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Utilisation of statistics to assess fire risks in buildings

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VTT Building and Transport

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Abstract

This study is the first relatively broad statistical survey utilising the statistical data collected in the national accident database, Pronto. As a result valuable new information relating to fire risks is obtained and quantitative methods for fire risk assessment of buildings are presented. This work is a step forward in the field of risk-analysis-based fire safety design and overall a step towards a better understanding of the anatomy of fires.

The use of statistical information is a good objective way of attempting to characterise fires. This study concentrates on ignition frequency, economic fire losses and fire department operation in the event of building-fires. Ignition frequency was derived as a function of total floor area for different building categories. The analysis showed that the variations of ignition frequency are dependent on initial floor area distributions of the buildings hit by fire and at risk. For engineering design purposes, the generalisation of the theory starting from the initial floor area distributions, leading to a sum of two power laws, was found suitable. The parameters and partial safety coefficients for the model were estimated for three building groups. The model is suitable for determining the ignition frequency of buildings with a total floor area of between 100 and 20 000 m^2.

The elements describing the fire department operation were analysed on the basis of statistical information. In the presented approach, the buildings in which fire safety depends completely on automatic extinguishing systems can be distinguished from those in which the fire department is able to arrive at the fire scene early enough to have a good chance of saving the building. The most important factor affecting the performance of the rescue force was found to be the travel time to the fire scene. Thus, to make the task easier for the fire department, special attention must be paid to rapid fire detection and locating of

the fire seat. Delays in these actions lengthen the total response time and reduce significantly the chances of the fire department successfully intervening in the progress of the fire.

Economic losses were considered as consequences of the fires. The analysis showed the dependency of loss and value-at-risk of the building on the floor area. Clear local peaks were detected for both the ignition frequency and fire losses. A more detailed analysis of residential buildings where the phenomenon was most apparent revealed that the peaks were located around the floor-area region where the dominant building type of the building stock, and thus the compartmentation manner, changed. With small values of the total floor area of the building, the rise of the loss was very steep, but levelled off to substantially slower growth with large values. A natural explanation for the behaviour is compartmentation. Both the ignition frequency and the fire losses should therefore be examined in relation to the size of the ignition compartment, which would be a significantly more appropriate descriptor than the total floor area of the building. Hence, it is essential that the information becomes available to the Finnish accident database, in which it is not at the moment included. The analysis shows that the type of building and compartmentation, rather than the material of the load-bearing member itself, was the factor having the greatest effect on the risk of fire.

The use of the information gathered was demonstrated through a simple example case in which the fire risk was assessed using the time-dependent event-tree approach.

This study concentrates on the utilisation of statistics to collect information and gain an understanding of the elements affecting fire risks in buildings. Many of the methods used are well known in other application areas; the available statistical data now offers the possibility of applying them in connection with fire-risk problems as well. In risk-analysis-based design, the presented approach is very useful and the methods can be used for fire-risk assessment of buildings. Nevertheless, this study should be considered the first part of a major research effort and further studies will be needed to improve the tentative models to obtain more detailed and reliable risk estimates. In this work a preliminary exploration is carried out and a good base for further research is established.

Preface

This work has been carried out under the auspices of the Technical Research Centre of Finland (VTT) and Helsinki University of Technology (TKK) with the financial support of the Helsinki University of Technology, Academy of Finland and Tekniikan edistämissäätiö.

I wish to acknowledge Docent Olavi Keski-Rahkonen for his guidance and encouragement during this work. I am most grateful to Esko Mikkola for his support and advice. I also wish to thank Dr. Jukka Hietaniemi for his valuable comments during the completion of this thesis.

Furthermore, I wish to thank my colleagues in the fire research group of VTT Building and Transport for their helpful attitude towards my questions and for creating a pleasant working environment.

Finally, I wish to express my sincere gratitude to my family and friends for their endless support, encouragement and understanding, which have carried me through the difficult times during this work. I am deeply grateful to my closest ones for bearing my ups and downs, for enduring the endless discussions with me and for constantly encouraging me at those times when it seemed impossible to go on. Thank You!

Espoo, August 2003

Kati Tillander

Author's contribution

The work presented in Sections 5–7 was carried out in co-operation with the supervisor of this thesis, Docent Olavi Keski-Rahkonen. Some of the results are presented in Finnish in a series of VTT Research Notes and journal articles, in addition to three conference proceedings in English. The related articles, not all of them published, are mentioned at the beginning of each section and referred to in the body of text. The research methods used in Sections 5–7 were based on the ideas suggested by Docent Keski-Rahkonen. The author had the main responsibility for carrying out the statistical analysis, validation of the models and interpretation of the results under the supervision of Docent Keski-Rahkonen. The author also had the main responsibility of writing all the collaborative reports, publications and conference papers, as well as of conference presentations.

Contents

List of symbols and definitions

Symbols

A	Floor area [m^2]
a, b, c, d	Constants
C	Intensity of simultaneous fires $C=\lambda\tau$
c_1, c_2, r, s	Coefficient of the Barrois model
f_m''	Ignition frequency [$1/m^2a$]
$f(t)$	Probability mass function
$F(t)$	Cumulative distribution function
FR	Water flow rate [l/s]
$G(t)$	Cumulative normal distribution
$g(t)$	Probability density function of normal distribution
$h(z)$	Hazard function
n	Number of fires
N	Number of observations, number of buildings at risk
$P(A)$	Probability of fire starting
Q_c	Heat release rate [MW]
Q_w	Theoretical absorption energy of water going from a liquid at ambient temperature to vapour at 100°C, equivalent to 2.6 MW
s	Travel distance [km]
S_k	Total floor area of the smallest building
t	Time [min], [h]
T	Travel time [s]

V	Value–at-risk [€]
$v_n(A)$	Density function of the floor area for buildings involved in fires [1/m^2]
$v_N(A)$	Density function of the floor area for buildings at risk [1/m^2]
x, X	Loss [€]
z	ln(x), logarithm of loss x
α,β	Parameters of the gamma function
$\Gamma(\alpha)$	Gamma function
λ	Intensity [1/h]
λ_k	Constant of the Pareto distribution
μ	Average
η	Cooling efficiency of water
σ	Standard deviation
τ	Operating time [min], [h]

Definitions

CFAST	Consolidated Compartment Fire and Smoke Transport Model
consequential loss	Losses due to a interruption of the normal operation in a building caused by fire [€]
FDS3	Fire Dynamics Simulator (version 3)
ignition frequency	Probability per floor area and time unit of a building catching fire [1/m^{2}a]

loss of building	Financial losses to a building structures caused by fire [€]
operating time	Length of time from the moment the unit is notified until it returns back to the fire station [min], [h]
Ontika	Predecessor of the accident database Pronto
Pronto	National accident database maintained by the Ministry of the Interior
property loss	Financial losses to a movable property caused by fire [€]
response time	Length of time from the moment the fire is reported until the fire unit reaches the fire scene [min]
RHR	Rate of heat release [W]
search time	Length of time from the moment the fire unit arrives to the scene until extinguishing actions start [s], [min]
total loss	Sum of property loss, loss of building and consequential loss [€]
travel time	Length of time from the moment the unit leaves the fire station until it reaches the fire scene [min]
turnout time	Length of time from the moment fire unit is notified until it leaves the fire station [s], [min]

1. Introduction

1.1 Background, motivation

Fires have a significant role in society from the viewpoints of human safety and economics. Personal safety is an issue people are seldom willing to compromise over, because the possible loss is immeasurable. However, at some levels, the fires are a daily threat to the safety of everyone. Fires also have considerable annual economic effects. In addition to direct damage due to fires, the prevention measures and rescue service investments are expenses unavoidable in promoting fire safety. The research efforts being undertaken to establish a better understanding of the anatomy of fires are essential; the improved knowledge of the phenomenon will be invaluable in the attempt to find ways to reduce the effects of fires.

Demands on the living environment grow continuously while the implementation of these demands, in building construction, for example, becomes all the more complicated and while the safety of buildings must still be ensured. Modern architecture favours continually larger compartment sizes and other exceptional solutions that cannot be carried out using prescriptive fire safety regulations. In Finland, in the fire-code reform of 1997, performance-based fire engineering was introduced as an alternative to prescriptive regulations. In design using performance-based principles, acceptability is based on assessment of the total fire risk of the building. This brought about the demand for a better understanding of fire-risk components, which is essential for making reliable risk estimates. Determination of the fire risk of an individual building or a small group of buildings is complicated by the effects of human actions on the risk of fire. Furthermore, the spectrum of buildings is large and includes unique buildings, in which individual features affect the amount of fire loss. Nevertheless, a detailed study of statistical material is still worthwhile as it is an effective and objective way of attempting to characterise fires.

In Finland, the Ministry of the Interior has, since 1995, maintained the national accident database, Pronto (formerly Ontika), which contains information on every accident for which the public fire department has been alarmed. A patient compilation of statistical data in the national accident database over the years has generated a valuable source of information on fires that actually occurred and has opened up the possibility of examining the fire-risk problem in detail, in addition to basing fire-risk assessment on actual statistical data. Although there will always be a discussion of the accuracy of the statistical data, the fact is that the statistics already contain a considerable amount of good and objective information on fires, which should be examined in detail to improve our understanding of the characteristics of fires. Also, the introduction of the performance-based fire safety design has emphasised the need to utilise statistics to back-up the currently used methods and to develop new techniques of risk assessment. Until now, the available statistical information in Pronto has not been utilised in this way.

