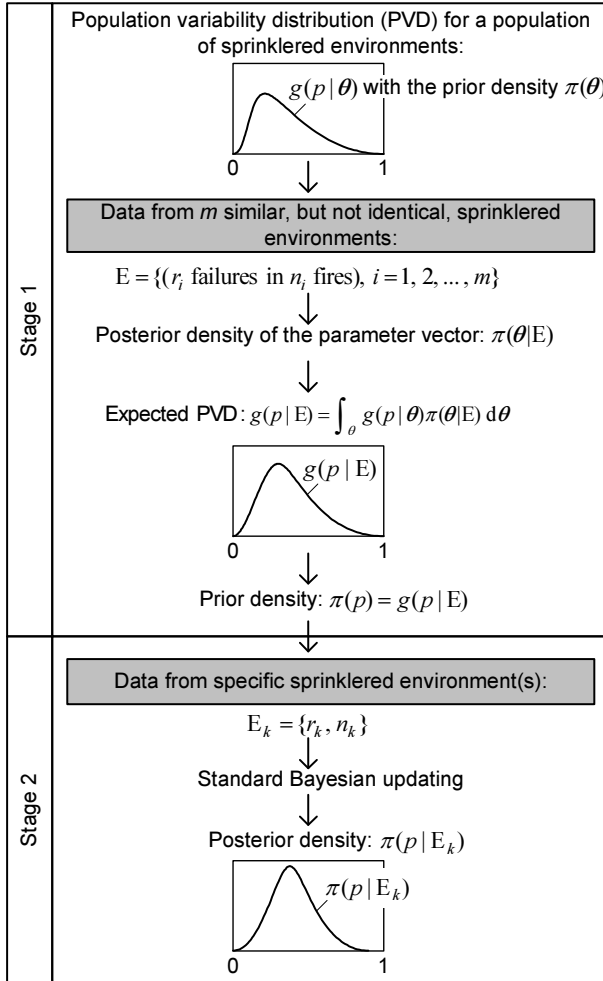


Fig. B.2. The position of sprinkler failure data in the two-stage Bayes method applied to the binomial parameter p (this method is a special case of the hierarchical Bayes method, e.g., Siu and Kelly 1998)

2. It might be problematic to state what are similar, but not identical, sprinklered environments (or plants in conventional terms of QRA). What degree of difference between such environments is still acceptable?
3. The data E and E_k does not contain direct information on human errors and ageing as potential causes of sprinkler failures. Thus the estimates $\pi(p)$ and $\pi(p|E)$ will not allow to say anything about the contribution of these factors to failures.

It is difficult to say with certainty, how much the probability p is influenced by ageing, repairs and modifications of sprinklers. However, an existence of an upwards or downwards trend in p and other changes of p over time will require to apply time-dependent modelling which must be backed by specific failure data.

B.4.2. Data to analyse ageing

The basic model of ageing is a time trend (gradual change) in p expressed as $p(t)$ (Fig. B.3). The standard choice of $p(t)$ is the logit model

$$\ln(p(t)/(1 - p(t))) = \alpha + \beta t \quad (\text{B.1})$$

with the intercept parameter α and the trend parameter β . They can be estimated from data by means of either frequentist or Bayesian inference (Atwood *et al.* 2003). The presence of trend can also be checked from available data by applying either frequentist or Bayesian methods (Kelly and Smith 2009). If $p(t)$ is small, the logit model can be approximated by the loglinear model

$$\ln(p(t)) = \alpha + \beta t \quad (\text{B.2})$$

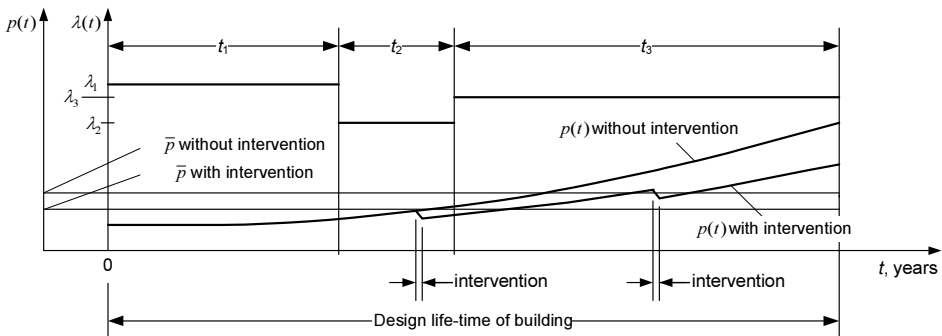


Fig. B.3. Two evolutions of the sprinkler failure probability $p(t)$ during the life-time of the building divided in three periods with different fire hazards expressed by annual fire rates (Poisson parameters) λ_1 , λ_2 , and λ_3

The raw data used to test for presence of trend and to obtain confidence intervals of $p(t)$ (in the frequentist case) and posterior distributions of $p(t)$ (in the Bayesian case) must be collected by counting number of demands and number of failures on demand during some period of time. This data must be generated by a population of objects (say, sprinklers of specific type) to which the object under analysis can be attributed.

To carry out the frequentist or Bayesian analysis, the raw data is combined into bins, usually, calendar years. In this way the so-called binned binomial data is obtained. As we did not find an example of binned data related to sprinkler failures, such data is illustrated in Table B.4 for a demand event in nuclear industry (high pressure coolant injection). Binned binomial data can also be obtained by testing some number of components during an annual plant outage (Pulkkinen and Simola 2000).

Table B.4. Binned data of failures on demand of a critical system in 23 nuclear reactors (Atwood *et al.* 2003)

Calendar year (bin)	Number of failures	Number of demands	Exposure time (years)*
1987	4	16	14.63
1988	2	10	14.15
1989	1	7	15.75
1990	3	13	17.77
1991	2	9	17.11
1992	0	6	17.19
1993	0	2	17.34

* The number of years in the bin when the reactors were producing steam

In principle, binned binomial data can be extracted from the general data on sprinkler failures. Binning must be preceded by a determination of a relevant population which will generate the data. A natural choice is a population consisting of nominally identical or very similar components or systems installed in comparable environments. At the present time, any attempts to analyse the time trend in the failures of sprinklers by means of binned binomial data are not known to us.

One can expect that the trend in the sprinkler failure probability p will be positively influenced by interventions of relatively short duration (maintenance, modifications and repairs of sprinklers) (Fig. B.3). Changes of $p(t)$ may take place several times within the life-time of sprinklers and parent building. In

principle it is possible to accumulate data which indicates time, duration, technical content and rate of the interventions. However, theoretical models which would allow to relate such data to potential changes in $p(t)$ is are not available to date. Thus it is not clear how to collect data which could “feed” such models.

If failures of some sprinkler component are detected during routine inspections and this leads to repairs, the formalism of reparable systems can be applied to predict the failure rate of this component, $\lambda(t | a, b)$ (parameter of a non-homogenous Poisson process). Data used for the estimation of a and b are successive failure times (e.g. Deshpande and Purohit 2005). The estimation of a and b is possible in the Bayesian format (Kelly and Smith 2009). Unfortunately, it is not clear how to determine the exact failure times of sprinkler components if inspections are relatively rare, say, annual ones. Even if the data will be available, the relation between the models $\lambda(t | a, b)$ and $p(t)$ must be developed.

Annex C. Computer code MCS

The present annex contains the computer code MCS used to solve MCDM problems with random decision making matrix. The code was written in FORTRAN programming language. It consists of main source file “MCS_Main.for” and a number of subroutines and functions. The structure of the computer code is explained in Fig. C.1. Some of the code modules, which were used for technical purposes, are not included in Fig. C.1 and this annex.

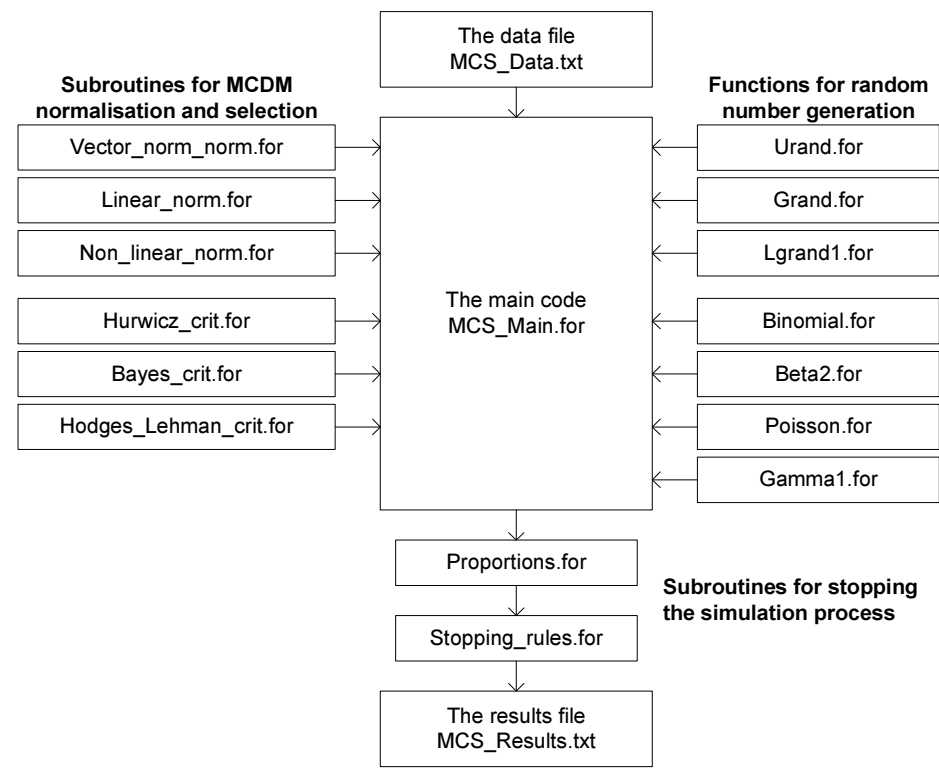


Fig. C.1. The structure of the computer code MCS (Multi-criteria selection)

Text of “MCS Main.for”
<pre>PROGRAM MCS ! (Multi-criteria selection) * * INCLUDE 'MCS_CONSTANTS.FOR' * 1 * Arrays for the matrix of soluiton and matrix of dimensionless attributes REAL*8 p(MAXALTERN,MAXATTRIB), ps(MAXALTERN,MAXATTRIB) * Vectors for flags of max/min preferences (max=1, min=0) INTEGER prefflag(MAXATTRIB) CHARACTER*3 prefs(MAXATTRIB)</pre>

```

* Flag variable for using the weights and array for weights
  CHARACTER*10 weight_flag
  REAL*8 weights(MAXATTRIB)
* Variables for the choice of normalisation method and MCS criterion
  INTEGER normalisation_method, criterion
  REAL*8 rowmax(MAXATTRIB), rowmin(MAXATTRIB)
  REAL*8 colmax(MAXALTERN), colmin(MAXALTERN)
* Index for the rows and index for the columns
  INTEGER ii, jj
* Number of rows and number of columns in the decision making matrix
  INTEGER ni, nj
* Sums of column elements and row elements
  REAL*8 sumc(MAXATTRIB), sumr(MAXALTERN)
* Array containing ones and zeros indicating the best alternative
  INTEGER binary(MAXALTERN)
* Array containing frequencies of selecting alternatives in the process of
simulation
  REAL*8 fr(MAXALTERN), sumfr(MAXALTERN)
* Arrays for current column and rows
  REAL*8 curc(MAXALTERN), curr(MAXATTRIB)
* The weighting factor for the Hurwicz's criterion
  REAL*8 lamda
* Number of Monte Carlo simulations, no of current simulation and
corresponding variable & seed
  INTEGER nmontecarlo, imc, seed
* Variable containing format for writing the required number of columns
* r stands reals, i for integers, c for characters
  CHARACTER*15 frmt(30)
* Variable used to indicate the reduction of the zero hypothesis about
equality of
* the proportions in the current simulation loop
* (istop_current=1, if H0 is rejected for all combinations of the
proportions, and
* istop_current=0, if H0 is accepted for at least one combination of the
proportions)
  INTEGER istop_current
* Flag variable for the activation of the stopping rule used in the MC
simulation
  INTEGER istop_flag
* Variable used to indicate the termination of the simulation loop
* based on comparison of proportions
  INTEGER n_stop_proportions
* Binary variable indicating the stop of the simulation process according to
the currently
* used stopping rule
  INTEGER i_final_stop
* Functions
  REAL*8 vecmin, vecmax, BETA2, LGRAND1
* 2
  OPEN (INPUT, FILE='MCS_Data.txt', STATUS='OLD', FORM='FORMATTED')
  OPEN (OUTPUT, FILE='MCS_Results.txt', STATUS='OLD', FORM='FORMATTED')
  OPEN (OUTPUT1, FILE='Sprinklers.txt', STATUS='OLD', FORM='FORMATTED')
  OPEN (OUTPUT2, FILE='Sequences.txt', STATUS='OLD', FORM='FORMATTED')
  OPEN (OUTPUT3, FILE='Frequencies.txt', STATUS='OLD', FORM='FORMATTED')
  OPEN (OUTPUT4, FILE='Z_values.txt', STATUS='OLD', FORM='FORMATTED')
  WRITE(*, '(A20/)') 'MCS is running ...'
* 3
* Read the number of alternatives & attributes
  READ (INPUT, '(I10)') ni
  READ (INPUT, '(I10)') nj
* Prepare format for writing the required number of columns (attributes)
  CALL formats(nj, frmt(1), ' G13.06')
  CALL formats(nj, frmt(2), ' (A9,4X)')
  CALL formats(nj, frmt(3), ' D13.04')
  CALL formats(nj, frmt(4), ' G10.04')
  CALL formats2(ni, frmt(5))

```

```

* Read & check initial data
  READ (INPUT,frmt(4)) ((p(ii,jj),jj=1,nj),ii=1,ni)
  READ (INPUT,frmt(4)) (prefflag(jj),jj=1,nj)

*
  READ (INPUT,'(A5)')      weight_flag
  IF(weight_flag.EQ.'no') THEN
    WRITE (OUTPUT,'(/A35)') 'Weights are not applied.'
    READ (INPUT,'(/)')
  ELSE IF (weight_flag.EQ.'yes') THEN
    READ (INPUT,frmt(4)) (weights(jj),jj=1,nj)
    CALL check_weights(weights,nj,1.0D-5)
  ELSE
    WRITE (OUTPUT,'(/A40)') 'The flag for weights is incorrect...'
    STOP
  END IF

*
  READ (INPUT,'(I10)')      normalisation_method
  READ (INPUT,'(I10)')      criterion
  READ (INPUT,'(I10)')      seed
  READ (INPUT,'(I10)')      nmontecarlo
  READ (INPUT,'(I10)')      istop_flag

* 4
* Write initial data
  WRITE (OUTPUT,'(A25,I10)') 'Number of alternatives: ', ni
  WRITE (OUTPUT,'(A25,I10)') ' Number of attributes: ', nj
  WRITE (OUTPUT,'(/A35)') 'Matrix of solution:'
  WRITE (OUTPUT,'(/A35)') 'The weights assigned to attributes:'
  WRITE (OUTPUT,frmt(1)) (weights(jj),jj=1,nj)
  WRITE (OUTPUT,'(A35)') 'Min/max preferences of attributes:'
  DO jj=1,nj
    IF(prefflag(jj).EQ.0) prefs(jj)='min'
    IF(prefflag(jj).EQ.1) prefs(jj)='max'
  END DO
  WRITE (OUTPUT,frmt(2)) (prefs(jj),jj=1,nj)

* 5
* Prepare information related to the Monte Carlo simulation
  IF(nmontecarlo .NE.1) THEN
    WRITE (OUTPUT,'(/A47,I9)')
    &      'The initial number of Monte Carlo simulations:',
    &      nmontecarlo
    WRITE(OUTPUT,'(/A35\))') 'Normalisation method:'
    IF(normalisation_method.EQ.1) WRITE(OUTPUT,'(A12)') 'vector-norm'
    IF(normalisation_method.EQ.2)
    &      WRITE(OUTPUT,'(A22)') 'linear normalisation'
    IF(normalisation_method.EQ.3)
    &      WRITE(OUTPUT,'(A26)') 'non-linear normalisation'
    WRITE(OUTPUT,'(A35\))') 'Criterion applied:'
    IF(criterion.EQ.1) WRITE(OUTPUT,'(A8)') 'Wald's'
    IF(criterion.EQ.2) WRITE(OUTPUT,'(A9)') 'Savage's'
    IF(criterion.EQ.3) WRITE(OUTPUT,'(A10)') 'Laplace's'
    IF(criterion.EQ.4) WRITE(OUTPUT,'(A10)') 'Hurwicz's'
    IF(criterion.EQ.5) WRITE(OUTPUT,'(A10)') 'Bayes's'
    IF(criterion.EQ.6) WRITE(OUTPUT,'(A15)') 'Hodges-Lehman's'

* Check against using several MCS criteria
    IF(criterion.EQ.111) THEN
      WRITE (OUTPUT,'(/A40,A40)')
      &      'The use of more than one MCS criterion ',
      &      'is not allowed in case of simulation ...'
      STOP
    END IF
  END IF

* Assign values to the sums used in the stopping rules
  n_stop_proportions=0
  i_final_stop=0

* *** THE MONTE CARLO LOOP ***
  DO imc=1,nmontecarlo