1.2 Research problem

Fire risk is defined as the potential realisation of unwanted, adverse consequences caused by fire (Watts & Hall 2002). The main issues in fire-risk determination are the probability of the outbreak of fire and the probable outcomes caused by it; fire risk can generally be expressed as a product of these two components. However, the detailed features of these components are still not entirely clear.

When performance-based design was introduced in 1997, no exact guidelines or methods for the design process were presented. In contrast to prescriptive regulations, risk-analysis-based design acknowledges the intervention of the fire department also. As a backup for the risk-analysis-based design, reliable knowledge of fire department operations, fire-risk components, ignition frequency and fire losses is essential. The introduction of performance-based design has also emphasised a need for the utilisation of quantitative tools in the fire-risk assessment of buildings.

A better understanding of fires increases the potential to reduce their effects and to focus on preventative measures appropriately. For this purpose, a detailed study on the dependencies of fire risks is extremely valuable.

A current subject of concern in communities is the level of the service of fire departments. The research information on their operation is invaluable to the assessment of the level of service and it forms a basis for the techniques for optimising and allocating resources as part of the process of improving the standard level of service.

The national accident database contains information on building-fires since 1996. In some parts, the information from its predecessor Ontika is available for the period 1994–97. This database has not been utilised in an extensive study related to fires until now, but some smaller-scale experiments have proved its potential for a broader survey. The use of the statistical information brings an objective viewpoint to estimating the probability of ignition and its consequences, as well as to the operation of the fire department, and offers new and valuable information and insights into subjects relating to building-fires.

1.3 Objective

This work is the first phase of a long research effort to characterise fires. In this work, statistical information on building-fires in Pronto is utilised in order to establish a general view of ignition frequency, consequences of fires and the operation of the fire department, as well as to examine their dependencies on different factors. The aim is to generate valuable new information related to fire risks in buildings and to produce quantitative tools and methods for risk assessment that would also be suitable for engineering-design purposes.

The fire-risk components, i.e. the probability of ignition and financial consequences, are studied to examine their dependencies on the different features of the building, such as size, load-bearing structure or type of use. Simple models are adapted to the data to find out if there are some mathematical functions derivable from theory that can be used to model dependencies and be utilised in the fire-risk assessment of buildings. Fire deaths are also considered briefly, as information relating to the economic losses in fatal fires is now available.

The statistical data in connection with the fire department operation is analysed and simple models from literature adapted to the data. The aim is to produce quantitative evaluation methods to estimate the influence of the fire department in case of a building fire. In the approach adopted the operative assignment of the fire department is divided into separate components. As these are connected again to each other, it is simple, for example, to distinguish those scenarios in which the fire department has a good chance of saving the building from those in which the fire safety of the building depends completely on automatic fire extinguishing systems.

The use of the presented methods and results is illustrated by means of a few simple examples.

1.4 Research methods

Although not as familiar in the context of fire research, the methods used are known in other application areas. The methods are now applied in connection to the fire-risk problem and combined in order to be used to assess the fire risks in buildings. The basic research methods used in this work are described in detail in Section 2.

1.5 Scope of the research

The study concentrates on fires in buildings based on the data in Pronto.

The work can be categorised within the more general area of operational research, where the problem is approached with statistical analysis tools and quantitative models in order to examine the influence of different factors on the operation of the total system. The models are not flawless; nevertheless, they can be used to describe the nature of the phenomena corresponding to the real world.

The anatomy of fires is not a well-known or well-defined problem. After ignition, a fire behaves as natural phenomenon, the development of which can be described physically quite accurately using deterministic models. In this study, instead of individual fires, a large number of fires is examined in order to produce new information related to fire risks.

The complexity of the approach arises from the fact that the main measurable quantities are determined on the basis of the statistical data, while the properties of the initial populations considered are poorly known. Furthermore, at the beginning of the work, the real potential of utilising the database was unknown, although some positive indications were obtained from preliminary studies. Thus, the aim of this first research effort in an unknown area is not to carry out an extremely profound analysis of the phenomena, but to establish a general view and basis for more detailed studies in the future.

Thus the research problem is approached from exploratory viewpoint and the approach can therefore be considered more practical than mathematical. The aim was not a rigorous mathematical modelling during this first phase of the continuing research work. New modelling efforts were not carried out; the models used were taken from literature as they were found and tested roughly with the statistical data available.

The dependability and effectiveness of automatic fire detection and extinguishing systems is outside the scope of this study. The reliability of sprinkler systems has been examined using Finnish data by Rönty et al. (2003, 2004).

1.6 Contribution

Fires must be regarded as a major threat from the human safety, as well as from the economic, point of view and research related to fire risks is therefore essential. Statistics offer an excellent way to learn from the actual events of real life.

This work is one step forward in the field of risk-analysis-based fire safety design. As a result of this work, the tentative methods based on observations of fires that have actually occurred are presented for utilisation in the fire-risk assessment of buildings. When the risk of fire can be expressed in quantitative terms, the comparison of design alternatives is simple. The analysis of the fire department operation is useful when the resources and allocation of the fire departments are optimised. The detailed analysis of statistics leads towards a better understanding of the reasons behind the variation of the fire risk and has direct use in planning fire prevention measures and fighting fires.

This work is the first relatively broad survey of the fire statistics available in the accident database and the first attempt to utilise it extensively to examine the characteristics of fires and the operation of the fire department. As a result of this study, valuable new information on the fire risks of buildings, in addition to their dependencies on different factors, is obtained. The use of statistics as a backup to risk-analysis techniques brings objectivity to the analysis. In this work, initial proposals for risk-assessment methods based on statistical information are introduced.

2. Research methods

2.1 Problem approach

This work represents the first phase of a long effort to characterise fires. Fires cause a considerable number of deaths and a large amount of financial loss every year, and so are always of interest. At present, the amount of data compiled in Pronto is adequate for a survey. In this work, the fire-risk problem is approached through the contents of Pronto in order to establish reliable information and useful tools that can be utilised in the risk-assessment of buildings.

The use of statistical information is an objective way to characterise the fire. However, the statistics represent historic conditions and the nature of the fire hazard may change over time, as for example the configuration of buildings, the contents and building products change (Hall 2001, Meacham 2002). In this study statistics are used to predict the future risks assuming that the changes of the main features affecting fire risk, like human behaviour and the building stock, are slow. Thus the past experience can be used to predict the future with reasonable accuracy.

This work can be divided into the three main conceptual areas presented in Figure 1: probability of ignition, consequences caused by fire and fire-department intervention. These three areas are considered separately on the basis of the statistical data relating to building fires registered in the database.

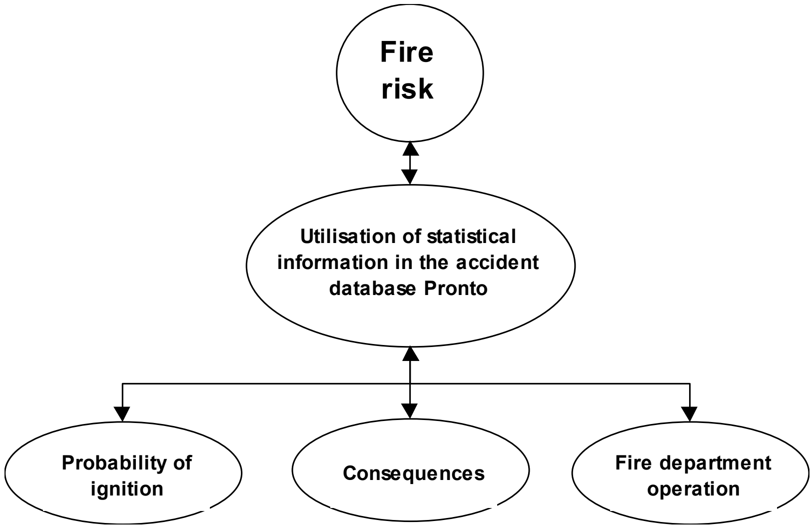

Figure 1. The main conceptual areas considered in this work.

The approach used in this work is frequentistic; the model parameters are estimated on the basis of observations. During the analysis, the dependencies of the phenomena on different variables (discrete, continuous, nominal) are examined. The main variables in each context are presented in Figure 2.

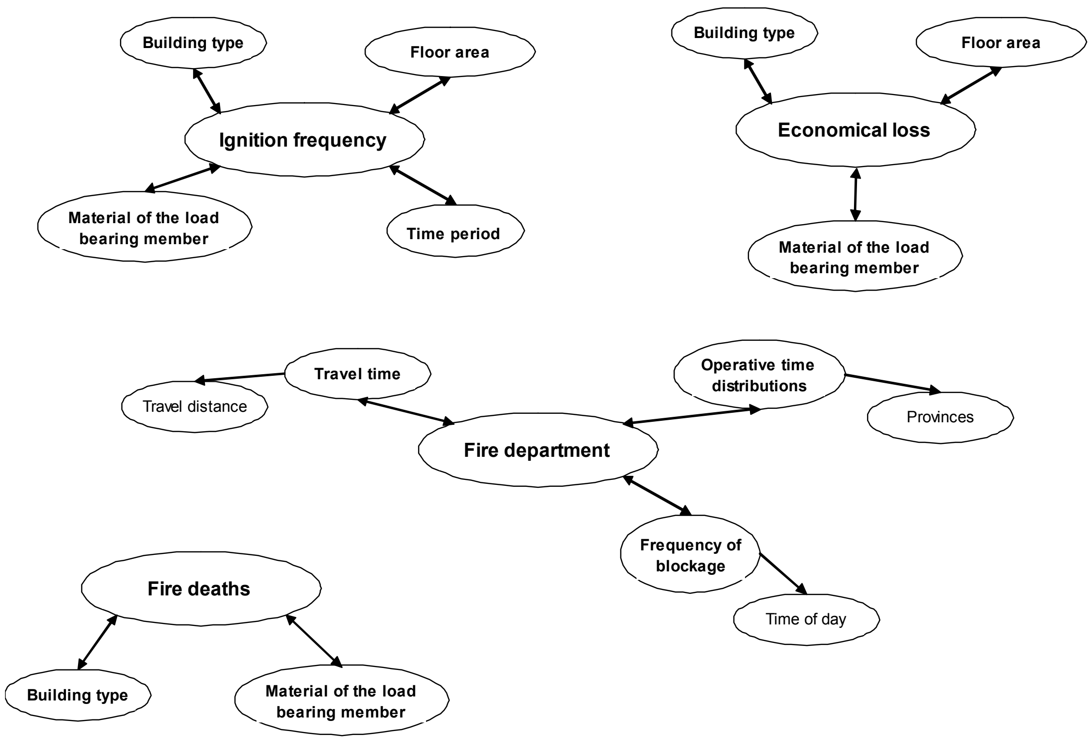

Figure 2. The main variables, the influence of which on the main phenomena is examined.

The fire-risk problem is not well-defined, because of the nature of the phenomenon. When this work was started, the significance of the available data as part of our research area was somewhat unknown. At the beginning of the work, the quality of the data in each context was also unknown, which complicated both the detailed defining of the problem and the determination of possible solution methods. Because of these factors, in addition to the intention of keeping the scope of the thesis reasonable, it was concluded that the aim of this work was not an extremely profound examination of the phenomena from a mathematical point of view, although some simple statistical analysis techniques were to be utilised. As the nature of the phenomena has now been established at a general level, it would be useful if future studies were undertaken to develop the mathematical treatment of them at a more detailed level.

The methods utilised are shown in Figure 3. They are divided under two headlines, analysis of statistical data and fire-risk analysis.

The ‘analysis of statistical data’ area in Figure 3 represents the phase of work during which the raw statistical data is examined, the dependencies of the phenomena are acknowledged, statistical tests carried out to test the differences, frequency and cumulative distributions determined and the uncertainty estimated and plotted with error bars.

The ‘fire-risk analysis’ area in Figure 3 represents the phase during which the models and probability distributions are adapted to the data and the quantitative tools to be utilised in fire-risk assessment of buildings generated. In this phase, the information gathered as a result of the analysis of the raw data is utilised.

In reality, the ‘analysis of statistical data’ and ‘fire-risk analysis’ areas overlap; overall, the division is not as unambiguous as shown in Figure 3. In this figure, to the left are the methods related to the actual observations, while to the right are the methods including distribution fitting or adaptation of the models. The utilised methods shown in Figure 3 are presented briefly in the following sections.

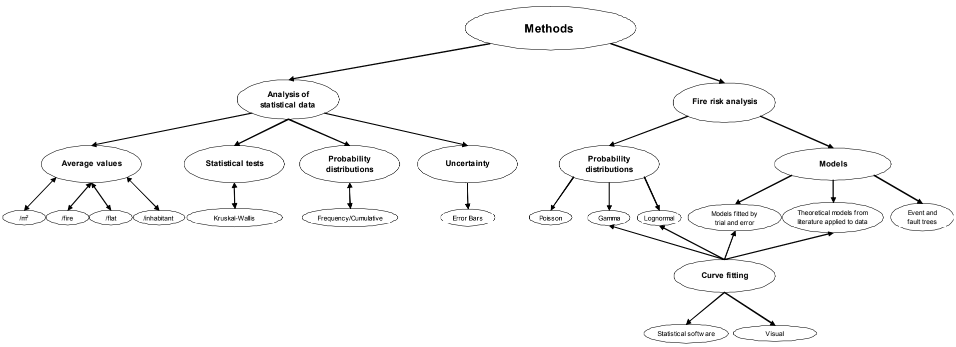

Figure 3. The utilised methods.

2.2 Average values

The average values are used for a quick comparison of general differences between nominal variables, such as building type, material of the load-bearing member, time periods etc. As seen from Figure 3, the average values are determined per unit suitable for the circumstances, like per square meter, fire, flat, inhabitant etc.

2.3 Probability distributions

2.3.1 Frequency and cumulative distributions

In general, all the elements considered are associated with at least one of the following: the number of fires or of fire deaths, the performance of the fire department (operative time distributions) or economic fire losses. These are considered as random variables, associated with probabilities. From the main variables, the number of fires and fire deaths are considered as discrete, while fire losses and time distributions of the fire department as continuous.

The probability distribution of a random variable is determined by the cumulative distribution function, and in general, the variables mentioned are at first approached through the density or cumulative distribution functions of the statistical observations. It is from this viewpoint that probability models are applied to the observed data. For some elements, the required statistical information was not available, so some probabilities needed to be estimated on the basis of expert opinions.

In the following sections, the basic statistical distributions utilised in this work are briefly introduced.

2.3.2 Poisson distribution

In queuing or telecommunication theory, the Poisson process is often used to describe the arrival process of customers or calls. Poisson process describes discrete arrivals, the number of which, X, follows the Poisson-distribution i.e. X~Poisson(λt)

$$P(X = k) = \frac{(\lambda t)^k}{k!} \exp(-\lambda t) \tag{1}$$

where λ is the intensity of arrivals. Similarly, the occurrence of fires and fire deaths can be treated as a Poisson process.

The non-homogeneous Poisson process describes the situation in which the intensity λ is not constant but dependent on time, i.e. $\lambda = \lambda(t)$ in Equation (1).

2.3.3 Gamma distribution

The gamma distribution is an extension of the Poisson distribution. In reliability theory, gamma distribution is used to describe the lifetime distribution of components, while in queuing theory it is used to describe the service time distribution compounded of several stages (Laininen 1998). In this work, gamma distribution is considered in connection with the operative time distributions of the fire department.

The gamma density function (Milton & Arnold 1990)

$$f(t) = \frac{1}{\Gamma(\alpha)\beta^{\alpha}} t^{\alpha-1} e^{-\frac{t}{\beta}} . \tag{2}$$

The cumulative gamma distribution (McCormick 1981)

$$F(t) = \frac{1}{\Gamma(\alpha)} \int_0^{\frac{t}{\beta}} y^{\alpha-1} e^{-y} dy = \frac{1}{\Gamma(\alpha)} \gamma(\alpha, \frac{t}{\beta}) , \tag{3}$$

The sum of two gamma density distributions

$$f(t) = a \cdot \frac{1}{\Gamma(\alpha_1)\beta_1^{\alpha_1}} t^{\alpha_1-1} e^{-\frac{t}{\beta_1}} + (1-a) \cdot \frac{1}{\Gamma(\alpha_2)\beta_2^{\alpha_2}} t^{\alpha_2-1} e^{-\frac{t}{\beta_2}} . \tag{4}$$

where α, β are the parameters of the gamma distribution, $\Gamma(\alpha)$ is a gamma function and $\gamma(\alpha,\tau)$ an incomplete gamma function with parameters α and τ.

2.3.4 Lognormal distribution

The lognormal distribution is used in connection with fire losses. The lognormal density distribution is obtained from (McCormick 1981)

$$f(z) = \frac{1}{\sqrt{2\pi}\sigma} \exp\left[-\frac{1}{2} (\frac{z-\mu}{\sigma})^2 \right] \tag{5}$$

where z is the logarithm of loss x, μ and σ are the average and standard deviation of $\ln(x)$ and

$$z = \ln(x) \tag{6}$$

2.4 Curve fitting

The fitting of the models to data is carried out either using statistical software Statistica or visual curve fitting. The visual curve fitting is used because of the nonlinear nature of the considered phenomena. When random outliers distort the results, visual curve fitting is a quick and effective way of filtering them out. Also, the small number of observations in some data points generates these outlying points, the value of which is associated with high uncertainty. This problem is dealt with by error bars plotted in each figure; these bars represent the uncertainty level of each data point. The uncertainty approach used is presented in detail in Section 2.7. For most of the fits, the goodness-of-fit is estimated on the basis of the chi-squared test. For a few of the cases, only a visual estimation could be carried out. The estimation method used is mentioned in connection with each fitting.

In addition to a linear presentation, in some figures, the coordinate-axes are plotted on a logarithmic scale. If there are large differences between the data points, the logarithmic presentation brings up the total distribution better, but, at the same time, it hides the smaller differences, which show better on a linear scale. For each figure, both ways of representation are considered and the most appropriate chosen. In most of the cases, both linear and logarithmic scales are considered when the models are fitted visually to the observations.

2.5 Models

2.5.1 Theoretical models from the literature

As the purpose of this work is not to actually model the phenomena, most of the models applied are taken as they are found in the literature. No broader improvement of the models is of interest during this phase of the work; the main goal is to test the compatibility of the suggested models with the available Finnish data. The utilised models are therefore presented and applied in their original forms, with references to the specific publications from which they were taken.