```

```

*
CALL sprinkler_risk(nmontecarlo,imc,seed,p,ni,nj)
*
IF(nmontecarlo.NE.1) THEN
* 6
WRITE(OUTPUT,'(A6,I6)') ' Loop ', imc
*   p(1,2)=BETA2(seed,4,48)
*   p(2,2)=BETA2(seed,7,55)
*   p(3,2)=BETA2(seed,5,25)
*   WRITE(OUTPUT,'(4D15.6)') (p(ii,1), ii=1,ni)
*   END IF
* 7
IF(nmontecarlo.EQ.1) THEN
  WRITE (OUTPUT,fmt(1)) ((p(ii,jj),jj=1,nj),ii=1,ni)
  END IF
*
  IF(nmontecarlo.EQ.1)
    &   WRITE (OUTPUT,'(/A35)') 'Matrix of dimensionless attributes:'
* 8
* Normalise the matrix of solution
  IF(normalisation_method.EQ.1) THEN
* Vector norm normalisation
    IF(nmontecarlo.EQ.1) WRITE (OUTPUT,'(A45)')
    &   ' (obtained by the vector-norm-normalisation)'
    CALL vector_norm_norm(p,ps,prefs,ni,nj)
    END IF
*
  IF(normalisation_method.EQ.2) THEN
* Linear normalisation
    IF(nmontecarlo.EQ.1) WRITE (OUTPUT,'(A45)')
    &   ' (obtained by the linear normalisation)'
    CALL linear_norm(p,ps,prefs,ni,nj)
    END IF
  IF(normalisation_method.EQ.3) THEN
* Non-linear normalisation
    IF(nmontecarlo.EQ.1) WRITE (OUTPUT,'(A45)')
    &   ' (obtained by the non-linear normalisation)'
    CALL non_linear_norm(p,ps,prefs,ni,nj)
    END IF
  IF(nmontecarlo.EQ.1)
    &   WRITE (OUTPUT,fmt(3)) ((ps(ii,jj),jj=1,nj),ii=1,ni)
*
* 9
* Select the best alternative
*
  IF(criterion.EQ.1.OR.criterion.EQ.111) THEN
* Wald's criterion
  IF(nmontecarlo.EQ.1)
    &   WRITE (OUTPUT,'(/A35)') 'Wald''s criterion:'
    DO ii=1,ni
      DO jj=1,nj
        curr(jj)=ps(ii,jj)
      END DO
      sumr(ii)=vecmin(curr,nj)
    END DO
    CALL locateminmax('max',sumr,ni,binary)
    IF(nmontecarlo.EQ.1) CALL results(sumr,binary,ni)
  END IF
  IF(criterion.EQ.2.OR.criterion.EQ.111) THEN
* Savage's criterion
  IF(nmontecarlo.EQ.1)
    &   WRITE (OUTPUT,'(/A35)') 'Savage''s criterion:'
    DO jj=1,nj
      DO ii=1,ni
        curc(ii)=ps(ii,jj)
      END DO

```

```

        sumc(jj)=vecmax(curr,ni)
    END DO
DO ii=1,ni
    DO jj=1,nj
        curr(jj)=sumc(jj)-ps(ii,jj)
    END DO
    sumr(ii)=vecmax(curr,nj)
END DO
CALL locateminmax('min',sumr,ni,binary)
IF(nmontecarlo.EQ.1) CALL results(sumr,binary,ni)
END IF
IF(criterion.EQ.3.OR.criterion.EQ.111) THEN
* Bernoulli-Laplace's criterion
    IF(nmontecarlo.EQ.1)
        & WRITE (OUTPUT,'(/A35)') 'Bernoulli-Laplace''s criterion:'
    DO ii=1,ni
        sumr(ii)=0.D0
        DO jj=1,nj
            sumr(ii)=sumr(ii)+ps(ii,jj)/nj
        END DO
    END DO
    CALL locateminmax('max',sumr,ni,binary)
    IF(nmontecarlo.EQ.1) CALL results(sumr,binary,ni)
END IF
IF(criterion.EQ.4.OR.criterion.EQ.111) THEN
* Hurwicz's criterion
    IF(nmontecarlo.EQ.1)
        & WRITE (OUTPUT,'(/A35)') 'Hurwicz''s criterion:'
        CALL Hurwicz_crit(p,ps,weights,'yes',ni,nj,0.5D0,sumr)
        CALL locateminmax('max',sumr,ni,binary)
        IF(nmontecarlo.EQ.1) CALL results(sumr,binary,ni)
    END IF
    IF(criterion.EQ.5.OR.criterion.EQ.111) THEN
* Bayes's criterion
        IF(nmontecarlo.EQ.1)
            & WRITE (OUTPUT,'(/A35)') 'Bayes''s criterion:'
            CALL Bayes_crit(p,ps,weights,ni,nj,0.0D0,sumr)
            CALL locateminmax('max',sumr,ni,binary)
            IF(nmontecarlo.EQ.1) CALL results(sumr,binary,ni)
        END IF
        IF(criterion.EQ.6.OR.criterion.EQ.111) THEN
* Hodges-Lehman's criterion
            IF(nmontecarlo.EQ.1)
                & WRITE (OUTPUT,'(/A35)') 'Hodges-Lehman''s criterion:'
                CALL Hodges_Lehman_crit(p,ps,weights,'yes',ni,nj,0.5D0,sumr)
                CALL locateminmax('max',sumr,ni,binary)
                IF(nmontecarlo.EQ.1) CALL results(sumr,binary,ni)
            END IF
        END IF
    END IF
* 10
* Output and aggregate the results of simulation
    IF(nmontecarlo.NE.1) THEN
        DO ii=1,ni
            sumfr(ii)=sumfr(ii)+binary(ii)
            fr(ii)=sumfr(ii)/imc
        END DO
        & WRITE(OUTPUT3,'(3E15.7)') (fr(ii), ii=1,ni)
    END IF
* Compute inter-alternative comparisons
    i_final_stop=0
    IF(istop_flag.EQ.1) THEN
        CALL proportions(imc,1.644854d0,ni,nj,
            & binary,fr,sumfr,istop_current)
        n_stop_proportions=n_stop_proportions+istop_current
        CALL stopping_rules(1,n_stop_proportions,1,i_final_stop)
* Terminate the simulation loop if the condition
* in the currently used stopping rule is satisfied

```

```

        IF(i_final_stop.EQ.1) GO TO 1000
      END IF
    * *** THE END OF THE MONTE CARLO LOOP ***
  END DO
* 11
* Write the results obtained by simulation
1000 IF(nmontecarlo.NE.1) THEN
      CALL locateminmax('max',fr,ni,binary)
      CALL results(fr,binary,ni)
      IF(i_final_stop.EQ.1) WRITE(OUTPUT,'(/A38,I7)')
      & 'The simulation was stopped in the loop', imc
      IF(i_final_stop.EQ.1) WRITE(OUTPUT2,'(/A38,I7)')
      & 'The simulation was stopped in the loop', imc
    END IF
*
  STOP
END

```

Text of “Vector_norm_norm.for”

```

SUBROUTINE Vector_norm_norm(p,ps,prefs,ni,nj)
*
  INCLUDE 'MCS_CONSTANTS.FOR'
  REAL*8 p(MAXALTERN,MAXATTRIB), ps(MAXALTERN,MAXATTRIB)
  CHARACTER*3 prefs(MAXATTRIB)
* Arrays for current collumn and rows
  REAL*8 curc(MAXALTERN), curr(MAXATTRIB)
  REAL*8 colmax(MAXALTERN), colmin(MAXALTERN)
* Sums of column elements and row elements
  REAL*8 sumc(MAXATTRIB), sumr(MAXALTERN)
* Functions
  REAL*8 vecmin,vecmax
*
* Index for the rows and index for the columns
  INTEGER ii,jj
* Number of rows and number of columns
  INTEGER ni,nj
*
  DO jj=1,nj
    sumc(jj)=0.D0
    DO ii=1,ni
      sumc(jj)=sumc(jj)+p(ii,jj)**2
    END DO
    DO ii=1,ni
      ps(ii,jj)=p(ii,jj)/DSQRT(sumc(jj))
    END DO
  END DO
*
  RETURN
END

```

Text of “Linear_norm.for”

```

SUBROUTINE Linear_norm(p,ps,prefs,ni,nj)
*
  INCLUDE 'MCS_CONSTANTS.FOR'
  REAL*8 p(MAXALTERN,MAXATTRIB), ps(MAXALTERN,MAXATTRIB)
  CHARACTER*3 prefs(MAXATTRIB)
* Arrays for current collumn and rows
  REAL*8 curc(MAXALTERN), curr(MAXATTRIB)
  REAL*8 colmax(MAXALTERN), colmin(MAXALTERN)
* Sums of column elements and row elements

```

```

      REAL*8 sumc(MAXATTRIB), sumr(MAXALTERN)
* Functions
      REAL*8 vecmin,vecmax
*
* Index for the rows and index for the columns
      INTEGER ii,jj
* Number of rows and number of columns
      INTEGER ni,nj
*
      DO jj=1,nj
        DO ii=1,ni
          curc(ii)=p(ii,jj)
        END DO
        colmax(jj)=vecmax(curc,ni)
        colmin(jj)=vecmin(curc,ni)
        sumc(jj)=colmax(jj)-colmin(jj)
      END DO
      DO jj=1,nj
        DO ii=1,ni
          IF(prefs(jj).EQ.'max') THEN
            ps(ii,jj)=(p(ii,jj)-colmin(jj))/sumc(jj)
          ELSE IF(prefs(jj).EQ.'min') THEN
            ps(ii,jj)=(colmax(jj)-p(ii,jj))/sumc(jj)
          ELSE
            WRITE(*,*) 'Something wrong with preferences of attributes'
          END IF
        END DO
      END DO
*
      RETURN
      END

```

Text of “Non linear norm.for”

```

      SUBROUTINE Non_linear_norm(p,ps,prefs,ni,nj)
*
      INCLUDE 'MCS_CONSTANTS.FOR'
      REAL*8 p(MAXALTERN,MAXATTRIB), ps(MAXALTERN,MAXATTRIB)
      CHARACTER*3 prefs(MAXATTRIB)
* Arrays for current collumn and rows
      REAL*8 curc(MAXALTERN), curr(MAXATTRIB)
      REAL*8 colmax(MAXALTERN), colmin(MAXALTERN)
* Sums of column elements and row elements
      REAL*8 sumc(MAXATTRIB), sumr(MAXALTERN)
* Functions
      REAL*8 vecmin,vecmax
*
* Index for the rows and index for the columns
      INTEGER ii,jj
* Number of rows and number of columns
      INTEGER ni,nj
*
      DO jj=1,nj
        DO ii=1,ni
          curc(ii)=p(ii,jj)
        END DO
        colmax(jj)=vecmax(curc,ni)
        colmin(jj)=vecmin(curc,ni)
      DO ii=1,ni
        IF(prefs(jj).EQ.'max') THEN
          ps(ii,jj)=(p(ii,jj)/colmax(jj))**2
        ELSE IF(prefs(jj).EQ.'min') THEN
          ps(ii,jj)=(colmin(jj)/p(ii,jj))**3
        ELSE

```

```

        WRITE(*,*) 'Something wrong with preferences of attributes'
    END IF
END DO
END DO
*
RETURN
END

```

Text of “Hurwicz_crit.for”

```

SUBROUTINE Hurwicz_crit(p,ps,weights,weight_flag,ni,nj,lambda,row)
*
    INCLUDE 'MCS_CONSTANTS.FOR'
* Number of rows and number of columns
    INTEGER ni,nj
* Arrays for the matrix of soluiton and matrix of dimensionless attributes
    REAL*8 p(MAXALTERN,MAXATTRIB), ps(MAXALTERN,MAXATTRIB)
* Array for weights
    REAL*8 weights(nj)
* Flag for applying weights
    CHARACTER*3 weight_flag
* An extra variable belonging to criterion
    REAL*8 lambda
* Array characterising each alternative (row)
    REAL*8 row(ni),sum
* Arrays for current collumn and rows as well as their extrema
    REAL*8 curc(ni), curr(nj)
    REAL*8 rowmin(ni)
* Functions
    REAL*8 vecmin,vecmax
*
    DO ii=1,ni
        DO jj=1,nj
            IF(weight_flag.EQ.'yes') THEN
                curr(jj)=ps(ii,jj)*weights(jj)
            ELSE IF(weight_flag.EQ.' no') THEN
                curr(jj)=ps(ii,jj)
            END IF
        END DO
        row(ii)=lambda*vecmin(curr,nj)+(1.D0-lambda)*vecmax(curr,nj)
    END DO
*
RETURN
END

```

Text of “Bayes_crit.for”

```

SUBROUTINE Bayes_crit(p,ps,weights,ni,nj,lambda,row)
*
    INCLUDE 'MCS_CONSTANTS.FOR'
* Number of rows and number of columns
    INTEGER ni,nj
* Arrays for the matrix of soluiton and matrix of dimensionless attributes
    REAL*8 p(MAXALTERN,MAXATTRIB), ps(MAXALTERN,MAXATTRIB)
* Array for weights
    REAL*8 weights(nj)
* An extra variable belonging to criterion
    REAL*8 lambda
* Array characterising each alternative (row)
    REAL*8 row(ni),sum
*
    DO ii=1,ni

```

```

        sum=0.D0
        DO jj=1,nj
            sum=sum+ps(ii,jj)*weights(jj)
        END DO
        row(ii)=sum
    END DO

*
    RETURN
END

```

Text of “Hodges Lehman crit.for”

```

SUBROUTINE Hodges_Lehman_crit(p,ps,weights,weight_flag,
&                                ni,nj,lambda,row)

*
    INCLUDE 'MCS_CONSTANTS.FOR'
* Number of rows and number of columns
    INTEGER ni,nj
* Arrays for the matrix of solution and matrix of dimensionless attributes
    REAL*8 p(MAXALTERN,MAXATTRIB), ps(MAXALTERN,MAXATTRIB)
* Array for weights
    REAL*8 weights(nj)
* Flag for applying weights
    CHARACTER*3 weight_flag
* An extra variable belonging to criterion
    REAL*8 lambda
* Array characterising each alternative (row)
    REAL*8 row(ni),sum
* Arrays for current column and rows as well as their extrema
    REAL*8 curc(ni), curr(nj)
    REAL*8 rowmin(ni)
* Functions
    REAL*8 vecmin,vecmax
*
    DO ii=1,ni
        DO jj=1,nj
            IF(weight_flag.EQ.'yes') THEN
                curr(jj)=ps(ii,jj)*weights(jj)
            ELSE IF(weight_flag.EQ.'no') THEN
                curr(jj)=ps(ii,jj)
            END IF
        END DO
        rowmin(ii)=vecmin(curr,nj)
        sum=0.D0
        DO jj=1,nj
            sum=sum+ps(ii,jj)*weights(jj)
        END DO
*
        WRITE(OUTPUT,'(2D15.4)') rowmin(ii), sum
        row(ii)=lambda*sum+(1.D0-lambda)*rowmin(ii)
    END DO
*
    RETURN
END

```

Text of “Urand.for”

```

REAL FUNCTION URAND(IY)
INTEGER IY

*
* URAND IS A UNIFORM RANDOM NUMBER GENERATOR BASED ON THEORY
* AND SUGGESTIONS GIVEN BY KNUTH (1969). THE INTEGER
* IY SHOULD BE INITIALIZED TO AN ARBITRARY INTEGER PRIOR TO THE