2.5.2 Models fitted by trial and error

Although no exact modelling or major improvements to the models taken from the literature is carried out, in some cases, simple functions are used and fitted to data by trial and error, or some minor changes are made to a few models obtained from the literature. For these cases, a few examples of simple functions are tried and the most satisfying alternative chosen on the basis of the goodness-of-fit estimated either visually or on the basis of the value of the chi-squared test or proportion of the variance explained. This concerns mainly functions of the floor area distribution presented in Section 5.3.2, diurnal variation in Section 5.4.1, correlation between the floor area and value-at-risk in Section 7.1.4 and average loss in section 8.2.1.2.

2.5.3 Event and fault trees

Event and fault trees are the basic risk analysis methods. In the approach, the outcomes of a specific initial event are acknowledged and described as branches of a tree. An example of a simple event tree is presented in Figure 4. In the event-tree method, the evolution in time is illustrated as transitions between discrete states. The time-dependency can be acknowledged by dividing the fire scenario to time periods and by constructing an event tree for every period separately (Hietaniemi et al. 2002, Korhonen et al. 2002).

In Figure 4 the initial event is an ignition of a fire, which is followed by the detection and extinction phases. The possible outcomes are that the fire either continues or is extinguished.

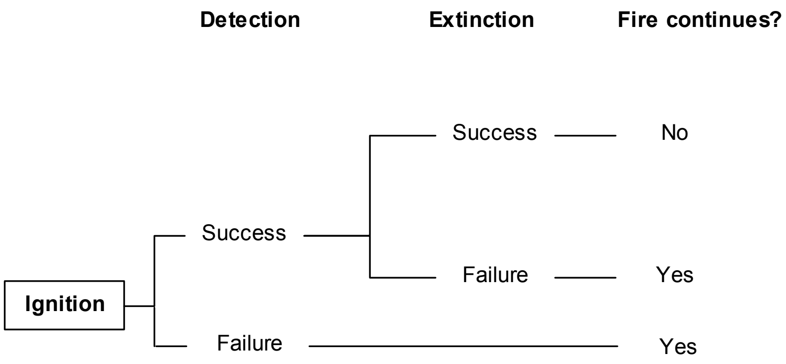

Figure 4. A simple example of an event tree.

Every branch of an event tree has a probability of occurrence and, as a result, the risk for all possible outcomes can be achieved. The consequences are connected with the associated end states. Thus, the structure of the event tree must be kept simple enough and the amount of possible fire scenarios and their possible outcomes limited. The increase of the scenarios and branches of the event tree leads to a large number of conditional probabilities, which are very difficult to handle by the approach.

Closely related to the event-tree method is the fault-tree method, which represents the logical combinations of various system states that lead to a particular outcome (Watts & Hall 2002). A simple example of a fault tree is presented in Figure 5. The top event, the fire continues, is similar to the outcome of the event tree in Figure 4.

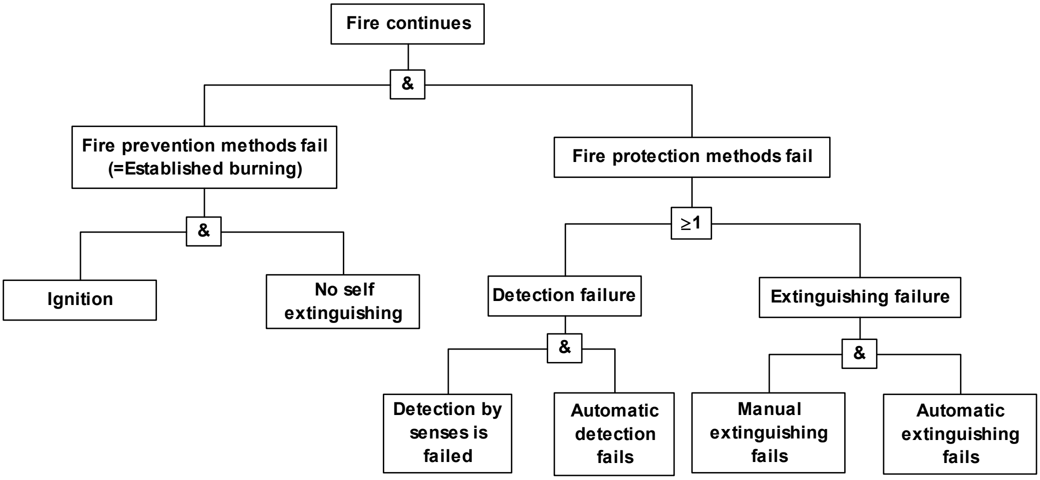

Figure 5. A simple example of a fault tree.

The branches down from the top event represent the events that lead to the occurrence of the top event. Thus, if the fire prevention methods fail, and the established burning may be developed and at the same time the fire protection methods fail, here it was assumed that either the detection or the extinguishing of the fire fails, the circumstances allow the fire to continue. The events are separated with AND (&) or OR (≥)-gates. As the probabilities of every event are known, the probability of the top event can be calculated. The events separated by an AND-gate are multiplied and with an OR-gate summed up. The fault tree may be expanded, by adding more events. The structure of the fault tree is often defined by the availability of information on the probabilities of the failure events.

Both event and fault tree methods are based on logical dependencies but a basic difference between them is that the outcome of an event tree is not binary (failure or success) but a quantitative measure (Hall 2001). The probability of failure is obtained as an outcome of a fault tree, while the expected value-of-loss is obtained as an outcome of an event tree. While the tree structure of the event tree is organised by temporal sequence, the fault tree is organised by logical dependency.

2.6 Statistical tests

In suitable parts, the statistical tests, using the statistical software Statistix, are carried out to analyse the differences between the nominal variables. The Kruskal-Wallis Test, which is a non-parametric alternative for one-way variance analysis, is used for group comparisons. It is effective especially in cases where the shapes of the distributions are similar.

2.7 Uncertainty

2.7.1 General

In general, the data is first studied as a single corpus and then divided to smaller groups according to some nominal (geographical area, building type, material of the load-bearing structure), discrete or continuous (time, floor area, inhabitants) variables. Unavoidably, the number of observations in some groups is small, which leads to the situation where the regularity of the phenomenon does not show. The estimated relative frequency calculated on the basis of these few observations is therefore very uncertain. In this work, this uncertainty is illustrated with error bars plotted in figures. In this first survey of the specific statistical data, this kind of visualisation of the uncertainties is essential to reduce the possibility of misinterpretation of the results. It is also useful when the models are fitted to the data.

All the variables presented in figures either are average values or connected to the number of fires. The methods used to calculate the standard deviation of the number of fires and of the mean are therefore required to estimate the error bars used to visualise the uncertainty of each data point.

2.7.2 Standard deviation of the number of fires

When the number of fires X can be considered Poisson distributed, the expected value is

$$E(X) = \lambda t \tag{7}$$

where λ is the intensity of fires. Furthermore, the variance σ^2 and standard deviation are σ

$$\begin{aligned} \sigma^2 &= \lambda t \\ \sigma &= \sqrt{\lambda t} \end{aligned} \tag{8}$$

Thus, the standard deviation of the number of fires is obtained as a square root of the average number of fires occurring in a considered time unit. This is later denoted also with $\sqrt{n}$, where n is the number of fires, estimated from the statistical data.

2.7.3 Standard deviation of the mean

In some cases, the phenomena are approached through average values such as the average fire loss or average travel time of fire units. The standard deviation of the mean is obtained from

$$\sigma_x = \frac{\sigma}{\sqrt{n}} \tag{9}$$

where σ is the standard deviation and n the number of observations, which are estimated from the statistical data.

2.7.4 Propagation of uncertainty

In a few cases, the estimated uncertainties have to be combined, because in the estimation of the uncertainty of the calculated values the uncertainties of every component must be acknowledged. In the estimation of the total uncertainty of calculated values, the theory of the propagation of error is used (Beers 1962). Thus, the uncertainty is obtained from

$$df = \sqrt{(\frac{\partial f}{\partial x_1})^2 (dx_1)^2 + (\frac{\partial f}{\partial x_2})^2 (dx_2)^2 + ... + (\frac{\partial f}{\partial x_N})^2 (dx_N)^2} \quad (10)$$

2.7.5 Visualisation of the uncertainty

The uncertainties are calculated from Equations (8)–(10) and visualised in figures with error bars plotted both in positive and negative y-directions. The larger the error bars, the fewer the observations in the data point and thus the larger the uncertainty of the value of the data point. The results are interpreted in such a way that, if the difference between the data points is beyond the error bars, one cannot be sure that the difference really exists. It is simplistically assumed that if the difference is more than three deviations it can be considered a significant difference. Also, when the models are fitted to the observations, most attention is paid to the data points with smaller error bars.

2.8 Interpretation of the results

The error bars, plotted to visualise the uncertainty due to the number of observations in each data point, are used to reduce the possibility of misinterpretation of the results. As this is the first relatively broad study in connection with the phenomena examined in this work, the visualisation of the uncertainties as described in Section 2.7 is considered necessary. Thus, when observations on the phenomena are made on the basis of the figures, the uncertainty error bars must be acknowledged. The larger the error bar of the data point, the larger uncertainty is associated with the value.

In suitable parts, the statistical tests are carried out to analyse the differences between the nominal variables. For comparisons of the groups the Kruskal-Wallis Test is used and the tests are carried out by using the statistical software Statistix.

In some cases, the statistical tests are not carried out, when, for example, the number of observations is very small. Then the error bars plotted in figures are utilised. As the differences are analysed, any difference exceeding three deviations (error bar indicates one deviation) is considered significant. In each case, it is mentioned whether the statistical tests or an interpretation on the basis of the error bars is used.

3. Fire-risk assessment

3.1 Concept

The concept of fire risk can be defined as the probability of a fire causing a loss of life (or injury) and/or damage to property (Commission of the European Communities 2002a). Fire-risk assessment is the process of estimating the fire safety level of the building. The definitions of the terms used frequently in the context of risk analysis are introduced in Table 1.

Table 1. Definitions of the terms used in the context of risk analysis (Watts & Hall 2002).

Term	**Definition**
Hazard	Chemical or physical condition or any situation that has the potential for causing damage to people, property or the environment.
Risk	Potential for realisation of unwanted adverse consequences to human life, health, property or the environment.
Probability	According to frequency interpretation, probability is the proportion of the time an event will occur in the long run.
Consequence	Measure of the expected effects of an incident outcome case.
Risk analysis	Detailed examination, including risk assessment, risk evaluation and risk management alternatives, performed to understand the nature of unwanted, negative consequences to human life, health, property or the environment. An analytical process to provide information regarding undesirable events and the process of quantification of the probabilities and expected consequences for identified risks.
Risk assessment	Process of establishing information regarding acceptable levels of a risk and/or levels of risk for an individual, group, society or the environment.
Risk estimation	The scientific determination of the characteristics of risks such as magnitude, spatial scale, duration and intensity of adverse consequences and their associated probabilities as well as a description of the cause and effect links.
Risk evaluation	A component of risk assessment in which judgments are made about the significance and acceptability of risk.
Risk identification	Recognising that a hazard exists and trying to define its characteristics.

Quantitatively, the risk can be expressed as a product of the incident frequency and the probable magnitude of the consequences caused by the incident. The undesirable consequences can be a loss of any value, ranging from human deaths or injuries and financial loss to environmental or cultural loss. When the level of fire risk is assessed, the fires with negligible damage may be excluded (Ramachandran 2001).

3.2 Objective

The use of fire-risk analysis seeks to avoid fatalities, ensure the safety of people and reduce financial loss caused by fires (Bukowski 1996b, Wright 1999). Fire-risk analysis methods provide effective tools to assess the different alternatives to the fire precaution measures in buildings, which seek to prevent the occurrence of ignitions, to detect and extinguish the occurring fires effectively and thus to minimise the damages caused by them (Fernandez 1996). Using fire-risk analysis, the fire risk and the costs of the different fire safety measures can be compared in quantitative terms and, furthermore, a solution achieving the optimal fire safety level can be found. The approach can be applied to the design of new buildings or the appraisal of existing buildings.

3.3 Fire safety design

Fire statistics are a valuable source in the development of methods of risk assessment. Using such statistics, probabilities of unwanted events and adverse consequences, for example, can be estimated. Statistical determination of the fire risks in buildings has been of interest for some time, especially from the viewpoint of performance-based fire safety design.

In performance-based design, the assessed level of fire risk settles the acceptability of the design. It is therefore essential that all features affecting the total fire risk are acknowledged. All factors must be quantified, such as fire ignition and fire development, performance of the building occupants, level and reliability of the fire safety systems (incorporating both the active and passive measures), intervention of the fire department, and damages caused by fire in addition to their interactions. For example, with specific fire safety measures some relaxations, such as larger compartment sizes or longer maximum travel distances to the exits, can be accepted (Ramachandran 2001) as long as the assessed fire risk to the entire building is at an acceptable level. During the fire safety design process, the effect of time should also be recognised, because the impact of fire on a building and its occupants is different at different stages (BSI 1997). Thus, in addition to where and how the fire could occur, it should be established how quickly it could develop into a serious incident and the point in time when the degree of fire risk becomes excessive (Woolhead 1995, Wright 1999). During the design process, many alternatives can be considered and the most appropriate to fulfilling the requirements chosen.

In addition to meeting a tolerable level of fire risk, the design must also meet the requirements of the building, fire, and insurance authorities (FCRC 1996a). The European council directive (89/106/EEC) in respect to construction products (Commission of the European Communities 2002b, 1993, 1988) sets essential requirements for the safety of construction works in case of fire. The essential requirements state that the construction works must be designed and built in such a way that in case of a fire the load-bearing capacity can be assumed for a specific period of time, the generation and spread of fire and smoke are limited, the spread of fire to neighbouring construction works is limited and the safety of rescue teams is taken into consideration (Commission of the European Communities 1988).

3.4 Acceptable risk

Determining the level of acceptable risk is complicated. Often, even the determination of the appropriate unit of the fire risk poses problems (Bukowski 1996a). In general, the magnitude of the consequences and, furthermore, the fire risk, is expressed as the extent of spread, area damaged, duration of burning or financial loss (Ramachandran 2001). For long, the insurance industry has used financial loss as the risk measure, because it is easily comparable to the premiums. Although the fire safety regulations are more concerned with the human loss, the fire risk expressed in monetary terms might often be easier to understand by the public, since the benefits of the investments in reducing fire risk or insurance indemnities can be directly compared to the fire risk (Bukowski 1996a).

The level of safety achieved is often difficult to establish in absolute terms. When the concept of absolute risk is used, the fire safety system is assessed against the agreed performance criteria, such as the life safety of the occupants (FCRC 1996a), in addition to consideration of the safety of the fire fighters and property. The tolerable probability of consequences of the fire is established on the basis of economy and general acceptance (CIB W14). However, the risk acceptance varies according to whom it concerns. People are more willing to accept the death or injury of strangers than themselves or their own families (Bukowski 1996a). Overall, completely risk-free alternatives do not exist, while the reduction of fire risk may increase other risk forms. The need, therefore, is to assess the safety level that society is willing to accept (Bukowski 1996a).

Another approach is to use relative risk, i.e. to compare the risk associated with buildings constructed along prescriptive codes, and assume that level reasonable (Bukowski 1996a). When the concept of relative risk is used, it is assumed that the current regulations represent the socially acceptable level of fire safety. However, there is a danger that the possible flaws in regulations are not corrected while it is assumed that the building can be constructed as long as the hazard goes unrecognised by the prescriptive regulations (Bukowski 1996a). Thus, in addition to the use in building and construction design, fire-risk analysis can also be used in tasks with more general scope. One important application of risk analysis is to examine the risks resulting from the traditional prescriptive requirements in general and, if judged necessary, to indicate amendments to them.

3.5 Methods

The fire-risk assessment process generally comprises the definition of the probable fire scenarios or design fires, assessment of probability of ignition and quantification of the unwanted consequences. The risk estimate is obtained as a combination of these. The fire risk can be approached with risk analysis methods, which can be classified to several categories (Watts & Hall 2002).

The most elementary approach is used to just identify the most hazardous areas, while the events are not ranked according to degree of hazard (Frantzich 1998). The elementary methods rely on the judgement of the user. The next step is to define consequences as low, medium or high severity and to assess probability similarly. The risk is obtained as their product. The method is useful for quickly overviewing the risk size, but generally too simple for more detailed purposes.

In general, in semi-quantitative methods, the hazards are ranked according to a simple numerical score based on, for example, the floor area of the building, level of fire safety measures etc. Both frequency and consequences are considered and the alternatives are compared on the basis of the resulting scores (Frantzich 1998). The methods are usually quick to perform and can be used to rank design alternatives, but do not give absolute or even relative risk values. Also, a large degree of uncertainty is associated with the results obtained.

The quantitative methods are the most advanced and accurate form of risk assessment. The quantitative risk analysis methods use information regarding the questions (Frantzich 1998, Watts & Hall 2002): What can go wrong? How often will it happen? If it happens, what are the consequences? The best source of information regarding these questions is the fire statistics. However, the statistical approach can be used only on existing buildings on which the data is not too sparse. When suitable statistics are available, the point estimates or the probability distributions can be derived. The quantitative risk analysis process can be described according to Figure 6.

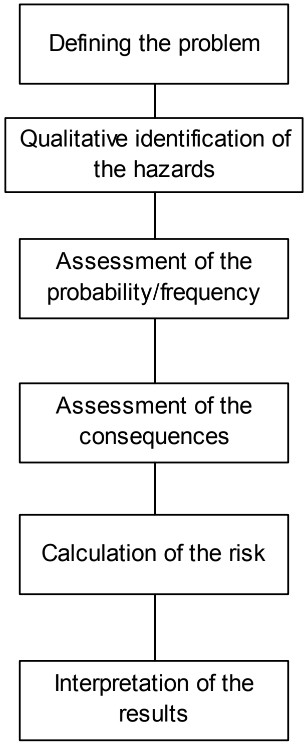

Figure 6. Basic risk- analysis process.

The first step before the actual risk quantification is the preparation phase when the problem to be considered and features of the system are defined and formulated as accurately as possible. The required background information on the building to be considered, together with statistical data, is also gathered. In the qualitative review, the characteristics of the building, environment and occupants, as well as the fire hazards and possible consequences are identified and possible fire scenarios specified for analysis. In addition, acceptance criteria are determined.

After qualitative identification of the hazards, these are quantified and the appropriate frequencies and consequences assessed. Furthermore, the probabilities and quantified consequences are then combined to form risk estimates. For the assessment of the consequences, mathematical models have been developed that provide the quantification of the damage in a fire in exact terms (Ramachandran 2001). It may often be convenient to split the analysis into parts and approach by using either deterministic or probabilistic procedures (BSI 1997).