```

```

* FIRST CALL TO URAND. THE CALLING PROGRAM SHOULD NOT ALTER THE
* VALUE OF IY BETWEEN SUBSEQUENT CALLS TO URAND. VALUES OF URAND
* WILL BE RETURNED IN THE INTERVAL (0,1).
*
      INTEGER IA, IC, ITWO, M2, M, MIC
      real*8 HALFM
      real*8 S
      DATA M2/ 0/, ITWO/ 2/
*
* IN FIRST ENTRY, COMPUTE MACHINE INTEGER WORD LENGTH
      IF( M2 .EQ. 0 )THEN
        M = 1
10      IF( M .GT. M2 )THEN
          M2 = M
          M = ITWO * M2
          GOTO 10
        END IF
        HALFM = M2
*
* COMPUTE MULTIPLIER AND INCREMENT FOR LINEAR CONGRUENTIAL METHOD
      IA = 8 * INT(HALFM * ATAN(1.D0) / 8.D0) +5
      IC = 2 * INT(HALFM * (0.5D0 - SQRT(3.D0) / 6.D0)) + 1
      MIC = (M2 - IC) + M2
*
* S IS THE SCALE FACTOR FOR CONVERTING TO FLOATING POINT
      S = 0.5 / HALFM
      END IF
*
* COMPUTE NEXT RANDOM NUMBER
      IY = IY * IA
*
* THE FOLLOWING STATEMENT IS FOR COMPUTERS WHICH DO NOT ALLOW
* INTEGER OVERFLOW ON ADDITION
      IF( IY .GT. MIC ) IY = (IY - M2) - M2
*
      IY = IY + IC
*
* THE FOLLOWING STATEMENT IS FOR COMPUTERS WHERE THE
* WORD LENGTH FOR ADDITION IS GREATER THAN FOR MULTIPLICATION
      IF( IY / 2 .GT. M2 ) IY = (IY - M2) - M2
*
* THE FOLLOWING STATEMENT IS FOR COMPUTERS WHERE INTEGER OVERFLOW
* AFFECTS THE SIGN BIT
      IF( IY .LT. 0 ) IY = (IY + M2) + M2
      URAND = FLOAT(IY) * S
      RETURN
      END

```

.for"

Text of "Grand.for"

```

REAL FUNCTION GRAND*8(IY, STDEV, AMEAN)
* A ROUTINE TO GENERATE PSEUDO RANDOM NUMBERS FROM A GAUSSIAN
* DISTRIBUTION WITH A MEAN OF AMEAN AND A STANDARD DEVIATION OF
* STDEV AS SPECIFIED BY USER.
* THE ROUTINE MAKES USE OF THE FACT THAT THE DISTRIBUTION OF
* SAMPLE MEANS IS GAUSSIAN. SAMPLE MEANS OF 12 UNIFORMLY
* DISTRIBUTED PSEUDO RANDOM NUMBERS ARE TAKEN AND TRANSFORMED
* TO THE DESIRED DISTRIBUTION.
* THE REPRODUCIBILITY OF THE VALUES RETURNED WILL BE AFFECTED BY
* ANY USE THAT IS MADE OF URAND IN THE INTERIM.
* THIS ROUTINE REFERENCES URAND TO GENERATE THE UNIFORMLY
* DISTRIBUTED RANDOM NUMBERS
*
      real*8 STDEV, AMEAN

```

```

GRAND = 0.0D0
DO 10 I = 1,12
    GRAND = GRAND + URAND(IY)
10 CONTINUE
GRAND = (GRAND - 6.0D0) * STDEV + AMEAN
RETURN
END

```

Text of "Lgrand1.for"

```

REAL FUNCTION LGRAND1*8(IY, STDEV, AMEAN)
* A ROUTINE TO GENERATE PSEUDO RANDOM NUMBERS FROM A LOG-NORMAL
* DISTRIBUTION WITH A MEAN OF AMEAN AND A STANDARD DEVIATION OF
* STDEV AS SPECIFIED BY USER.
* DISTRIBUTED PSEUDO RANDOM NUMBERS OF STANDARD NORMAL DISTRIBUTION
* ARE TAKEN AND TRANSFORMED TO THE DESIRED DISTRIBUTION.
* THE REPRODUCIBILITY OF THE VALUES RETURNED WILL BE AFFECTED BY
* ANY USE THAT IS MADE OF URAND IN THE INTERIM.
* THIS ROUTINE REFERENCES GRAND TO GENERATE THE NORMAL DISTRIBUTED
* RANDOM NUMBERS AND URAND TO GENERATE THE UNIFORMLY DISTRIBUTED
* RANDOM NUMBERS
*
    real*8 STDEV, AMEAN
    real*8 M, SIGMA, Z
*
    SIGMA = DSQRT( DLOG( 1.D0 + (STDEV**2)/(AMEAN**2) ) )
    M = DLOG(AMEAN / DSQRT( 1.D0 + (STDEV**2)/(AMEAN**2) ))
    Z = DEXP( M + SIGMA * GRAND(IY,1.D0,0.D0) )
    LGRAND1 = Z
    RETURN
END

```

Text of "Binomial.for"

```

INTEGER FUNCTION BINOMIAL(seed,p,n)
*
    REAL*8 URANMD, GRAND
    INTEGER seed, n
    REAL*8 p, p0, c, b, a
    CHARACTER*1 yn
    INTEGER k
*
    p0=(1.d0-p)**n
    c=p0
    b=c
    k=0
    u=URAND(seed)
*   WRITE(*,'(A3,4(A3,F7.5))') '****','p0=',p0,' u=',u, ' B=',b,
*   &                               ' C=',c
    DO WHILE(u.GT.B)
        a=((n-k)*p)/((k+1)*(1.d0-p))
        k=k+1
        c=a*c
        b=b+c
*       WRITE(*,'(A2,I2,4(A3,F7.5))') 'k=',k,' u=',u, ' A=',a,
*       &                               ' C=',c, ' B=',b
*       WRITE(*,'(A5\)' ) 'Stop?'
*       READ(*,'(A1)' ) yn
*       IF(yn.EQ.'y') STOP
    END DO
    BINOMIAL=k
*   END IF

```

```

*
RETURN
END

```

Text of “Beta2.for”

```

REAL*8 FUNCTION BETA2(seed,alpha,beta)
*
*   ATTENTION ! The parameters 'alpha' and 'beta' must be integers
*   The function 'GAMA1' is applied
*   Algorithm Be-1 from R.Y.Rubinstein, Sec. 3.6.3
*
    INTEGER seed,alpha,beta
    REAL*8 y1,y2
    REAL*8 GAMA1
*
    y1=GAMA1(seed,alpha,1.D0)
    y2=GAMA1(seed,beta,1.D0)
*
    BETA2=y1/(y1+y2)
*
    RETURN
END

```

Text of “Poisson.for”

```

INTEGER FUNCTION POISSON(seed, LAMBDA)
*
    REAL*8 URANMD, GRAND
    INTEGER seed
    REAL*8 LAMBDA, u
    REAL*8 p, p0, c, b, a
    INTEGER k
*
    p0=DEXP(-LAMBDA)
    c=p0
    b=c
    k=0
    u=URAND(seed)
*
    WRITE(*,'(A3,4(A3,F7.5))') '***', 'p0=',p0, ' u=',u, ' B=',b,
*
    & ' C=',c
    DO WHILE(u.GT.B)
        a=LAMBDA/(k+1)
        k=k+1
        c=a*c
        b=b+c
*
        WRITE(*,'(A2,I2,4(A3,F7.5))') 'k=',k, ' u=',u, ' A=',a,
*
        & ' C=',c, ' B=',b
        WRITE(*,'(A5)') 'Stop?'
*
        READ(*,'(A1)') yn
*
        IF(yn.EQ.'y') STOP
    END DO
    POISSON=k
*
    IF(LAMBDA.GT.10.d0) THEN
*
        z=GRAND(seed,1.d0,0.d0)
*
        POISSON = DMAX1(0.d0,INT(LAMBDA+z*DSQRT(LAMBDA)-0.5d0)*1.d0)+1
*
    ELSE
*
        k=0
*
        p=1.d0
*
        L=DEXP(-LAMBDA)
*
        DO WHILE(p.GT.L)
*
            k=k+1

```

```

*      u=URAND(seed)
*      p=p*u
*      END DO
*      POISSON=k-1
*      END IF
*
*      RETURN
*      END

```

Text of “Gama1.for”

```

REAL*8 FUNCTION GAMA1(seed,alpha,beta)
*
*  ATTENTION ! The parameter 'alpha' must be an integer
*  Algorithm G-1 from R.Y.Rubinstein, Sec. 3.6.2
*
*      INTEGER seed,alpha
*      REAL*8 beta,x,v,URAND
*
*      x=.0D0
*      DO i=1,alpha
*          v=-DLOG(URAND(seed))
*          x=x+v
*      END DO
*      GAMA1=x/beta
*
*      RETURN
*      END

```

Text of “Proportions.for”

```

SUBROUTINE proportions(imc,z_alpha,ni,nj,
&                      binary,fr,sumfr,istop_current)
*
*  The sunroutine computes values of the statistic used to test hypothesis
about
*  equality of binomial proportions
*
*      INCLUDE 'MCS_CONSTANTS.FOR'
*
*  No of current Monte Carlo simulation
*      INTEGER imc
*  Quantile of the standard normal distribution
*      REAL*8 z_alpha
*  Index for the rows and index for the columns
*      INTEGER ii,jj
*  Number of rows and number of columns in the decision making matrix
*      INTEGER ni,nj
*  Array for the values of the statistic used to test hypothesis about
proportions
*      REAL*8 zp(ni,ni)
*  Array containing ones and zeros indicating the best alternative
*      INTEGER binary(ni)
*  Array containing frequencies of selecting alternatives in the process of
simulation
*      REAL*8 fr(ni),sumfr(ni)
*
*      CHARACTER*15 frmt(5)
*  Auxiliary variables
*      REAL*8 p
*  Variable used to indicate the reduction of the zero hypothesis about
equality of

```

```

* the proportions in the current simulation loop
* (istop_current=1, if H0 is rejected for all combinations of the
proportions, and
* istop_current=0, if H0 is accepted for at least one combination of the
proportions)
  INTEGER istop_current
* Prepare information for the writing format
  CALL formats2(ni,frmt(1))
* Assign zeros to elements of the matrix containing statistic values
  DO i=1,ni
    DO j=1,ni
      zp(i,j)=0.d0
    END DO
  END DO
* Count the number of pairs for which the statistic will be computed
  n_pairs=0
  DO ii=1,ni-1
    DO jj=ii+1,ni
      n_pairs=n_pairs+1
    END DO
  END DO
* Compute the values of the statistic used to compare alternative-related
proportions
* Check the alternatives about equality of the proportions
  istop_current=0
  IF(imc.EQ.162) THEN
    CONTINUE
  END IF
*
  DO ii=1,ni-1
    DO jj=ii+1,ni
      p=(sumfr(ii)+sumfr(jj))/(2*imc)
      IF(p.GT.0.d-50) THEN
        zp(ii,jj)=(fr(ii)-fr(jj))/DSQRT(2*p*(1.d0-p)/imc)
        IF((imc.GE.100).AND.
&      (DABS(zp(ii,jj)).GE.z_alpha))istop_current=istop_current+1
        ELSE
          zp(ii,jj)=777.d0
        END IF
      END DO
    END DO
  IF(istop_current.EQ.n_pairs) THEN
    istop_current=1
  ELSE
    istop_current=0
  END IF
* Write the current results of simulation
  WRITE(OUTPUT2,'(//)')
  WRITE(OUTPUT2,'(I7, '//TRIM(frmt(1))//I2, '//TRIM(frmt(1))//I5)')
&      imc, (binary(ii),ii=1,ni), (INT(sumfr(ii)),ii=1,ni)
* Write the values of the statistic
  WRITE(OUTPUT2,'( '//TRIM(frmt(1))//F10.3)')
*
  DO i=1,ni
    WRITE(OUTPUT2,'(5X, '//TRIM(frmt(1))//F10.3)') (zp(i,j),j=1,ni)
  END DO
*
  IF(imc.LT.100) THEN
    WRITE(OUTPUT2,'(5X,A62)')
&      'H0 was not checked: the number of MC simulations less than 100'
    ELSE
      IF(istop_current.EQ.0) WRITE(OUTPUT2,'(5X,A43,I2)')
&      'Accept H0 for for at least one combination:',istop_current
      IF(istop_current.EQ.1) WRITE(OUTPUT2,'(5X,A31,I2)')
&      'Reject H0 for all combinations:',istop_current
    END IF
*

```

```

RETURN
END

```

Text of “Stopping_rules.for”

```

SUBROUTINE stoping_rules(i_rule,n_stop_proportions,
&                        n_times,i_final_stop)
*
  INCLUDE 'MCS_CONSTANTS.FOR'
*
* The number of rule used to stop the simulation process
  INTEGER i_rule
* The number of not-necessarily subsequent times where the stiping condition
is satisfied
  INTEGER n_times
* Binary variable indicating the stop of the simulation process according to
the currently
* used stoping rule
  INTEGER i_final_stop
*
  WRITE(OUTPUT2,'(5X,A61,I7)')
  & 'The number of times when the stoping condition was satisfied:',
  & n_stop_proportions
* 1st stoping rule
  IF(i_rule.EQ.1) THEN
    IF(n_stop_proportions.GE.n_times) i_final_stop=1
  END IF
  WRITE(OUTPUT2,'(5X,A61,I7)')
  & 'The final stop variable:',
  & i_final_stop
*
  RETURN
END

```

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

This annex contains calculations of fire safety variables $S_k(\mathbf{x}_{1i})$ and fire risk variables $R_k(\mathbf{x}_{2i})$ which appear in the expression of the FSES fire risk index $I_{FSES}(\mathbf{x}_i)$ ($k = 1, 2, 3, 4$) (Eqs. (2.1) and (2.2)). The variables were calculated for the patient care department, therapy department and traumatology department. The calculations are presented in the respective sections D.1, D.2 and D.3.

The fire safety variables $S_k(\mathbf{x}_{1i})$ were calculated by applying the following formula (FSES 1996):

$$S_k(\mathbf{x}_{1i}) = \sum_{l=1}^{13} x_{l1i} \quad (\text{D.1})$$

The summands x_{l1i} are summarised in Tables D.1, D.5 and D.9 for all four alternatives. The calculations of the sums in Eq. (D.1) are presented in Tables D.2, D.6 and D.10. In line with the FSES index, the calculated values S_1 to S_3 must be compared with the minimum values known also as mandatory safety requirements and given in Tables D.3 and D.7.

Values of $R_1(\mathbf{x}_{2i})$ to $R_3(\mathbf{x}_{2i})$ were obtained directly from Tables D.3 and D.7. The values of $R_4(\mathbf{x}_{2i})$ were calculated by the following formula (FSES 1996):

$$R_4(\mathbf{x}_{2i}) = 0.6 \prod_{l=1}^5 x_{l2i} \quad (\text{D.2})$$

Where x_{2i} are the input variables, the values of which are given in Tables D.4, D.8 and D.11. The result of the calculated occupancy risk R_4 for the patient care department is $R_4(\mathbf{x}_{2i}) = 2.7$, therapy department is $R_4(\mathbf{x}_{2i}) = 1.3$ and traumatology department is $R_4(\mathbf{x}_{2i}) = 1.2$.

The $I_{FSES}(\mathbf{x}_i)$ index involves the calculation of four pairs ($S_k(\mathbf{x}_{1i}), R_k(\mathbf{x}_{2i})$) which quantitatively express four aspects of fire safety. These pairs allow to measure the safety by the differences $S_k(\mathbf{x}_{1i}) - R_k(\mathbf{x}_{2i})$ which are safety margins in essence.