Basically, in deterministic analysis, the probability of occurrence is neglected and the approach is to describe the hazards in terms of the consequences. The objective is to show that, on the basis of the initial assumptions, the defined outcome will not occur (BSI 1997). Deterministic procedures quantify the fire growth and spread as well as smoke movement and the consequences to the building or the occupants, which are based on well-known physical relationships, scientific theories and empirical methods. In deterministic analysis, the set of circumstances that will lead to a single outcome are evaluated. Thus, the design will either be acceptable or not. Special attention should be paid to the validity of the used models and the solutions justified by, for example, sensitivity analysis (BSI 1997).

In the probabilistic approach, both the probability of occurrence and consequences are based on observations. The objective is to show that the probability of an occurrence of an unwanted event is acceptably low (BSI 1997). The outcome is presented in terms of life or property risk levels for the whole building (Hadjisophocleous & Benichou 1999). Primarily, the aim is to use a probabilistic approach whenever possible. However, the lack of statistical data may sometimes prevent this. In that case, the methods coupling probabilistic methods with deterministic can be applied.

One probabilistic risk assessment tool often used is the event-tree method presented briefly in Section 2.5.3. As mentioned there, if the number of scenarios and branches of the event tree is increased, it leads to a large number of conditional probabilities, which are very difficult to handle by the approach. In this context, the Monte-Carlo simulation is more flexible. The main difference between this method and the event-tree method is that the used probability distributions are continuous. The Monte-Carlo approach is in accordance with the classic probability concept, in which the occurrence probability p_A of an event A in the long sequence of observations is the proportion of events A to all events (Hietaniemi et al. 2002). Thus, in the Monte-Carlo approach, a large number of fire scenarios are calculated through, and the probability of a specific event is obtained as, a proportion of the calculation results in which the event occurred. In the event-tree method, the cumulative effect of uncertainty of input parameters can be quite large and thus the accuracy of absolute risk estimates imprecise. The Monte Carlo simulation allows the increase of the number of calculated fire scenarios, which improves the resulting probability obtained.

3.6 Historical review of fire risk theory

In the course of time, several persons have considered the fire risk problem and it has especially exercised the minds of the actuaries. One interesting and quite difficult question is how the risk varies as a function of the size of the building. A very brief historical introduction of the subject is presented in reports, at the moment unpublished, by Rahikainen & Keski-Rahkonen and Tillander & Keski-Rahkonen. In this section, a broader, but still a brief review and references to earlier literature of the subject are presented.

For generations, it has been known that the size of the building has an important effect on the fire risk. The size of the building can be expressed in different terms characteristic to the object: the floor area, volume, sum insured etc. In addition to size, the fire risk varies with number of floors, arrangements, type of use, caution of the inmates and state of fire protection (Johansen 1957). However, all these elements can be reduced to the two components defining the fire risk: the probability of outbreak of a fire and its presumed propagation. In addition to financial loss, the propagation of fire can also be expressed as the extent of fire spread, area damaged or duration of burning (Ramachandran 1988). However, the risk of each individual building will vary and evolve over time, and thus cannot be considered stationary (Almer 1963).

The fire risk has especially been considered in the insurance field to construct fair tariffing principles. The basic concept in the insurance business is the insurance policy. At simplest, after sustaining damage, the policyholder is entitled to demand from the insurer a specific sum of money X named in the insurance policy. To obtain this right, the policyholder pays the premium P to the insurance company. When the probability of damage is p, the premium is obtained from Equation (11).

$$P = pX \tag{11}$$

This is called the net premium, which is based on the assumption that the sum of expected indemnities and insurance premiums are equal. Generally, the net premium can be determined from Equation (12).

$$P = \int_0^\infty x f(x) \tag{12}$$

where $f(x)$ is the loss density function. Equation (12) describes the expected value of x. Generally, the risk of fire can be expressed as a product of the sum insured and the frequency of damages. The sum insured determines the maximum indemnity in case of damage.

According to Johansen (1979), in early studies, the frequency of damage, or, in this case, the ignition frequency, was assumed constant for example by Barrois (1835), although later the increasing trend as a function of the size of the risk was discovered as well. Several persons have verified that in similar groups of buildings the ignition frequency can be expressed as a function of the sum insured, which is one alternative way to describe the size of the building or the value-at-risk. For instance, Benktander (1953) and Johansen (1957) as well as von Savitsch (1907) according to Benktander (1953), discovered a linear relationship whereas Benkert & Jung (1974), Ramachandran (1979/80) and according to Rahikainen & Keski-Rahkonen also D'Addario (1940) proposed a power law dependence. Recent studies using Finnish data (Rahikainen 1998a, Rahikainen & Keski-Rahkonen 1998a, b, Tillander & Keski-Rahkonen 2001b, c, 2002a) proved that the floor-area dependence of the ignition frequency could be described well with the model of sum of two power laws, generalised from the theory introduced by Barrois (1835). Johansen (1957) proposed that, if small fires were excluded, the risk of fire is obtained as a product of the ignition frequency and value-at-risk. According to report by Rahikainen & Keski-Rahkonen, d'Addario (1940) also proposed power law dependence of the fire risk on the value-at-risk. As the other component of the fire risk, the extent of loss, i.e. the loss in proportion to the sum insured, has also been used (Whitney 1909). The risk of fire as a product of ignition frequency and extent of damage has been proposed, for instance, by von Savitsch (1909) and Benktander (1953).

The approach applied to the economic losses in this study was based on the theory introduced by Ramachandran (1975, 1979/80, 1982, 1998) and is presented in Appendix D.

Consider the fire loss *X*. Earlier, it was shown (Ramachandran 1975) that the logarithm of fire loss is of an exponential type, the failure function of which is

$$\phi(t) = \exp(-\int_{o}^{t} h(u)du) \tag{13}$$

The failure function describes the conditional probability of extinction of the fire during (*t*, *t*+*dt*), assuming it has burnt at least for the period of time *t*. In a simple case, the probability of fire extinction is independent of the duration of burning, and so the failure function is constant. This is almost the case in fires that can spread freely and in which the amount of fire load is unlimited. In reality, the fire is not able to burn freely and at some time extinguishing actions are performed by automatic extinguishing systems or the fire department if the fire has not died out earlier, due to, for example, a lack of oxygen or the fire load. Then the probability of extinction is dependent on the duration of burning, and so it is more realistic to consider the failure function as a 'bath tub' curve. Ramachandran rationalizes this with an assumption that the fire loss *X* is proportional to the time *T*, in which the fire department gains control of the fire. A reasonable assumption is that the proportion *X*/*T* increases as a function of the time *T*. Here Ramachandran refers to Thomas (1959), who has stated that the time *T* is proportional to the square root of the area *A* burnt such that $X \propto T^2$. Generally, the fire loss *X* increases exponentially as a function of the duration of burning *t,* and so the fire loss *X,* or the logarithm of loss *z,* is proportional to the duration of burning.

Immediately after ignition, the logarithm of loss is small and the value-of-failure function high, because for some reason the fire may die out and the propagation stop. If the fire survives over this so-called 'infant-mortality period', it has a chance to spread and the failure function decreases. After that, it remains at constant value for a short period until it starts to increase again at large values of *z*. Thus, the shape of the failure function can be described with a 'bath tub' curve.

The failure function can be considered as increasing if the small fires at the first part of the curve are considered economically negligible and are ignored.

Lognormal distribution fills the conditions introduced above and, excluding the tails, turned out to describe the fire loss fairly well (Benkert 1962, Ramachandran 1979/80, 1982, 1998). The large losses at the tail of the distribution have exercised the minds of the actuaries for a long time and specific statistical methods have been generated for the treatment of these (Ramachandran 1974, 1976, 1982). The issue is substantive, particularly for companies where the large risks are not reinsured. Naturally, the reinsurer is also interested in the variation of large losses.

3.7 Uncertainty

Uncertainty, variability and unknowns are the essential features of every risk problem. The qualitative design review process draws upon the experience and knowledge of the persons carrying out the analysis. Problem identification, data collection and reduction, as well as the integration of information, are all replete with subjective evaluations, and the risk estimate is greatly influenced by the perspective of the evaluation and value judgement of the evaluation maker. The qualitative methods do not give absolute or even relative risk values and a large uncertainty is associated with the results.

The quantitative methods are the most accurate form of risk assessment. However, there is no totally objective scientific way to measure risk. Uncertainty and variability are present due to, for example, the choice and definition of fire scenarios. Furthermore, quantification of the scenarios includes uncertainties associated with formulation of used theoretical and computational models, lack of statistical data or uncertainty of input data and other parameters (BSI 1997).

The classic method of treating uncertainty in building codes and design, is to use safety factors, especially when the predicted result is very sensitive to the used data or initial assumptions (Bukowski 1996b). The uncertainty can also be brought to light by carrying out the sensitivity analysis, in which the influence of the changes of individual input parameters on the output parameters is analysed. This may be carried out manually or, if more detailed information on the variability of the result is needed, with Monte Carlo techniques (Hostikka & Keski-Rahkonen 2003). The Monte Carlo techniques are usable if the uncertainty due to used models is negligible compared to uncertainties caused by input parameters.