D.1. Patient care department

Table D.1. Values of the components of the vector x_{1i} used for the calculation of the fire safety parameter $S_k(x_{1i})$ (FSES 1996)

No	Parameters	Parameters values						
For all four alternatives								
1.	Construction x_{11i}	Combustible types III, IV and V				Non-combustible types I and II		
		Wood frame		Ordinary				
	Floor zone	Unprotected	Protected	Unprotected	Protected	Unprotected	Protected	Fire resist.
	First	-2	0	-2	0	0	2	2
	Second	-7	-2	-4	-2	-2	2	4
	Third	-9	-7	-9	-7	-7	2	4
	4 th and above	-13	-7	-13	-7	-9	-7	4
2.	Interior finish (corr. and exit) x_{21i}			Class C		Class B		Class A
				-5		0	3	
3.	Interior finish (rooms) x_{31i}			Class C		Class B		Class A
				-3		1	3	
4.	Corridor partitions/walls x_{41i}	None or incomplete		<1/3 hr		>1/3<1.0 hr		≥1.0 hr
		-10 (0)		0		1 (0)		2 (0)
5.	Doors to corridor x_{51i}	No door		<20 min. fr		>20 min. fr		>20 min. fr and auto clos.
		-10		0		1 (0)		2 (0)
6.	Zone dimensions x_{61i}	Dead end more than 100		Dead end 30 - 100		No dead ends > 30 and zone length is		
						>150		100 – 150
		-6 (0)		-4 (0)		-2		0
7.	Vertical openings x_{71i}	Open 4 or more floors	Open 2 or 3 floors	Enclosed with indicated fire resist.				
				< 1 hr		≥1 hr < 2 hr		≥ 2 hr
		-14		-10		0		2 (0)

Table D.1. Continued

No	Parameters	Parameters values					
For all four alternatives							
8.	Hazards areas x_{81i}	Double deficiency		Single deficiency		No deficiencies	
		In zone	Outside zone	In zone	In adjacent zone		
		-11	-5	-6	-2		0
9.	Smoke control x_{91i}	No control		Smoke partition		Mech. assisted systems	
						By zone	By corridor
		-5 (0)		0		3	4
10.	Emergency movement routes $x_{10,1i}$	<2 routes	Multiple routes				
			Deficient capacity	W/o horizontal exit(s)	Horizontal exit(s)	Direct exit(s)	
		-8	-2	0	1	5	
11.	Manual fire alarm $x_{11,1i}$	No manual fire alarm		Manual fire alarm			
				W/o f. d. comn.		W/ f. d. comn.	
		-4		1		2	
Alternative A ($i = 1$)							
12.	Smoke detection and alarm $x_{12,11}$	None	Corridor only	Rooms only	Corridor and habit. space	Total space	
		0	2	3	4	5	
13.	Automatic sprinklers $x_{13,11}$	None	Corridor	Corridor and habit. space		Total space	
		0	2 (0)	8		10	
Alternative B ($i = 2$)							
12.	Smoke detection and alarm $x_{12,12}$	None	Corridor only	Rooms only	Corridor and habit. space	Total space	
		0	2	3	4	5	
13.	Automatic sprinklers $x_{13,12}$	None	Corridor	Corridor and habit. space		Total space	
		0	2 (0)	8		10	

Table D.1. Continued

No	Parameters	Parameters values				
Alternative C ($i = 3$)						
12.	Smoke detection and alarm $x_{12,13}$	None	Corridor only	Rooms only	Corridor and habit. space	Total space
		0	2	3	4	5
13.	Automatic sprinklers $x_{13,13}$	None	Corridor	Corridor and habit. space		Total space
		0	2 (0)	8		10
Alternative D ($i = 4$)						
12.	Smoke detection and alarm $x_{12,14}$	None	Corridor only	Rooms only	Corridor and habit. space	Total space
		0	2	3	4	5
13.	Automatic sprinklers $x_{13,14}$	None	Corridor	Corridor and habit. space		Total space
		0	2 (0)	8		10

Table D.2. Values of the input variables used to calculate the fire risk index I_{FSES} for alternatives of fire safety systems*

No	Safety parameters	Containment safety ($S_1(x_{1i})$)	Extinguishment safety ($S_2(x_{1i})$)	People movement safety ($S_3(x_{1i})$)	General safety ($S_4(x_{1i})$)
1.	Construction x_{11i}	4	4	—	4
2.	Interior finish (corridors and exits) x_{21i}	0	—	0	0
3.	Interior finish (rooms) x_{31i}	1	—	—	1
4.	Corridor partitions/walls x_{41i}	2	—	—	2
5.	Doors to corridor x_{51i}	1	—	1	1
6.	Zone dimensions x_{61i}	—	—	1	1

Table D.2. Continued

No	Safety parameters	Containment safety ($S_1(x_{1i})$)	Extinguishment safety ($S_2(x_{1i})$)	People movement safety ($S_3(x_{1i})$)	General safety ($S_4(x_{1i})$)
7.	Vertical openings x_{71i}	2	–	2	2
8.	Hazards areas x_{81i}	0	0	–	0
9.	Smoke control x_{91i}	–	–	3	3
10.	Emergency movement routes $x_{10,1i}$	–	–	1	1
11.	Manual fire alarm $x_{11,1i}$	–	-4	–	-4
Alternative A ($i = 1$)					
12.	Smoke detection and alarm $x_{12,11}$	2	2	2	2
13.	Automatic sprinklers $x_{13,11}$	0	0	$0 : 2 = 0$	0
Total value		$S_1 = 10$	$S_2 = 2$	$S_3 = 10$	$S_4 = 13$
Alternative B ($i = 2$)					
12.	Smoke detection and alarm $x_{12,12}$	5	5	5	5
13.	Automatic sprinklers $x_{13,12}$	0	0	$0 : 2 = 0$	0
Total value		$S_1 = 10$	$S_2 = 5$	$S_3 = 13$	$S_4 = 16$
Alternative C ($i = 3$)					
12.	Smoke detection and alarm $x_{12,13}$	2	2	2	2
13.	Automatic sprinklers $x_{13,13}$	8	8	$8 : 4 = 0$	8
Total value		$S_1 = 18$	$S_2 = 10$	$S_3 = 14$	$S_4 = 21$

Table D.2. Continued

No	Safety parameters	Containment safety ($S_1(x_{1i})$)	Extinguishment safety ($S_2(x_{1i})$)	People movement safety ($S_3(x_{1i})$)	General safety ($S_4(x_{1i})$)
Alternative D ($i = 4$)					
12.	Smoke detection and alarm $x_{12,14}$	5	5	5	5
13.	Automatic sprinklers $x_{13,14}$	10	10	10 : 2 = 5	10
Total value		$S_1 = 20$	$S_2 = 15$	$S_3 = 18$	$S_4 = 26$
* Numerical values given in this table were taken from the description of the FSES index by FSES (1996) and the references cited therein					

Table D.3. Values of the mandatory safety requirements $R_1(x_{2i})$, $R_2(x_{2i})$ and $R_3(x_{2i})$ (FSES 1996)

Zone location	Containment $R_1(x_{2i})$	Extinguishment $R_2(x_{2i})$	People movement $R_3(x_{2i})$
1st story	5	4	1
2nd or 3rd story	9	6	3
4th story or higher	9	6	3

Table D.4. Values of the components of the vector x_{2i} used for the calculation of the occupancy risk parameter $R_4(x_{2i})$ (FSES 1996)

No	Component of x_{2i}	Risk factor values				
For all four alternatives						
1.	Patient mobility x_{12i}	Mobility status	Mobile	Limited mobility	Not mobile	Not movable
		Risk factor	1.0	1.6	3.2	4.5
2.	Patient density x_{22i}	Patient	1–5	6–10	11–30	>30
		Risk factor	1.0	1.2	1.5	2.0

Table D.4. Continued

No	Component of x_{2i}	Risk factor values					
For all four alternatives							
3.	Zone location x_{32i}	Floor	1st	2 nd or 3 rd	4 th to 6 th	7 th and above	Basements
		Risk factor	1.1	1.2	1.4	1.6	1.6
4.	Ratio of patients to attendants x_{42i}	Patients attendant	<u>1–2</u> 1	<u>3–5</u> 1	<u>6–10</u> 1	<u>≥11</u> 1	<u>One or more</u> ⁽¹⁾ None
		Risk factor	1.0	1.1	1.2	1.5	4.0
5.	Patient average age x_{52i}	Age	Under 65 years and over 1 year			65 years and over 1 year and younger	
		Risk factor	1.0			1.2	

⁽¹⁾ Risk factor of 4.0 is charged to any zone that houses patients without any staff in immediate attendance

The values of $R_4(x_{2i})$ were calculated:

$$R_4(x_{2i}) = 0.6 \cdot (1.6 \cdot 1.5 \cdot 1.4 \cdot 1.1 \cdot 1.2) = 2.7$$

Results of fire safety system (alternative A) are got as following:

$$\text{Containment safety: } S_1(x_{11}) - R_1(x_{21}) = 10 - 9 = 1 > 0$$

$$\text{Extinguishment safety: } S_2(x_{11}) - R_2(x_{21}) = 2 - 6 = -4 < 0$$

$$\text{People movement safety: } S_3(x_{11}) - R_3(x_{21}) = 10 - 3 = 7 > 0$$

$$\text{General safety: } S_4(x_{11}) - R_4(x_{21}) = 13 - 2.7 = 10.3 > 0$$

These results suggest that containment, people movement and general safeties are acceptable, whereas the extinguishment safety is not acceptable.

Results of fire safety system (alternative B) are got as following:

$$\text{Containment safety: } S_1(x_{12}) - R_1(x_{22}) = 10 - 9 = 1 > 0$$

$$\text{Extinguishment safety: } S_2(x_{12}) - R_2(x_{22}) = 5 - 6 = -1 < 0$$

$$\text{People movement safety: } S_3(x_{12}) - R_3(x_{22}) = 13 - 3 = 10 > 0$$

$$\text{General safety: } S_4(x_{12}) - R_4(x_{22}) = 16 - 2.7 = 13.3 > 0$$

These results suggest that containment, people movement and general safeties are acceptable, whereas the extinguishment safety is not acceptable.

Results of fire safety system (alternative C) are got as following:

$$\text{Containment safety: } S_1(x_{13}) - R_1(x_{23}) = 18 - 9 = 9 > 0$$

$$\text{Extinguishment safety: } S_2(x_{13}) - R_2(x_{23}) = 10 - 6 = 4 > 0$$

$$\text{People movement safety: } S_3(x_{13}) - R_3(x_{23}) = 14 - 3 = 11 > 0$$

$$\text{General safety: } S_4(x_{13}) - R_4(x_{23}) = 21 - 2.7 = 18.3 > 0$$

These results suggest that containment, people movement, extinguishment and general safeties are acceptable.

Results of fire safety system (alternative D) are got as following:

$$\text{Containment safety: } S_1(x_{14}) - R_1(x_{24}) = 20 - 9 = 11 > 0$$

$$\text{Extinguishment safety: } S_2(x_{14}) - R_2(x_{24}) = 15 - 6 = 9 > 0$$

$$\text{People movement safety: } S_3(x_{14}) - R_3(x_{24}) = 18 - 3 = 15 > 0$$

$$\text{General safety: } S_4(x_{14}) - R_4(x_{24}) = 26 - 2.7 = 23.3 > 0$$

These results suggest that containment, people movement, extinguishment and general safeties are acceptable.

D.2. Therapy department

Table D.5. Values of the components of the vector x_{1i} used for the calculation of the fire safety parameter $S_k(x_{1i})$ (FSES 1996)

No	Parameters	Parameters values						
For all four alternatives								
1.	Construction x_{11i}	Combustible types III, IV and V				Non-combustible types I and II		
		Wood frame		Ordinary				
	Floor zone	Unprotected	Protected	Unprotected	Protected	Unprotected	Protected	Fire resist.
	First	-2	0	-2	0	0	2	2
	Second	-7	-2	-4	-2	-2	2	4
	Third	-9	-7	-9	-7	-7	2	4
	4 th and above	-13	-7	-13	-7	-9	-7	4
2.	Interior finish (corr. and exit) x_{21i}			Class C		Class B		Class A
				-5		0		3
3.	Interior finish (rooms) x_{31i}			Class C		Class B		Class A
				-3		1		3
4.	Corridor partitions/ walls x_{41i}	None or incomplete		<1/3 hr		>1/3<1.0 hr		≥1.0 hr
		-10 (0)		0		1 (0)		2 (0)
5.	Doors to corridor x_{51i}	No door	<20 min. fr	>20 min. fr		>20 min. fr and auto clos.		
		-10	0	1 (0)		2 (0)		
6.	Zone dimensions x_{61i}	Dead end more than 100		Dead end 30 - 100		No dead ends > 30 and zone length is		
						>150	100 – 150	<100
		-6 (0)		-4 (0)		-2	0	1
7.	Vertical openings x_{71i}	Open 4 or more floors	Open 2 or 3 floors	Enclosed with indicated fire resist.				
				< 1 hr		≥1 hr < 2 hr		≥ 2 hr
		-14	-10	0		2 (0)		3 (0)

Table D.5. Continued

No	Parameters	Parameters values				
For all four alternatives						
8.	Hazards areas x_{81i}	Double deficiency		Single deficiency		No deficiencies
		In zone	Outside zone	In zone	In adjacent zone	
		-11	-5	-6	-2	0
9.	Smoke control x_{91i}	No control	Smoke partition		Mech. assisted systems	
				By zone	By corridor	
		-5 (0)	0		3	4
10.	Emergency movement routes $x_{10,1i}$	<2 routes	Multiple routes			
			Deficient capacity	W/o horizontal exit(s)	Horizontal exit(s)	Direct exit(s)
		-8	-2	0	1	5
11.	Manual fire alarm $x_{11,1i}$	No manual fire alarm		Manual fire alarm		
				W/o f. d. conn.		W/ f. d. conn.
		-4		1	2	
Alternative A ($i = 1$)						
12.	Smoke detection and alarm $x_{12,11}$	None	Corridor only	Rooms only	Corridor and habit. space	Total space
		0	2	3	4	5
13.	Automatic sprinklers $x_{13,11}$	None	Corridor	Corridor and habit. space		Total space
		0	2 (0)	8		10
Alternative B ($i = 2$)						
12.	Smoke detection and alarm $x_{12,12}$	None	Corridor only	Rooms only	Corridor and habit. space	Total space
		0	2	3	4	5
13.	Automatic sprinklers $x_{13,12}$	None	Corridor	Corridor and habit. space		Total space
		0	2 (0)	8		10

Table D.5. Continued

No	Parameters	Parameters values				
Alternative C ($i = 3$)						
12.	Smoke detection and alarm $x_{12,13}$	None	Corridor only	Rooms only	Corridor and habit. space	Total space
		0	2	3	4	5
13.	Automatic sprinklers $x_{13,13}$	None	Corridor	Corridor and habit. space		Total space
		0	2 (0)	8		10
Alternative D ($i = 4$)						
12.	Smoke detection and alarm $x_{12,14}$	None	Corridor only	Rooms only	Corridor and habit. space	Total space
		0	2	3	4	5
13.	Automatic sprinklers $x_{13,14}$	None	Corridor	Corridor and habit. space		Total space
		0	2 (0)	8		10

Table D.6. Values of the input variables used to calculate the fire risk index I_{FSES} for alternatives of fire safety systems*

No	Safety parameters	Containment safety ($S_1(x_{1i})$)	Extinguishment safety ($S_2(x_{1i})$)	People movement safety ($S_3(x_{1i})$)	General safety ($S_4(x_{1i})$)
1.	Construction x_{11i}	4	4	—	4
2.	Interior finish (corridors, exits) x_{21i}	0	—	0	0
3.	Interior finish (rooms) x_{31i}	1	—	—	1
4.	Corridor partitions/walls x_{41i}	2	—	—	2
5.	Doors to corridor x_{51i}	1	—	1	1
6.	Zone dimensions x_{61i}	—	—	1	1

Table D.6. Continued

No	Safety parameters	Containment safety ($S_1(x_{1i})$)	Extinguishment safety ($S_2(x_{1i})$)	People movement safety ($S_3(x_{1i})$)	General safety ($S_4(x_{1i})$)
7.	Vertical openings x_{71i}	2	—	2	2
8.	Hazards areas x_{81i}	0	0	—	0
9.	Smoke control x_{91i}	—	—	3	3
10.	Emergency movement routes $x_{10,1i}$	—	—	1	1
11.	Manual fire alarm $x_{11,1i}$	—	-4	—	-4
Alternative A ($i = 1$)					
12.	Smoke detection and alarm $x_{12,11}$	2	2	2	2
13.	Automatic sprinklers $x_{13,11}$	0	0	$0 : 2 = 0$	0
Total value		$S_1 = 10$	$S_2 = 2$	$S_3 = 10$	$S_4 = 13$
Alternative B ($i = 2$)					
12.	Smoke detection and alarm $x_{12,12}$	5	5	5	5
13.	Automatic sprinklers $x_{13,12}$	0	0	$0 : 2 = 0$	0
Total value		$S_1 = 10$	$S_2 = 5$	$S_3 = 13$	$S_4 = 16$
Alternative C ($i = 3$)					
12.	Smoke detection and alarm $x_{12,13}$	2	2	2	2
13.	Automatic sprinklers $x_{13,13}$	8	8	$8 : 2 = 4$	8
Total value		$S_1 = 18$	$S_2 = 10$	$S_3 = 14$	$S_4 = 21$

Table D.6. Continued

No	Safety parameters	Containment safety ($S_1(x_{1i})$)	Extinguishment safety ($S_2(x_{1i})$)	People movement safety ($S_3(x_{1i})$)	General safety ($S_4(x_{1i})$)
Alternative D ($i = 4$)					
12.	Smoke detection and alarm $x_{12,14}$	5	5	5	5
13.	Automatic sprinklers $x_{13,14}$	10	10	10 : 2 = 5	10
Total value		$S_1 = 20$	$S_2 = 15$	$S_3 = 18$	$S_4 = 26$
* Numerical values given in this table were taken from the description of the FSES index by FSES (1996) and the references cited therein					

Table D.7. Values of the mandatory safety requirements $R_1(x_{2i})$, $R_2(x_{2i})$ and $R_3(x_{2i})$ (FSES 1996)

Zone location	Containment $R_1(x_{2i})$	Extinguishment $R_2(x_{2i})$	People movement $R_3(x_{2i})$
1st story	5	4	1
2nd or 3rd story	9	6	3
4th story or higher	9	6	3

Table D.8. Values of the components of the vector x_{2i} used for the calculation of the occupancy risk parameter $R_4(x_{2i})$ (FSES 1996)

No	Component of x_{2i}	Risk factor values				
For all four alternatives						
1.	Patient mobility x_{12i}	Mobility status	Mobile	Limited mobility	Not mobile	Not movable
		Risk factor	1.0	1.6	3.2	4.5
2.	Patient density x_{22i}	Patient	1–5	6–10	11–30	>30
		Risk factor	1.0	1.2	1.5	2.0

Table D.8. Continued

No	Component of x_{2i}	Risk factor values					
For all four alternatives							
3.	Zone location x_{32i}	Floor	1st	2 nd or 3 rd	4 th to 6 th	7 th and above	Basements
		Risk factor	1.1	1.2	1.4	1.6	1.6
4.	Ratio of patients to attendants x_{42i}	Patients attendant	<u>1–2</u> 1	<u>3–5</u> 1	<u>6–10</u> 1	<u>≥11</u> 1	<u>One or more⁽¹⁾</u> None
		Risk factor	1.0	1.1	1.2	1.5	4.0
5.	Patient average age x_{52i}	Age	Under 65 years and over 1 year			65 years and over 1 year and younger	
		Risk factor	1.0			1.2	

⁽¹⁾ Risk factor of 4.0 is charged to any zone that houses patients without any staff in immediate attendance

The values of $R_4(x_{2i})$ were calculated:

$$R_4(x_{2i}) = 0.6 \cdot (1.6 \cdot 1.0 \cdot 1.2 \cdot 1.2 \cdot 1.0) = 1.3$$

Results of safety system (alternative A) are got as following:

$$\text{Containment safety: } S_1(x_{11}) - R_1(x_{21}) = 10 - 9 = 1 > 0$$

$$\text{Extinguishment safety: } S_2(x_{11}) - R_2(x_{21}) = 2 - 6 = -4 < 0$$

$$\text{People movement safety: } S_3(x_{11}) - R_3(x_{21}) = 10 - 3 = 7 > 0$$

$$\text{General safety: } S_4(x_{11}) - R_4(x_{21}) = 13 - 1.3 = 11.7 > 0$$

These results suggest that containment, people movement and general safeties are acceptable, whereas the extinguishment safety is not acceptable.

Results of fire safety system (alternative B) are got as following:

$$\text{Containment safety: } S_1(x_{12}) - R_1(x_{22}) = 10 - 9 = 1 > 0$$

$$\text{Extinguishment safety: } S_2(x_{12}) - R_2(x_{22}) = 5 - 6 = -1 < 0$$

$$\text{People movement safety: } S_3(x_{12}) - R_3(x_{22}) = 13 - 3 = 10 > 0$$

$$\text{General safety: } S_4(\mathbf{x}_{12}) - R_4(\mathbf{x}_{22}) = 16 - 1.3 = 14.7 > 0$$

These results suggest that containment, people movement and general safeties are acceptable, whereas the extinguishment safety is not acceptable.

Results of fire safety system (alternative C) are got as following:

$$\text{Containment safety: } S_1(\mathbf{x}_{13}) - R_1(\mathbf{x}_{23}) = 18 - 9 = 9 > 0$$

$$\text{Extinguishment safety: } S_2(\mathbf{x}_{13}) - R_2(\mathbf{x}_{23}) = 10 - 6 = 4 > 0$$

$$\text{People movement safety: } S_3(\mathbf{x}_{13}) - R_3(\mathbf{x}_{23}) = 14 - 3 = 11 > 0$$

$$\text{General safety: } S_4(\mathbf{x}_{13}) - R_4(\mathbf{x}_{23}) = 21 - 1.3 = 19.7 > 0$$

These results suggest that containment, people movement, extinguishment and general safeties are acceptable.

Results of fire safety system (alternative D) are got as following:

$$\text{Containment safety: } S_1(\mathbf{x}_{14}) - R_1(\mathbf{x}_{24}) = 20 - 9 = 11 > 0$$

$$\text{Extinguishment safety: } S_2(\mathbf{x}_{14}) - R_2(\mathbf{x}_{24}) = 15 - 6 = 9 > 0$$

$$\text{People movement safety: } S_3(\mathbf{x}_{14}) - R_3(\mathbf{x}_{24}) = 18 - 3 = 15 > 0$$

$$\text{General safety: } S_4(\mathbf{x}_{14}) - R_4(\mathbf{x}_{24}) = 26 - 1.3 = 24.7 > 0$$

These results suggest that containment, people movement, extinguishment and general safeties are acceptable.

D.3. Traumatology department

Table D.9. Values of the components of the vector x_{1i} used for the calculation of the fire safety parameter $S_k(x_{1i})$ (FSES 1996)

No	Parameters	Parameters values						
For all four alternatives								
1.	Construction x_{11i}	Combustible types III, IV and V				Non-combustible types I and II		
		Wood frame		Ordinary				
	Floor zone	Unprotected	Protected	Unprotected	Protected	Unprotected	Protected	Fire resist.
	First	-2	0	-2	0	0	2	2
	Second	-7	-2	-4	-2	-2	2	4
	Third	-9	-7	-9	-7	-7	2	4
	4 th and above	-13	-7	-13	-7	-9	-7	4
2.	Interior finish (corr. and exit) x_{21i}			Class C		Class B		Class A
				-5		0		3
3.	Interior finish (rooms) x_{31i}			Class C		Class B		Class A
				-3		1		3
4.	Corridor partitions/ walls x_{41i}	None or incomplete		<1/3 hr		>1/3<1.0 hr		≥1.0 hr
		-10 (0)		0		1 (0)		2 (0)
5.	Doors to corridor x_{51i}	No door		<20 min. fr		>20 min. fr		>20 min. fr and auto clos.
		-10		0		1 (0)		2 (0)
6.	Zone dimensions x_{61i}	Dead end more than 100		Dead end 30 - 100	No dead ends > 30 and zone length is			
					>150		100 – 150	
		-6 (0)		-4 (0)		-2		0
7.	Vertical openings x_{71i}	Open 4 or more floors	Open 2 or 3 floors	Enclosed with indicated fire resist.				
				< 1 hr		≥1 hr < 2 hr		≥ 2 hr
		-14		-10		0		2 (0)

Table D.9. Continued

No	Parameters	Parameters values				
For all four alternatives						
8.	Hazards areas x_{81i}	Double deficiency		Single deficiency		No deficiencies
		In zone	Outside zone	In zone	In adjacent zone	
		-11	-5	-6	-2	0
9.	Smoke control x_{91i}	No control		Smoke partition		Mech. assisted systems
				By zone	By corridor	
		-5 (0)		0		3
10.	Emergency movement routes $x_{10,1i}$	<2 routes	Multiple routes			
			Deficient capacity	W/o horizontal exit(s)	Horizontal exit(s)	Direct exit(s)
		-8	-2	0	1	5
11.	Manual fire alarm $x_{11,1i}$	No manual fire alarm		Manual fire alarm		
				W/o f. d. conn.		W/ f. d. conn.
		-4		1		2
Alternative A ($i = 1$)						
12.	Smoke detection and alarm $x_{12,11}$	None	Corridor only	Rooms only	Corridor and habit. space	Total space
		0	2	3	4	5
13.	Automatic sprinklers $x_{13,11}$	None	Corridor	Corridor and habit. space		Total space
		0	2 (0)	8		10
Alternative B ($i = 2$)						
12.	Smoke detection and alarm $x_{12,12}$	None	Corridor only	Rooms only	Corridor and habit. space	Total space
		0	2	3	4	5
13.	Automatic sprinklers $x_{13,12}$	None	Corridor	Corridor and habit. space		Total space
		0	2 (0)	8		10

Table D.9. Continued

No	Parameters	Parameters values				
Alternative C ($i = 3$)						
12.	Smoke detection and alarm $x_{12,13}$	None	Corridor only	Rooms only	Corridor and habit. space	Total space
		0	2	3	4	5
13.	Automatic sprinklers $x_{13,13}$	None	Corridor	Corridor and habit. space		Total space
		0	2 (0)	8		10
Alternative D ($i = 4$)						
12.	Smoke detection and alarm $x_{12,14}$	None	Corridor only	Rooms only	Corridor and habit. space	Total space
		0	2	3	4	5
13.	Automatic sprinklers $x_{13,14}$	None	Corridor	Corridor and habit. space		Total space
		0	2 (0)	8		10

Table D.10. Values of the input variables used to calculate the fire risk index I_{FSES} for alternatives of fire safety systems*

No	Safety parameters	Containment safety ($S_1(x_{1i})$)	Extinguishment safety ($S_2(x_{1i})$)	People movement safety ($S_3(x_{1i})$)	General safety ($S_4(x_{1i})$)
1.	Construction x_{11i}	4	4	—	4
2.	Interior finish (corridors, exits) x_{21i}	0	—	0	0
3.	Interior finish (rooms) x_{31i}	1	—	—	1
4.	Corridor partitions/walls x_{41i}	2	—	—	2
5.	Doors to corridor x_{51i}	1	—	1	1
6.	Zone dimensions x_{61i}	—	—	1	1

Table D.10. Continued

No	Safety parameters	Containment safety ($S_1(x_{1i})$)	Extinguishment safety ($S_2(x_{1i})$)	People movement safety ($S_3(x_{1i})$)	General safety ($S_4(x_{1i})$)
7.	Vertical openings x_{71i}	2	—	2	2
8.	Hazards areas x_{81i}	0	0	—	0
9.	Smoke control x_{91i}	—	—	3	3
10.	Emergency movement routes $x_{10,1i}$	—	—	1	1
11.	Manual fire alarm $x_{11,1i}$	—	-4	—	-4
Alternative A ($i = 1$)					
12.	Smoke detection and alarm $x_{12,11}$	2	2	2	2
13.	Automatic sprinklers $x_{13,11}$	0	0	$0 : 2 = 0$	0
Total value		$S_1 = 10$	$S_2 = 2$	$S_3 = 10$	$S_4 = 13$
Alternative B ($i = 2$)					
12.	Smoke detection and alarm $x_{12,12}$	5	5	5	5
13.	Automatic sprinklers $x_{13,12}$	0	0	$0 : 2 = 0$	0
Total value		$S_1 = 10$	$S_2 = 5$	$S_3 = 13$	$S_4 = 16$
Alternative C ($i = 3$)					
12.	Smoke detection and alarm $x_{12,13}$	2	2	2	2
13.	Automatic sprinklers $x_{13,13}$	8	8	$8 : 2 = 4$	8
Total value		$S_1 = 18$	$S_2 = 10$	$S_3 = 14$	$S_4 = 21$

Table D.10. Continued

No	Safety parameters	Containment safety ($S_1(\mathbf{x}_{1i})$)	Extinguishment safety ($S_2(\mathbf{x}_{1i})$)	People movement safety ($S_3(\mathbf{x}_{1i})$)	General safety ($S_4(\mathbf{x}_{1i})$)
Alternative D ($i = 4$)					
12.	Smoke detection and alarm $x_{12,14}$	5	5	5	5
13.	Automatic sprinklers $x_{13,14}$	10	10	10 : 2 = 5	10
Total value		$S_1 = 20$	$S_2 = 15$	$S_3 = 18$	$S_4 = 26$
* Numerical values given in this table were taken from the description of the FSES index by FSES (1996) and the references cited therein					

Table D.11. Values of the components of the vector $\mathbf{x}_{2i}$ used for the calculation of the occupancy risk parameter $R_4(\mathbf{x}_{23})$ (FSES 1996)

No	Risk parameters	Risk factor values						
For all four alternatives								
1.	Patient mobility x_{12i}	Mobility status	Mobile	Limited mobility	Not mobile		Not movable	
		Risk factor	1.0	1.6	3.2		4.5	
2.	Patient density x_{22i}	Patient	1–5	6–10	11–30		>30	
		Risk factor	1.0	1.2	1.5		2.0	
3.	Zone location x_{32i}	Floor	1st	2 nd or 3 rd	4 th to 6 th		7 th and above	Basements
		Risk factor	1.1	1.2	1.4		1.6	1.6
4.	Ratio of patients to attendants x_{42i}	Patients attendant	$\frac{1-2}{1}$	$\frac{3-5}{1}$	$\frac{6-10}{1}$		$\frac{\geq 11}{1}$	$\frac{\text{One or more}^{(1)}}{\text{None}}$
		Risk factor	1.0	1.1	1.2		1.5	4.0

Table D.11. Continued

No	Risk parameters	Risk factor values		
For all four alternatives				
5.	Patient average age x_{52i}	Age	Under 65 years and over 1 year	65 years and over 1 year and younger
		Risk factor	1.0	1.2
⁽¹⁾ Risk factor of 4.0 is charged to any zone that houses patients without any staff in immediate attendance				

The values of $R_4(x_{2i})$ were calculated:

$$R_4(x_{2i}) = 0.6 \cdot (1.6 \cdot 1.0 \cdot 1.2 \cdot 1.0 \cdot 1.0) = 1.2$$

Results of safety system (alternative A) are got as following:

$$\text{Containment safety: } S_1(x_{11}) - R_1(x_{21}) = 10 - 9 = 1 > 0$$

$$\text{Extinguishment safety: } S_2(x_{11}) - R_2(x_{21}) = 2 - 6 = -4 < 0$$

$$\text{People movement safety: } S_3(x_{11}) - R_3(x_{21}) = 10 - 3 = 7 > 0$$

$$\text{General safety: } S_4(x_{11}) - R_4(x_{21}) = 13 - 1.2 = 11.8 > 0$$

These results suggest that containment, people movement and general safeties are acceptable, whereas the extinguishment safety is not acceptable.

Results of fire safety system (alternative B) are got as following:

$$\text{Containment safety: } S_1(x_{12}) - R_1(x_{22}) = 10 - 9 = 1 > 0$$

$$\text{Extinguishment safety: } S_2(x_{12}) - R_2(x_{22}) = 5 - 6 = -1 < 0$$

$$\text{People movement safety: } S_3(x_{12}) - R_3(x_{22}) = 13 - 3 = 10 > 0$$

$$\text{General safety: } S_4(x_{12}) - R_4(x_{22}) = 16 - 1.2 = 14.8 > 0$$

These results suggest that containment, people movement and general safeties are acceptable, whereas the extinguishment safety is not acceptable.

Results of fire safety system (alternative C) are got as following:

$$\text{Containment safety: } S_1(x_{13}) - R_1(x_{23}) = 18 - 9 = 9 > 0$$

$$\text{Extinguishment safety: } S_2(x_{13}) - R_2(x_{23}) = 10 - 6 = 4 > 0$$

$$\text{People movement safety: } S_3(x_{13}) - R_3(x_{23}) = 14 - 3 = 11 > 0$$

$$\text{General safety: } S_4(x_{13}) - R_4(x_{23}) = 21 - 1.2 = 19.8 > 0$$

These results suggest that containment, people movement, extinguishment and general safeties are acceptable.