The ongoing scientific work, development of models and analysis of statistics improve the solid ground for risk assessment based on proven relationships and decreases the uncertainty of the process. Nevertheless, for a sufficient quantitative risk analysis process it is still essential that the uncertainty factors are identified and addressed properly.

4. Utilised statistical databases

4.1 Accident database Pronto

Pronto (formerly Ontika) is the Finnish accident database maintained by the Ministry of the Interior. It includes information on every accident to which the fire department has been alarmed. Also, it contains information on the resources of the fire department. Part of the information is delivered to the database by the alarm control centre. The detailed information on the accident and, in case of a building fire, on the features of the building is delivered to the database by the fire department. After every incident, three standard forms are filled in relation to the alarm, the accident and the building, respectively; the information entered is later made available to the database.

In the first part of the work, the data was picked out from Ontika, the predecessor of Pronto. Information registered in Ontika at that time covered the years 1994–1997. Later, several samples were picked out from Pronto covering the years 1996–99 and, in some cases, also the years 2000–01. The first year available in Pronto is 1996; the database is continuously updated.

Like any database collected by several people, Pronto has some flaws. Pronto replaced the former system Ontika in the year 2000. The data transmission to Ontika had some difficulties during its lifetime, which were overcome to some extent in the new version Pronto. Also, when the information concerning the years 1996–99 was transferred from Ontika to Pronto, a large part of the erroneous data was corrected. Although the major technical problems were fixed in the new version, it must be remembered that the first links in the data collection are the people who enter the information into the database. Their carefulness has the greatest effect on the quality of the statistical information.

Because of the continuous updating of the database, the number of observations between samples of the same periods of time might differ a little. Also, in all sections, some observations were not accepted because not all the required information was entered properly. The number of qualified observations is mentioned in every section respectively. In

Table 2 most of the data fields of Pronto utilised in this work are presented. A few other fields were also tried, but the poor quality of the data prevented their further utilisation. To give a view of the distribution of fires to different building categories, the percentual division of all building fires (N = 13 166) is presented in Figure 7.

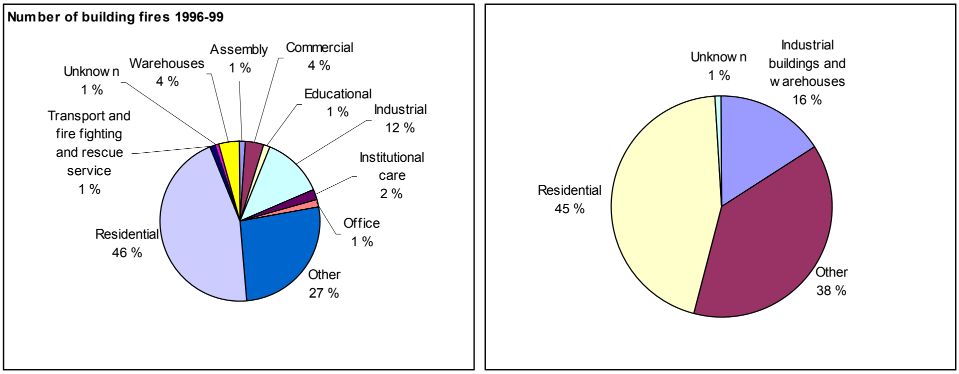

Figure 7. Percentual division of all building fires during 1996–99 to different building categories.

Table 2. Data fields in Pronto included in this work.

<table>
<tr><th colspan="3">DATA SHEET</th></tr>
<tr><th>ALARM</th><th>ACCIDENT</th><th>BUILDING</th></tr>
<tr><td>Identification data</td><td>Type of accident</td><td>Information on the object</td></tr>
<tr><td>Identification number
Community
Time</td><td>Type of accident</td><td>Building type
Ignition space
Total floor area [m^2]
Number of fire compartments (One/Several)</td></tr>
<tr><td>Fire units</td><td>Human losses</td><td>Surface layer characteristics</td></tr>
<tr><td rowspan="5">Unit symbol
Moment of notification
Moment of turnout
Moment of arrival to the scene
Moment of return</td><td>Deaths
Injuries</td><td>Influence of the surface layer</td></tr>
<tr><td>First-hand extinguishing</td><td>Estimate of losses</td></tr>
<tr><td>Influence to the fire progress</td><td>Loss of building [€]
Loss of property [€]
Consequential loss [€]
Value-at-risk, building [€]
Value-at-risk, property [€]</td></tr>
<tr><td>Ignition origin and estimate of the extent of the fire</td><td>Load-bearing member</td></tr>
<tr><td>Stage of fire at the fire department arrival
Extent of fire at the fire department arrival
Extent of damage at the end</td><td>Material of the load bearing member</td></tr>
</table>

4.2 Building stock

The building stock information was delivered by Statistics Finland. The reference year used was 1999.

The buildings were categorised into thirteen different building categories presented in Table 3. Buildings that are either not populated year-round or are allowed to be constructed without a construction license are not registered in the building stock. Thus, for example, summer cottages, animal sheds and small warehouses are not included. In this work, the categories E and L were combined as one group (symbolised with E+L) and similarly categories B, M and N (symbolised with N).

Table 3. Building categories. Subgroups are presented in Appendix A.

Key	Major group	Number of buildings		Floor area [m^2]
		All	Floor area known	
A	Residential buildings	1 112 737	1 086 732	231 565 978
B	Free –time residential buildings	7 759	7 007	478 444
C	Commercial buildings	39 546	32 216	18 990 450
D	Office buildings	10 851	10 145	16 354 516
E L	Transport and communications buildings Fire fighting and rescue-service buildings	42 731	36 606	10 627 751
F	Buildings for institutional care	6 881	6 492	8 780 942
G	Assembly buildings	12 619	10 905	7 379 199
H	Educational buildings	9 048	8 637	15 801 759
J	Industrial buildings	35 155	29 876	40 321 357
K	Warehouses	5 728	5 503	7 434 710
M	Agricultural buildings	2 097	1 793	901 407
N	Other buildings	5 803	3 485	1 058 109
	Total	**1 290 955**	**1 239 397**	**359 694 622**

To obtain the best achievable statistical accuracy, the buildings were either treated as a single group or divided to three groups: i) residential buildings, ii) industrial buildings and warehouses, iii) all other buildings. The last group included commercial, office, transport, fire fighting and rescue-service buildings, assembly and educational buildings as well as buildings for institutional care and other buildings (including B, M and N). In particular cases, the group of ‘other buildings’ (including B, M and N, symbolised with N) was also separated from other categories. In most of the cases, division down to those listed in Table 3 could not be carried out because some of the groups had such a small number of observations that uncertainty of the results would have grown excessive.

The division in Table 3 follows the classification of buildings from 1994 by Statistics Finland, which is presented in detail in Appendix A. The distribution of buildings and floor area in the building stock to different building categories[1] is shown in Figure 8.

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[1] Based on electronic data on building stock on 31.12.1999 delivered by Statistics Finland.

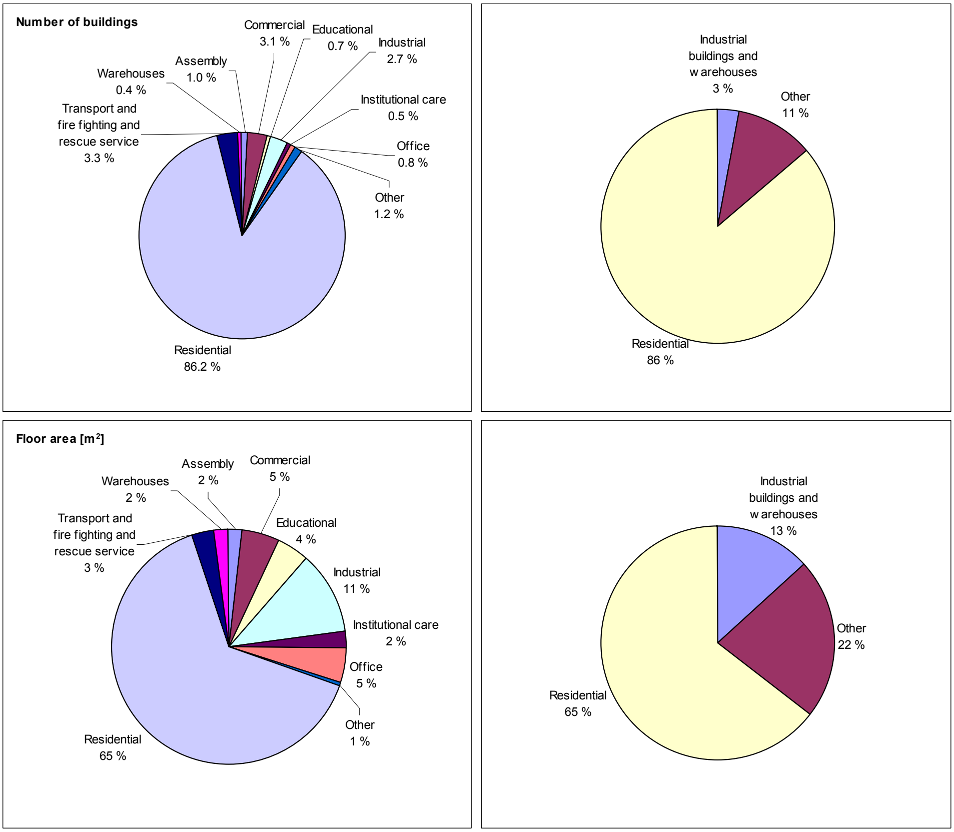


Figure 8. Percentual division of buildings and floor area to different building categories by Statistics Finland 31.12.1999.