Results of fire safety system (alternative D) are got as following:

$$\text{Containment safety: } S_1(\mathbf{x}_{14}) - R_1(\mathbf{x}_{24}) = 20 - 9 = 11 > 0$$

$$\text{Extinguishment safety: } S_2(\mathbf{x}_{14}) - R_2(\mathbf{x}_{24}) = 15 - 6 = 9 > 0$$

$$\text{People movement safety: } S_3(\mathbf{x}_{14}) - R_3(\mathbf{x}_{24}) = 18 - 3 = 15 > 0$$

$$\text{General safety: } S_4(\mathbf{x}_{14}) - R_4(\mathbf{x}_{24}) = 26 - 1.2 = 24.8 > 0$$

These results suggest that containment, people movement, extinguishment and general safeties are acceptable.

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

The FRAME method calculates the fire risk in buildings for buildings and its content $I_{FRAME,1}(x_i)$, for the occupants $I_{FRAME,2}(x_i)$ and for the activities in it $I_{FRAME,3}(x_i)$ (FRAME 2008). This index is calculated by the following formula:

$$I_{FRAME,k}(x_i) \equiv I_k(x_i) = \frac{P_k(x_{1i}, x_{2i}, x_{3i})}{A_k(x_{1i}, x_{2i}, x_{3i}) D_k(x_{2i}, x_{3i})} \leq 1.0 \quad (k = 1, 2, 3) \quad (E.1)$$

where the values of subscript k are related to the fire risk to building and its content, occupants and business activities, respectively; and x_{1i} , x_{2i} and x_{3i} are subcomponents of x_i . Functions on the right-hand side of the above formula are explained in Table 1.1.

Risk for a building and its content

$P_1(\cdot)$ as “potential danger” is a function of the building and its content that influence fire ignition and the spread of fire and can be written as:

$$P_1(x_{1i}, x_{2i}, x_{3i}) = q(x_{2i}) \times i(x_{2i}) \times g(x_{1i}) \times e(x_{3i}) \times v(x_{1i}, x_{2i}) \times z(x_{1i}, x_{3i}) \quad (E.2)$$

where the first 3 factors in the formula reflect the fire scenario: duration (factor $q(\cdot)$), development (factor $i(\cdot)$) and flashover (factor $v(\cdot)$). The other 3 factors reflect the impact of the building configuration on controllability of the fire by the fire brigade: compartment characteristics (factor $g(\cdot)$), level (factor $e(\cdot)$) and access possibilities (factor $z(\cdot)$). The combination of fire scenario and the controllability define the severity of the fire risk.

The acceptable risk level $A_1(\cdot)$ is calculated from maximum value 1.6, the number of fire sources (the activation factor $a(\cdot)$), the priority for the human safety (the evacuation factor $t(\cdot)$) and the severity of the loss (the value factor $c(\cdot)$):

$$A_1(x_{1i}, x_{2i}, x_{3i}) = 1.6 - a(x_{2i}) - t(x_{1i}, x_{2i}) - c(x_{3i}) \quad (E.3)$$

The scenario for defining the risk for the building and its contents is that of total destruction. The protection level D_1 includes and considers all elements that can reduce the probability of such total destruction:

$$D_1(x_{2i}, x_{3i}) = W(x_{2i}, x_{3i}) \times N(x_{2i}, x_{3i}) \times S(x_{2i}, x_{3i}) \times F(x_{2i}, x_{3i}) \quad (E.4)$$

where are factors expressing effectiveness of the transportation of water to the place of fire ($W(\cdot)$), effectiveness of normal (conventional) fire protection measures ($N(\cdot)$), effectiveness of special protection measures ($S(\cdot)$) and capability of building structures to resist fire ($F(\cdot)$).

Risk for occupants

The potential risk $P_2(\cdot)$ is calculated by using five of the previously defined factors, which best reflect a developing fire, which is the likely scenario during evacuation period of the occupants:

$$P_2(\mathbf{x}_{1i}, \mathbf{x}_{2i}, \mathbf{x}_{3i}) = q(\mathbf{x}_{2i}) \times i(\mathbf{x}_{2i}) \times e(\mathbf{x}_{3i}) \times v(\mathbf{x}_{1i}, \mathbf{x}_{2i}) \times z(\mathbf{x}_{1i}, \mathbf{x}_{3i}) \quad (\text{E.5})$$

The presence of fuel is considered in the fire-load factor $q(\cdot)$; the speed of the developing fires in the spread factor $i(\cdot)$; the threat of smoke is evaluated by the venting factor $v(\cdot)$. The complexity of evacuation in a high-rise building, compared to a ground level situation, the human reactions in such conditions, and difficulties encountered to bring adequate help are reflected in the formula by the level factor $e(\cdot)$, and the access factor $z(\cdot)$.

The acceptable risk level $A_2(\cdot)$ is defined as the maximum value 1.6 minus the number of fire sources (the activation factor $a(\cdot)$), the required safe egress time (the evacuation factor $t(\cdot)$), and the available safe egress time (the environment factor $r(\cdot)$):

$$A_2(\mathbf{x}_{1i}, \mathbf{x}_{2i}, \mathbf{x}_{3i}) = 1.6 - a(\mathbf{x}_{2i}) - t(\mathbf{x}_{1i}, \mathbf{x}_{2i}) - r(\mathbf{x}_{2i}) \quad (\text{E.6})$$

The protection level $D_2(\cdot)$ is defined as the product of the normal protection factor $N(\cdot)$ and the escape factor $U(\cdot)$:

$$D_2(\mathbf{x}_{2i}, \mathbf{x}_{3i}) = N(\mathbf{x}_{2i}, \mathbf{x}_{3i}) \times U(\mathbf{x}_{2i}) \quad (\text{E.7})$$

The calculations were carried out according to the FRAME method presented in FRAME (2008). The FRAME fire risk index was calculated for the alternative buildings considered in the example of selection of a building for a nursing home (Sec. 3.4). Values of FRAME index were calculated for two categories of fire risk: risk to a building and its content ($I_{FRAME,1}(\mathbf{x}_i)$) and risk to occupants ($I_{FRAME,2}(\mathbf{x}_i)$). Values of fire risk ($P_i(\cdot)$), acceptable risk level ($A_i(\cdot)$), and protection level ($D_i(\cdot)$) related to respective cases were calculated by means of formulas given in Table E.1. Input variables for calculation $I_{FRAME,i}$ index for the alternative buildings A, B and C are given in Table E.2.

Table E.1. Variables present in the mathematical expression of the constituents of the fire risk index $I_{FRAME,k}$ expression (FRAME 2008)

Constituent	Formula	Variables
Fire risk $P_f(\mathbf{x}_{1i}, \mathbf{x}_{2i}, \mathbf{x}_{3i})$		
Fire load factor $q(\cdot)$	$q = \frac{2}{3} \log(Q_i - Q_m) - 0.55$	Q_i – immobile fire load (MJ/m ²)
		Q_m – mobile fire load (MJ/m ²)
Venting factor $v(\cdot)$	$v = 0.84 + 0.1 \cdot \log Q_m - \sqrt{k \cdot \sqrt{h}}$	Q_m – mobile fire load (MJ/m ²)
		h – height between the floor and the ceiling of the storey (m)
		k – the smoke venting ratio
Access factor $z(\cdot)$	$z = 1 + 0.05 \cdot INT \left[\frac{b}{20 \cdot Z} + \frac{H^+}{25} \left \frac{H^-}{3} \right \right]$	Z – the number of cardinal points, that is north, east, south, west, from which such access is possible (the value of Z is 1, 2, 3 or 4)
		H^+ – a building height (m)
		H^- – a height of a basement (m)
Spread factor $i(\cdot)$	$i = 1 - \frac{T}{1000} - (0.1 \cdot \log m) + \frac{M}{10}$	T – destruction temperature (°C)
		m – subfactor ($m = 0.001, \dots, 1$)
		M – the flame propagation class ($M = 0, \dots, 5$)
Level factor $e(\cdot)$	$e = \frac{(E + 3)}{(E + 2)}^{(0.7 E)}$	E – level number of the building (the main access level has number $E = 0$; levels above: 1, 2, 3, etc., levels below: -1, -2, -3, etc.)
Area factor $g(\cdot)$	$g = \frac{5\sqrt[3]{(b^2 \cdot l)}}{200}$	l – the theoretical length of the compartment (m)
		b – the equivalent width (m)

Table E.1. Continued

Constituent	Formula	Variables
Acceptable risk level $A_i(\mathbf{x}_{1i}, \mathbf{x}_{2i}, \mathbf{x}_{3i})$		
Activation factor $a(\cdot)$	$a = \sum_{i=1}^5 a_i$	a_1 – main activities ($a_1 = 0, \dots, 0.4$)
		a_2 – secondary activities ($a_2 = 0.05, \dots, 0.2$)
		a_3 – process and room heating systems ($a_3 = 0, \dots, 0.15$)
		a_4 – electrical installations ($a_4 = 0, \dots, 0.2$)
		a_5 – flammable gases, liquids and dusts ($a_5 = 0.1, \dots, 0.3$)
Evacuation time factor $t(\cdot)$	$t = \frac{p[(b+l) + (X/x) + 1.25H^+ + 2H^-]}{800K[1.4x(b+l) - 0.44x]} \times$ $\times [x(b+l)]$	p – correction subfactor for the evacuation time estimation ($p = 1, \dots, 10$ depending on mobility of particular categories of people)
		X – the number of persons that can be present in the compartment (occupant load factor persons/m ²) ($X = 0.003, \dots, 3$)
		x – the number of exit units
		K – subfactor (the number of separate exit directions or exit paths available); $k = \min\{k_{ a }, k_{ b }, k_{ c }\}$
Value factor $c(\cdot)$	$c = c_1 + c_2$	c_1 – will evaluate the possibility to replace the building and its content ($c_1 = 0.01$ or 0.2)
		c_2 – will reflect the monetary value of the goods inside building (mln. LTL)
Environment factor $r(\cdot)$	$r = 0.1 \cdot \log(Q_i + 1) + \frac{M}{10}$	Q_i – immobile fire load (MJ/m ²)
		M – the flame propagation class ($M = 0, \dots, 5$)

Table E.1. Continued

Constituent	Formula	Variables
Protection level $D_i(\mathbf{x}_{2i}, \mathbf{x}_{3i})$		
Water supply factor $W(\cdot)$	$W = 0.95^w$ $w = \sum w_i$	Numbers of “penalty points”: w_i reflecting the difference in quality between the actual water supply and an adequate one.
		w_1 – type of water storage ($w_1 = 0, \dots, 10$)
		w_2 – capacity of water storage ($w_2 = 0, \dots, 4$)
		w_3 – distribution network ($w_3 = 0, \dots, 6$)
		w_4 – hydrants ($w_4 = 0, \dots, 3$)
		w_5 – water pressure ($w_5 = 0, \dots, 3$)
Normal protection factor $N(\cdot)$	$N = 0.95^n$ $n = \sum n_i$	n_1 – discovery and warning ($n_1 = 0, \dots, 2$)
		n_2 – manual firefighting ($n_2 = 0, \dots, 4$)
		n_3 – fire brigade intervention ($n_3 = 0, \dots, 10$)
		n_4 – education ($n_4 = 0, \dots, 4$)
Special protection factor $S(\cdot)$	$S = 1.05^S$ $s = \sum s_i$	s_1 – automatic fire detection ($s_1 = 2, \dots, 8$)
		s_2 – water supplies ($s_1 = 2, \dots, 12$)
		s_3 – sprinkler system and other automatic detection ($s_3 = 11, \dots, 20$)
		s_4 – responding fire station ($s_4 = 2, \dots, 14$) (day, h)

Table E.1. Continued

Constituent	Formula	Variables
Protection level $D_f(\mathbf{x}_{2i}, \mathbf{x}_{3i})$		
Fire resistance factor $F(\cdot)$	$F = \left[1 + \frac{f}{100} - \frac{f^{2.5}}{10^6} \right] \cdot \left[1 - \frac{(S-1)}{40} \right]$ $f = \frac{1}{2} f_s + \frac{1}{4} f_f + \frac{1}{8} f_d + \frac{1}{8} f_w$	f_s – the average fire resistance of the structural and separating elements (min.)
		f_f – the average fire resistance of the outside walls (min.)
		f_d – the average fire resistance of the ceiling or the roof (min.)
		f_w – the average fire resistance of interior walls (min.)
Escape factor $U(\cdot)$	$U = 1.05^U$ $u = \sum u_i$	u_1 – automatic detection and alarm ($u_1 = 2, \dots, 8$)
		u_2 – vertical evacuation paths ($u_2 = 2, \dots, 8$)
		u_3 – compartmentation ($u_3 = 0, \dots, 4$)
		u_4 – automatic protection ($u_4 = 4, \dots, 10$)
		u_5 – responding fire station ($u_5 = 2, \dots, 8$)

Table E.2. Input variables for calculation $I_{FRAME,k}$ index for the alternative buildings A, B and C

Constituent	Variables	Alternative building		
		A	B	C
Fire risk $P_i(\mathbf{x}_{1i}, \mathbf{x}_{2i}, \mathbf{x}_{3i})$				
Fire load factor $q(\cdot)$	Q_i – immobile fire load (MJ/m ²)	300	300	100
	Q_m – mobile fire load (MJ/m ²)	1500	1500	750
Venting factor $v(\cdot)$	Q_m – mobile fire load (MJ/m ²)	1500	1500	750
	h – height between the floor and the ceiling of the storey (m)	2.8	3	2.6
	k – the smoke venting ratio	0.04	0.05	0.03

Table E.2. Continued

Constituent	Variables	Alternative building		
		A	B	C
Fire risk $P_f(\mathbf{x}_{1i}, \mathbf{x}_{2i}, \mathbf{x}_{3i})$				
Access factor $z(\cdot)$	Z – the number of cardinal points, that is north, east, south, west, from which such access is possible (the value of Z is 1, 2, 3 or 4)	1	3	1
	H^+ – a building height (m)	8.4	9	5.2
	H^- – a height of a basement (m)	2.8	2.8	0
Spread factor $i(\cdot)$	T – destruction temperature ($^{\circ}\text{C}$)	212	212	212
	m – subfactor ($m = 0.001, \dots, 1$)	0.3	0.3	0.3
	M – the flame propagation class ($M = 0, \dots, 5$)	2	2	2
Level factor $e(\cdot)$	E – level number of the building (the main access level has number $E = 0$; levels above: 1, 2, 3, etc., levels below: -1, -2, -3, etc.)	2	2	1
Area factor $g(\cdot)$	l – the theoretical length of the compartment (m)	30	25	67
	b – the equivalent width (m)	20	20	12
Acceptable risk level $A_f(\mathbf{x}_{1i}, \mathbf{x}_{2i}, \mathbf{x}_{3i})$				
Activation factor $a(\cdot)$	a_1 – main activities ($a_1 = 0, \dots, 0.4$)	0	0	0
	a_2 – secondary activities ($a_2 = 0.05, \dots, 0.2$)	0.1	0.1	0.1
	a_3 – process and room heating systems ($a_3 = 0, \dots, 0.15$)	0	0	0
	a_4 – electrical installations ($a_4 = 0, \dots, 0.2$)	0.1	0.1	0.1
	a_5 – flammable gases, liquids and dusts ($a_5 = 0.1, \dots, 0.3$)	0.1	0.1	0.1
Evacuation time factor $t(\cdot)$	p – correction subfactor for the evacuation time estimation ($p = 1, \dots, 10$ depending on mobility of particular categories of people)	10	10	10
	X – the number of persons that can be present in the compartment (occupant load factor persons/m ²) ($X = 0.003, \dots, 3$)	0.4	0.4	0.4
	x – the number of exit units	3	5	5
	K – subfactor (the number of separate exit directions or exit paths available); $k = \min\{k_{ a }, k_{ b }, k_{ c }\}$	3	5	5

Table E.2. Continued

Constituent	Variables	Alternative building		
		A	B	C
Acceptable risk level $A_i(\mathbf{x}_{1i}, \mathbf{x}_{2i}, \mathbf{x}_{3i})$				
Value factor $c(\cdot)$	c_1 – will evaluate the possibility to replace the building and its content ($c_1 = 0, 0.1$ or 0.2)	0.1	0	0
	c_2 – will reflect the monetary value of the goods inside building (mln. LTL)	6.9	6.5	4.1
Environment factor $r(\cdot)$	Q_i – immobile fire load (MJ/m ²)	300	300	100
	M – the flame propagation class ($M = 0, \dots, 5$)	2	2	2
Protection level $D_i(\mathbf{x}_{2i}, \mathbf{x}_{3i})$				
Water supply factor $W(\cdot)$	Numbers of “penalty points”: w_i reflecting the difference in quality between the actual water supply and an adequate one. w_1 – type of water storage ($w_1 = 0, \dots, 10$)	0	0	0
	w_2 – capacity of water storage ($w_2 = 0, \dots, 4$)	0	0	0
	w_3 – distribution network ($w_3 = 0, \dots, 6$)	0	0	0
	w_4 – hydrants ($w_4 = 0, \dots, 3$)	0	0	0
	w_5 – water pressure ($w_5 = 0, \dots, 3$)	0	0	0
Normal protection factor $N(\cdot)$	n_1 – discovery and warning ($n_1 = 0, \dots, 2$)	0	0	0
	n_2 – manual firefighting ($n_2 = 0, \dots, 4$)	0	0	0
	n_3 – fire brigade intervention ($n_3 = 0, \dots, 10$)	2	2	2
	n_4 – education ($n_4 = 0, \dots, 4$)	2	2	2
Special protection factor $S(\cdot)$	s_1 – automatic fire detection ($s_1 = 2, \dots, 16$)	12	8	8
	s_2 – water supplies ($s_1 = 2, \dots, 12$)	3	3	3
	s_3 – sprinkler system and other automatic detection ($s_3 = 11, \dots, 20$)	11	11	11
	s_4 – responding fire station ($s_4 = 2, \dots, 14$) (day, h)	2	2	2

Table E.2. Continued

Constituent	Variables	Alternative building		
		A	B	C
Protection level $D_i(\mathbf{x}_{2i}, \mathbf{x}_{3i})$				
Fire resistance factor $F(\cdot)$	f_s – the average fire resistance of the structural and separating elements (min.)	90	90	90
	f_f – the average fire resistance of the outside walls (min.)	0	0	0
	f_d – the average fire resistance of the ceiling or the roof (min.)	0	0	0
	f_w – the average fire resistance of interior walls (min.)	15	15	15
Escape factor $U(\cdot)$	u_1 – automatic detection and alarm ($u_1 = 2, \dots, 16$)	12	8	8
	u_2 – vertical evacuation paths ($u_2 = 2, \dots, 8$)	4	4	4
	u_3 – compartmentation ($u_3 = 0, \dots, 4$)	0	0	2
	u_4 – automatic protection ($u_4 = 4, \dots, 10$)	10	3	4
	u_5 – responding fire station ($u_5 = 2, \dots, 8$)	2	2	2

The calculations of the risk for a building and its content (alternative A):

$$I_{FRAME,1}(\mathbf{x}_i) = \frac{1.12}{1.2 \cdot 4.34} = 0.22 < 1.0$$

$$P_1(\mathbf{x}_{1i}, \mathbf{x}_{2i}, \mathbf{x}_{3i}) = 2.17 \cdot 0.84 \cdot 0.57 \cdot 1.24 \cdot 0.82 \cdot 1.05 = 1.12$$

$$A_1(\mathbf{x}_{1i}, \mathbf{x}_{2i}, \mathbf{x}_{3i}) = 1.6 - 0.3 - 0.0013 - 0.1 = 1.2$$

$$D_1(\mathbf{x}_{2i}, \mathbf{x}_{3i}) = 1 \cdot 0.81 \cdot 3.92 \cdot 1.36 = 4.34$$

The calculations of the risk for occupants are following (alternative A):

$$I_{FRAME,2}(\mathbf{x}_i) = \frac{1.96}{0.85 \cdot 3.19} = 0.72 < 1.0$$

$$P_2(\mathbf{x}_{1i}, \mathbf{x}_{2i}, \mathbf{x}_{3i}) = 2.17 \cdot 0.84 \cdot 1.24 \cdot 0.82 \cdot 1.05 = 1.96$$

$$A_2(\mathbf{x}_{1i}, \mathbf{x}_{2i}, \mathbf{x}_{3i}) = 1.6 - 0.3 - 0.001 - 0.45 = 0.85$$

$$D_2(\mathbf{x}_{2i}, \mathbf{x}_{3i}) = 3.92 \cdot 0.81 = 3.19$$

The calculations of the risk for a building and its content (alternative B):

$$I_{FRAME,1}(\mathbf{x}_i) = \frac{1.14}{1.3 \cdot 3.83} = 0.23 < 1.0$$

$$P_1(\mathbf{x}_{1i}, \mathbf{x}_{2i}, \mathbf{x}_{3i}) = 1.62 \cdot 1.04 \cdot 0.54 \cdot 1.37 \cdot 0.87 \cdot 1.05 = 1.14$$

$$A_1(\mathbf{x}_{1i}, \mathbf{x}_{2i}, \mathbf{x}_{3i}) = 1.6 - 0.3 - 0.0005 - 0.0008 = 1.3$$

$$D_1(\mathbf{x}_{2i}, \mathbf{x}_{3i}) = 1 \cdot 0.81 \cdot 3.23 \cdot 1.46 = 3.83$$

The calculations of the risk for occupants are following (alternative B):

$$I_{FRAME,2}(\mathbf{x}_i) = \frac{2.11}{0.85 \cdot 1.87} = 1.32 > 1.0$$

$$P_2(\mathbf{x}_{1i}, \mathbf{x}_{2i}, \mathbf{x}_{3i}) = 2.62 \cdot 1.04 \cdot 1.37 \cdot 0.87 \cdot 1.05 = 2.11$$

$$A_2(\mathbf{x}_{1i}, \mathbf{x}_{2i}, \mathbf{x}_{3i}) = 1.6 - 0.3 - 0.0001 - 0.45 = 0.85$$

$$D_2(\mathbf{x}_{2i}, \mathbf{x}_{3i}) = 0.81 \cdot 2.29 = 1.87$$

The calculations of the risk for a building and its content (alternative C):

$$I_{FRAME,1}(\mathbf{x}_i) = \frac{0.91}{1.15 \cdot 3.64} = 0.22 < 1.0$$

$$P_1(\mathbf{x}_{1i}, \mathbf{x}_{2i}, \mathbf{x}_{3i}) = 1.40 \cdot 1.04 \cdot 0.53 \cdot 1.22 \cdot 0.91 \cdot 1.05 = 0.91$$

$$A_1(\mathbf{x}_{1i}, \mathbf{x}_{2i}, \mathbf{x}_{3i}) = 1.6 - 0.3 - 0.153 - 0.00005 = 1.15$$

$$D_1(\mathbf{x}_{2i}, \mathbf{x}_{3i}) = 1 \cdot 0.82 \cdot 3.23 \cdot 1.38 = 3.64$$

The calculations of the risk for occupants are following (alternative C):

$$I_{FRAME,2}(\mathbf{x}_i) = \frac{1.62}{0.75 \cdot 1.96} = 1.11 > 1.0$$

$$P_2(\mathbf{x}_{1i}, \mathbf{x}_{2i}, \mathbf{x}_{3i}) = 1.4 \cdot 1.04 \cdot 1.22 \cdot 0.91 \cdot 1.05 = 1.62$$

$$A_2(\mathbf{x}_{1i}, \mathbf{x}_{2i}, \mathbf{x}_{3i}) = 1.6 - 0.3 - 0.15 - 0.4 = 0.75$$

$$D_2(\mathbf{x}_{2i}, \mathbf{x}_{3i}) = 0.82 \cdot 2.41 = 1.96$$

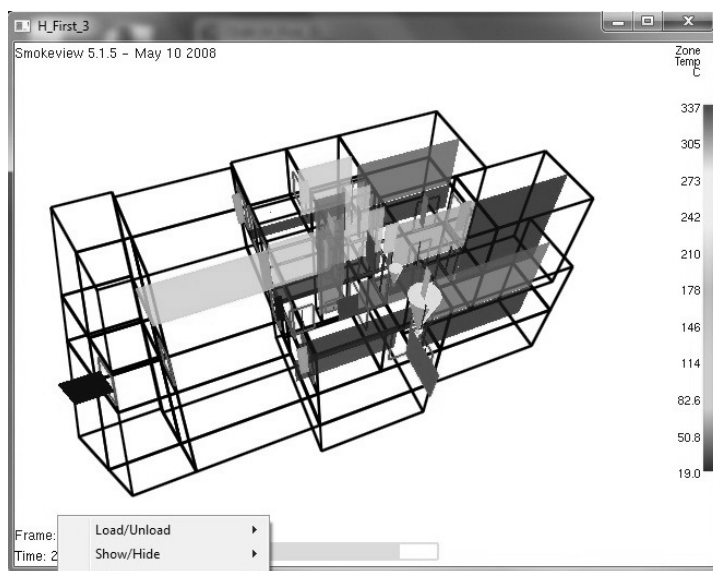
The results suggest that the risk to all three buildings and their content is acceptable. The risk to occupants is acceptable only for the alternative A. A sprinkler system and/or fire alarm may be necessary to install. This will allow to increase the protection level $D_i(\cdot)$ and so to decrease the value of $I_{FRAME,k}$. These values will be used as ones of an MCDM attribute characterising the overall fire safety of the buildings (Sec. 3.4.3).

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

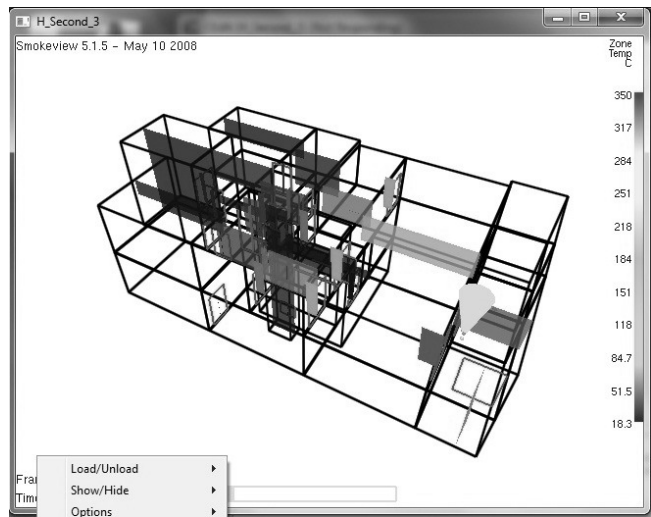
This annex contains graphical outputs obtained with the CFAST computer fire model developed for three alternative floor plans of the hospital building under reconstruction. The outputs indicate the fire rooms in the individual floor plans and the spread of gaseous combustion products through the first and second floors of the building. The outputs show the formation of two smoke layers with different concentration of the combustion gases. The height of the interface between these layers is used as a criterion of attaining untenable conditions on potential escape routes.

The graphical outputs were obtained with the SMOKEVIEW computer code (Forney 2007). This code creates the visualisation by applying numerical information computed with the CFAST model.

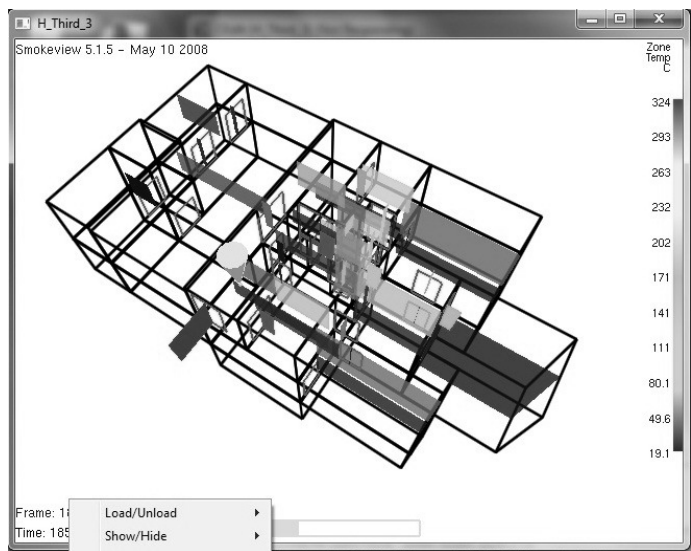
Floor plan A (the first MCDM alternative)



Floor plan B (the second MCDM alternative)



Floor plan C (the third MCDM alternative)



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

The present annex contains samples of the times to untenable conditions attained in the hospital building fires according to two fire scenarios described in the subsection “Fire development and scenarios“ of Sec. 3.5.2. The times to untenable conditions in the first scenario are modelled by the random variables $T_{u,i1}$ ($i = 1, 2, 3$) related to the alternative floor plans A, B and C, respectively. In this scenario, an attainment of the untenable conditions in the hemodialysis unit was simulated. The values of $T_{u,i1}$ were obtained by means of CFAST computer code and are presented in Table G.1. In the second fire scenario, the fire was confined to the second floor and the times to untenable conditions modelled by the random variables $T_{u,i2}$ ($i = 1, 2, 3$) related to the three floor plans. The simulated values of the times $T_{u,i2}$ are given in Table G.2.

Table G.1. Simulated values $t_{u,ik}$ of the times to untenable conditions, $T_{u,i1}$ ($i = 1, 2, 3$), related to the first fire scenario and the three alternative floor plans in the hospital building under reconstruction (Sec. 3.5.2)

k	$t_{u,11k}, s$	$t_{u,21k}, s$	$t_{u,31k}, s$
1	125	233	55.5
2	124.5	240	56.75
3	127	238	58.75
4	122	237	55.75
5	130	238	54.25
6	130	236	54.25
7	130	245	60
8	132	238	61.5
9	132	239	54.75
10	125	237	51.75
11	126.5	237	57
12	122.5	238	56
13	127	239	56.75
14	128	237	56
15	128	236	57
16	126	232	56.75
17	127	237	57
18	129	237	61.75
19	126	243	55.25
20	128	241	60.75
21	127	236	63.75
22	125.5	231	57.75
23	129	231	56.75
24	125	234	55.75
25	126	239	58

Table G.1. Continued

k	$t_{u,11k}, s$	$t_{u,21k}, s$	$t_{u,31k}, s$
26	125	234	54.75
27	128.5	240	55.25
28	123	240	55.75
29	127.5	237	57
30	122	235	61
31	128.5	243	65.75
32	125.5	235	57.75
33	127.5	237	58.25
34	127.5	232	60.75
35	127	235	58
36	126	234	62
37	122	239	58.75
38	128	241	55.75
39	126.5	235	58.25
40	125	238	56.25
41	124.5	236	57.75
42	131	243	57.75
43	125	239	55.75
44	126.5	234	54.75
45	126	239	58
46	124	237	58.25
47	125	233	58
48	121	238	58
49	130.5	241	59
50	128	236	53.25
51	125	241	55
52	128.5	230	55.75
53	128.5	241	57.25
54	122	241	59.75
55	127	236	57.25
56	121.5	235	59.25
57	125	240	55.25
58	121	235	59
59	122.5	230	55.75
60	128	241	57.25
61	126	233	59.5
62	125	241	61.25
63	125	232	55
64	128.5	240	56.25
65	125	238	59.75
66	128	235	58
67	130	238	57.75
68	127	234	56.25
69	125.5	229	56.25
70	121.5	231	57

Table G.1. Continued

k	$t_{u,11k}$, s	$t_{u,21k}$, s	$t_{u,31k}$, s
71	127	237	62.75
72	129	230	62.75
73	126	233	56.75
74	131	238	58
75	126	238	59.5
76	124.5	235	58
77	123	234	62
78	130	223	58.75
79	127	236	55
80	126	241	59.75
81	129	233	60
82	127.5	236	53.75
83	133	235	57.25
84	124	232	58
85	128.5	232	55.75
86	127	234	52.25
87	125	231	58.5
88	125	234	54
89	123	239	53.75
90	124	239	56.25
91	126.5	230	56
92	122	233	56.75
93	126	230	56.75
94	125	229	58.75
95	128	235	59
96	128	231	57.75
97	126	243	59
98	125.5	242	56
99	125.5	235	56
100	125.5	231	58.75

Table G.2. Simulated values $t_{u,i2k}$ of the times to untenable conditions, $T_{u,i2}$ ($i = 1, 2, 3$), related to the second fire scenario and the three alternative floor plans in the hospital building under reconstruction (Sec. 3.5.2)

k	$t_{u,12k}$, s	$t_{u,22k}$, s	$t_{u,32k}$, s
1	145	121	75.5
2	144	137	74.5
3	146	137	78
4	148	124	71.5
5	136	124	75
6	146	121	79
7	137	129	71.5
8	145	120	80.5

Table G.2. Continued

k	$t_{u,12k}, s$	$t_{u,22k}, s$	$t_{u,32k}, s$
9	138	131	73.5
10	132	118	71.5
11	137	121	78
12	141	121	70
13	145	122	73.5
14	139	119	72.5
15	139	118	72
16	156	122	70
17	146	125	74.5
18	134	133	80
19	139	118	75
20	133	122	70.5
21	138	130	70
22	138	121	77.5
23	156	119	77
24	145	118	75.5
25	154	118	73
26	140	120	77.5
27	147	128	72
28	148	117	74.5
29	151	135	73.5
30	133	124	75
31	151	121	77.5
32	137	124	74
33	148	126	73.5
34	144	121	74.5
35	146	130	77.5
36	147	131	74.5
37	139	129	69.5
38	143	122	77.5
39	142	119	75
40	143	127	71.5
41	136	126	74
42	154	115	74
43	146	116	69
44	140	112	74.5
45	140	124	73
46	144	127	72
47	138	124	76
48	133	119	74
49	149	134	71
50	145	130	73.5
51	136	130	78.5
52	132	139	68.5
53	138	124	77.5

Table G.2. Continued

k	$t_{u,12k}, s$	$t_{u,22k}, s$	$t_{u,32k}, s$
54	146	115	76
55	151	120	74
56	147	127	73.5
57	137	127	71
58	147	117	71
59	152	110	75.5
60	141	123	72.5
61	144	121	69.5
62	148	123	71.5
63	146	123	70.5
64	145	128	70.5
65	146	124	72.5
66	144	126	74
67	140	123	74
68	139	123	76
69	139	117	74.5
70	148	131	73.5
71	150	120	72
72	136	122	73.5
73	150	128	74.5
74	146	123	76
75	139	120	80
76	147	133	74
77	138	123	74
78	136	128	78
79	147	121	71.5
80	140	123	70.5
81	146	125	74.5
82	145	122	78
83	147	125	73
84	155	126	71.5
85	140	120	73.5
86	148	119	74.5
87	143	120	75
88	143	121	74
89	132	118	74.5
90	145	122	74.5
91	139	119	74.5
92	142	120	71.5
93	149	125	76.5
94	137	120	74.5
95	150	125	75.5
96	135	124	72
97	148	122	72
98	143	130	77

Table G.2. Continued

<i>k</i>	<i>t_{u,12<i>k</i>}</i> , S	<i>t_{u,22<i>k</i>}</i> , S	<i>t_{u,32<i>k</i>}</i> , S
99	142	127	72.75
100	144	131	76.75

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

This annex contains graphical and numerical outputs obtained with the SIMULEX model for the hospital building with three alternative floor plans.

Floor plan A

Number of Floors = 2

Number of Staircases = 1

Number of Links = 2

Number of Exits = 4

Number of People = 0

Floor1 (DXF file : 1AUKSTAS.DXF)

Number of People Initially in This Floor = 0

Link 1 : (6.45,0.90 m), -177.80 degrees, 1.20 m wide, connected to Staircase 1

Exit 1 : (4.72,24.92 m), -90.00 degrees, 1.20 m wide

Exit 2 : (7.05,0.80 m), 0.00 degrees, 1.20 m wide

Exit 3 : (2.97,0.80 m), 0.00 degrees, 1.20 m wide

Floor 2 (DXF file : 2A3VAR~1.DXF)

Number of People Initially in This Floor = 0

Link 2 : (6.04,6.01 m), -90.00 degrees, 1.20 m wide, connected to Staircase 1

Exit 5 : (4.95,24.95 m), -90.00 degrees, 1.50 m wide

Staircase 1 (1.30 m X 9.10 m)

Number of People Initially in This Stair = 0

Link 1 : (0.73,0.00 m), 270.00 degrees, 1.20 m wide, connected to Floor1

Link 2 : (0.57,9.10 m), 90.00 degrees, 1.20 m wide, connected to Floor 2

All people reached the exit in 0:16.1.

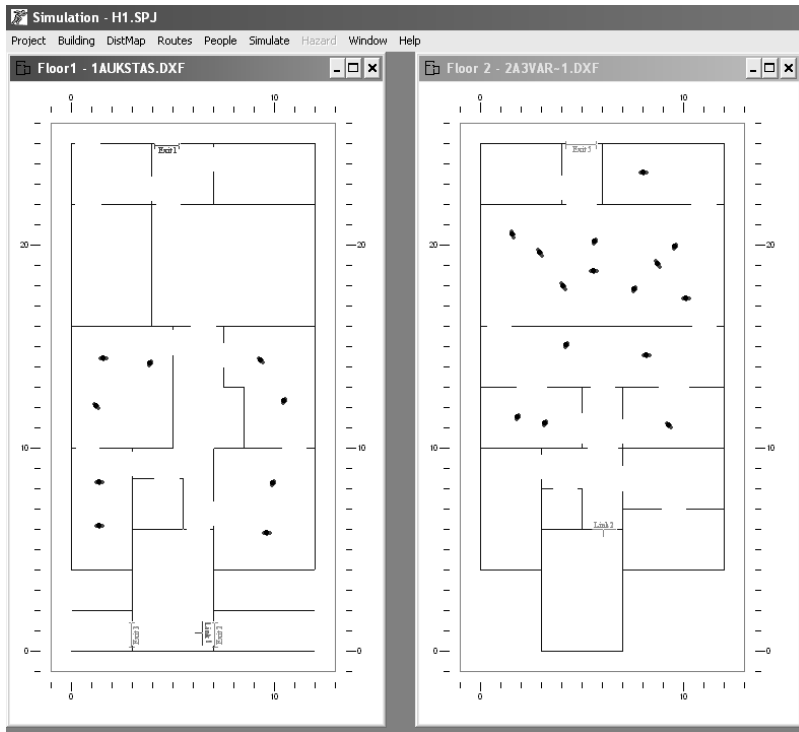
Time (sec.), Total number of people through final exits

5 0

10 5

15 13

20 15



Floor plan B

Number of Floors = 2

Number of Staircases = 1

Number of Links = 2

Number of Exits = 4

Number of People = 0

Floor1 (DXF file : 1AUKSTAS.DXF)

Number of People Initially in This Floor = 0

Link 1 : (6.69,0.99 m), 180.00 degrees, 1.20 m wide, connected to Staircase 1

Exit 1 : (6.95,1.00 m), -179.01 degrees, 1.20 m wide

Exit 2 : (4.65,25.00 m), -90.00 degrees, 1.20 m wide

Exit 3 : (2.90,0.90 m), 0.00 degrees, 1.20 m wide

Exit 4 : (-10001.00,0.00 m), 0.00 degrees, 1.20 m wide

Floor 2 (DXF file : 2A1VAR~1.DXF)

Number of People Initially in This Floor = 0

Link 3 : (6.06,6.01 m), -90.00 degrees, 1.20 m wide, connected to Staircase 1

 Staircase 1 (1.30 m X 9.10 m)

Number of People Initially in This Stair = 0

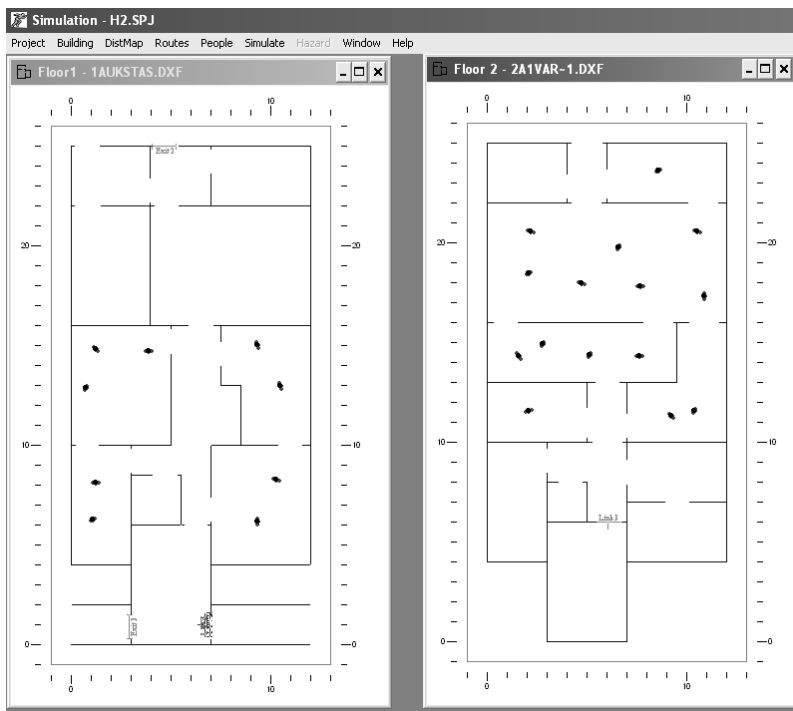
Link 1 : (0.63,9.10 m), 90.00 degrees, 1.20 m wide, connected to Floor1

Link 3 : (0.73,0.00 m), 270.00 degrees, 1.20 m wide, connected to Floor 2

All people reached the exit in 0:38.4.

Time (sec.), Total number of people through final exits

5	0
10	0
15	0
20	3
25	4
30	11
35	13
40	15



Floor plan C

Number of Floors = 2

Number of Staircases = 1

Number of Links = 2

Number of Exits = 5

Number of People = 0

Floor 1 (DXF file : 1AUKSTAS.DXF)

Number of People Initially in This Floor = 0

Link 1 : (6.41,0.93 m), 180.00 degrees, 1.30 m wide, connected to Staircase 1

Exit 1 : (4.68,24.96 m), -90.00 degrees, 1.20 m wide

Exit 2 : (6.95,0.95 m), 0.00 degrees, 1.20 m wide

Exit 3 : (2.95,0.85 m), 0.00 degrees, 1.20 m wide

Exit 4 : (-10001.00,0.00 m), 0.08 degrees, 1.50 m wide

Floor 2 (DXF file : 2A2VAR~1.DXF)

Number of People Initially in This Floor = 0

Link 2 : (6.05,6.00 m), -90.00 degrees, 1.20 m wide, connected to Staircase 1

Exit 5 : (4.90,25.00 m), -90.00 degrees, 1.50 m wide

Staircase 1 (1.30 m X 9.10 m)

Number of People Initially in This Stair = 0

Link 1 : (0.70,9.10 m), 90.00 degrees, 1.30 m wide, connected to Floor 1

Link 2 : (0.82,0.00 m), 270.00 degrees, 1.20 m wide, connected to Floor 2

All people reached the exit in 0:24.2.

Time (sec.), Total number of people through final exits

5 0

10 8

15 13

20 14

25 15

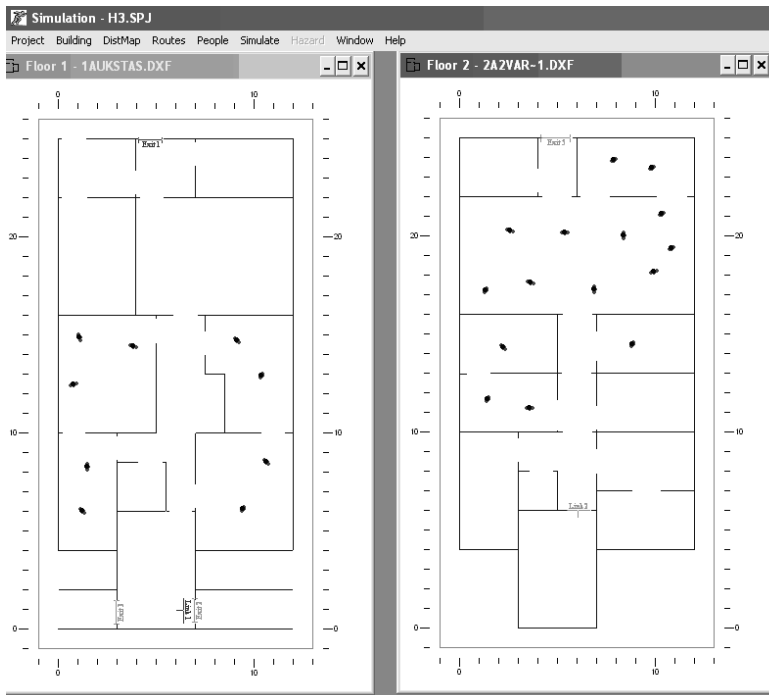


Table H.1. Simulated values $t_{lr,i2k}$ of the travel times $T_{lr,i2}$ ($i = 1, 2, 3$), related to the second fire scenario and the three alternative floor plans in the hospital building under reconstruction (Sec. 3.5.2)

k	Simulated number of visitors, ζ_{vk}	$t_{lr,12k}$, s	$t_{lr,12k}$, s	$t_{lr,12k}$, s
1	5	20.4	15.3	19.9
2	9	19.8	12.6	25.1
3	8	19.5	19.5	25.8
4	10	16.5	19.9	21.5
5	7	29	18.3	26.7
6	13	16.3	14.5	23.5
7	12	17.8	17.6	23.1
8	17	18.6	12.7	20.2
9	7	16.2	19.3	16.4
10	6	18.5	17.5	17.9
11	8	14.7	22.1	22.6
12	11	18.5	23.3	21.1
13	8	19.9	24.6	24.2
14	8	15.2	14.2	16.9
15	8	17.9	19.4	26.5
16	13	23	13.8	27

Table H.1. Continued

k	Simulated number of visitors, ζ_{vk}	$t_{lr,12k}, s$	$t_{lr,12k}, s$	$t_{lr,12k}, s$
17	11	20.4	16.8	18.5
18	11	16.9	16.2	16
19	9	21.1	23.6	20.3
20	8	24.4	15.8	21.2
21	3	17.9	21.6	19.9
22	7	19.9	24.5	19.3
23	10	22.6	18	21.6
24	11	22.5	15.7	23.6
25	12	18.5	14	26.8
26	10	20.2	22.8	27.8
27	11	19.5	18.7	20.1
28	10	19.5	18.3	19.8
29	3	19.4	21.3	18.5
30	11	15.5	18.7	18.5
31	9	15.8	14.2	19.8
32	10	20.6	15.3	21.3
33	13	21	14.2	20.1
34	8	18.5	15.9	22.8
35	9	16.3	22.5	20.7
36	9	18.9	13.6	18.9
37	8	19.7	17.1	21.7
38	14	17.4	22.5	20.9
39	11	24.2	17.2	27
40	10	20.3	14.3	24.8
41	16	18.7	19.5	18.7
42	8	21.8	16.2	21.5
43	11	19.8	20.8	21.6
44	9	18.3	25.7	26.2
45	4	17.8	19.9	28.7
46	7	24.9	19.7	20.7
47	6	19.8	15.9	20.5
48	11	16.4	24.8	21.7
49	11	20.3	24.1	23.3
50	8	20.7	20.8	22.5
51	6	21	19.2	23.7
52	12	25.6	21.8	21.5
53	9	24.5	17.3	22.6
54	13	21.2	18.1	22.7
55	10	18	17.1	22.9
56	6	21.8	19.5	20.3
57	10	24.3	23	19.5
58	5	19.2	18.7	22.2
59	11	17.3	23.1	21
60	7	20.7	18.8	15.8

Table H.1. Continued

k	Simulated number of visitors, ζ_{vk}	$t_{lr,12k}$, s	$t_{lr,12k}$, s	$t_{lr,12k}$, s
61	9	21.1	20.5	24.9
62	13	19.1	24.6	22.9
63	8	19.2	16.3	19.2
64	12	18.1	19.5	19.9
65	8	22	16.6	22.2
66	11	17.4	13.3	26.5
67	12	16.9	14.4	18.2
68	8	22.2	22.1	26.7
69	12	20.8	14	21.9
70	2	16.3	18.9	25.3
71	9	19.7	19.3	16.1
72	9	17.4	18.4	20.1
73	12	18.5	15.9	17.3
74	6	26.4	14.3	21.1
75	10	20.3	17.8	24.1
76	10	25.8	22.5	15.9
77	7	24.2	23.1	21.6
78	6	18.6	18.3	27.7
79	6	19.4	18	28.9
80	12	18.5	18.6	18.4
81	10	19.6	15.5	22.9
82	9	21.1	15.3	23.1
83	8	18.3	15.5	21.3
84	4	20.7	13.4	25.9
85	13	17.5	16.5	22.3
86	5	19.1	14.4	27
87	10	20.6	22.4	23.5
88	8	20	17.6	24.8
89	11	20.5	15.9	25.2
90	4	18.3	23.7	19.3
91	10	19.4	18.8	22.4
92	12	16.6	19.6	20
93	8	25.3	20.6	22.4
94	14	17.6	18.7	23.6
95	13	18.9	18.9	25.7
96	14	19.6	16.9	19.4
97	8	16.8	21.7	20.9
98	9	17	24	25.5
99	10	20.4	13.6	17.6
100	10	18	16.4	20.2