The classification used in Finnish Building Regulations, Part E1 (Fire Safety of Buildings) (Ministry of the Environment 2002) includes seven main groups: dwellings, accommodation premises, buildings for institutional care, assembly and commercial premises, work premises and manufacturing premises and storage facilities. The classification of Statistics Finland and E1 differ from each other a little. The congruencies of the classifications are presented in Table 4.

Table 4. Used division of building categories compared to the division presented in Building Regulations, Part E1 (Ministry of the Environment 2002). Explanations of the used symbols are presented in Appendix A.

E1	**Statistics Finland**
Dwellings	A, B
Accommodation	C12, C13
Institutional care	F
Assembly and commercial	C11, C14, G, H
Workplace	D
Manufacturing and storage	J, K, M

5. Ignition frequency

5.1 General

For quantitative estimation of fire risks, reliable knowledge of the ignition frequency derived from fire statistics is a prerequisite. Previous studies (Ramachandran 1979/80, Rahikainen & Keski-Rahkonen 1998a, b) have shown that ignition frequency is dependent on the floor area of the building. Here the ignition frequency and its dependencies were examined closer with a large amount of data. The analysis carried out using the data from the period 1996–99 is published in Finnish in a series of VTT Research notes (Tillander & Keski-Rahkonen 2001b) and in an abridged version in IAFFS7 (Tillander & Keski-Rahkonen 2002a). Here, the data was updated as necessary to cover the fires in buildings during 1996–2001 (N = 19 408).

As the data source was the national accident database Pronto, the definition of ignition was a fire to which the public fire department had been called. Thus small fires, which were, for example, extinguished by occupants and not reported to the fire department, were excluded. The information as to the building stock at the end of 1999 was delivered by Statistics Finland. Also, the influence of the assumed deficiencies of the used databases on the ignition frequency was estimated and partial safety coefficients were determined.

5.2 Average ignition frequency in different building categories

The division of buildings used was presented in Section 4.2. The division of the number of fires and floor area were plotted in Figure 7 and Figure 8. It should be noted that almost half of the number of ignitions and 65% of the floor area of buildings fall into residential category A.

The average ignition frequency [$1/m^2a$], the probability per floor area and time unit (annum a) of a building catching fire, was obtained by dividing the annual number of fires in the specific building category by its combined floor area. The average ignition frequency in different building categories is presented in Figure 9.

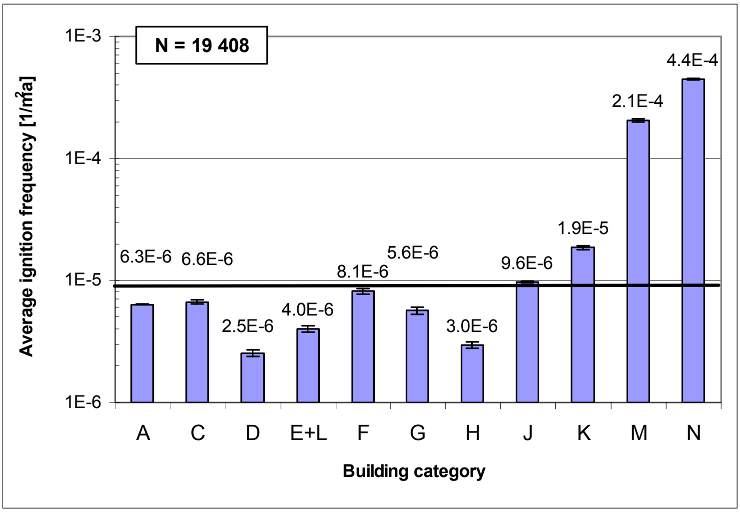


Figure 9. Average annual ignition frequencies of different building categories in the years 1996–2001. Definitions of symbols are presented in Table 3. The heavy horizontal line represents the average of all categories. The error bars represent the uncertainty due to the number of observations of each building category (see Section 2.7).

As can be seen from the small error bars in Figure 9, the numbers of observations in different classes were quite large. From Figure 9 it can be seen that the values of categories A, C, F, G and J are close to each other. The differences between categories were analysed with the Kruskal-Wallis test. The analysis was carried out using Statistix and the results are presented in Appendix F. The Kruskal-Wallis test showed that the means of the groups 1) A, C, F and G and 2) C, F and J were not significantly different from one another. In other words, the value of the category J differed significantly from the values of categories A and G in addition to M and N. Categories D, E+L and H formed a group for which the values of the ignition frequency were somewhat below the mean value 9E-6/m^{2}a.

A partial explanation for the large values of categories K, M and N is that only the buildings that are populated year-round are registered in the Finnish building stock. Consequently, the data included fires in buildings such as summer cottages and barns or small warehouses, which are registered as fires in the accident database, but their floor area is not registered in the building stock. This problem occurs especially in categories K and N, i.e. warehouses and other buildings. The coverage of the building stock of agricultural buildings (M) is especially poor and thus the result presented in Figure 9 cannot be considered statistically reliable. Therefore, the deficiencies of the available statistical information explain partly the extremely high values of the ignition frequency in those groups. However, the considered categories also include a great number of very small buildings, which presumably are poorly controlled and equipped in comparison to bigger buildings. Therefore, there might also be a genuine tendency towards high ignition frequency. Unfortunately, from the data available, the question could not be settled. The reliability and quality of the building stock is considered more closely in Section 9.2.

The average ignition frequencies are compared to the values of other countries in Table 5.

Table 5. Average ignition frequencies.

	London 1996–99 1)	Switzerland 1986–95 2)	Finland 1996–2001
	Ignition frequency·1E-6 [1/m²a]		
Industrial and storage	6.9		11.1
Shop and commercial	22.0		6.6
Office	5.3		2.5
Dwellings		33.3	6.3
Public and office		10.6	4.7
Industrial		11.6	9.6
All		32.3	9.0

1) Holborn et al. 2002.

2) Fontana et al. 1999.

The value of shop and commercial buildings in London was approximately three times that found of Finnish buildings and the office buildings two times. In Table 6 is presented the respective probability of ignition per building in London and Finland, which shows that the values in Finland are clearly higher. This indicates that the considered buildings in London on average are smaller than in Finland, which leads to a higher ignition frequency per floor area.

The values of dwellings and public, office, and all other buildings in Switzerland were clearly higher than Finnish values. However, the Swiss data included all fires, including also those that were not reported to the fire department. This increases the ignition frequency considerably, especially in dwellings. The values of industrial buildings presented in Table 5 were close to each other. This indicates that most of the fires in industrial buildings are probably reported to the fire department, although, with the information available, this could not be settled.

Table 6. Probability of ignition per building [1/a].

	London 1996–99[1)]	Finland 1996–2001
Industrial and storage	0.0035	0.0149
Shop and commercial	0.0030	0.0039
Office	0.0017	0.0041

1) Holborn et al. 2002.

5.3 Dependency on the floor area

5.3.1 General

The ignition frequency is plotted as a function of the floor area in Figure 10 for different building groups (Tillander & Keski-Rahkonen 2001b, 2002a). The used class intervals are presented in Appendix E. The solid line in Figure 10 represents the average ignition frequency of all buildings. Because the number of observations in some categories was insufficient, the building groups had to be combined to obtain better statistical accuracy. However, some general features could be discovered from Figure 10. There are both differences and striking similarities in the ignition frequency between categories. All of them have high values for small buildings but level off to a much lower value for large buildings. Two of the categories, K and N, deviate strongly from the main body for small floor areas. This behaviour is probably caused, at least partially, by systematic errors in data gathering, as already mentioned in Section 5.2 in relation to the average values.

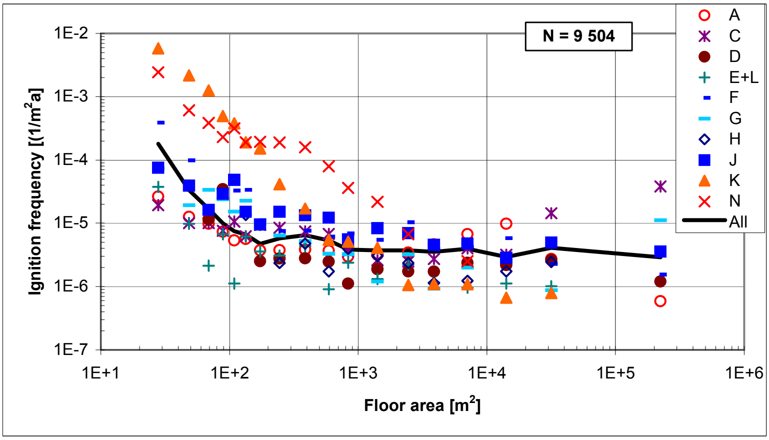


Figure 10. Average ignition frequency of different building categories as a function of the floor area, 1996–99. Definitions of symbols are explained in Table 3 and the used floor area class intervals in Appendix E in Table 38.

5.3.2 Density distributions of the floor area

The goal of the effort to model ignition frequency was to find out possible mathematical functions, which could be used to fit on the observations. Also, one of the main interests was to identify the mechanisms really producing area-dependent differences in ignition data.

Ramachandran (1979/80) derived the dependence of fire frequency on the floor area by using the floor area density distributions of the buildings hit by fire and at risk. Because the probability of fire starting in any building depends on the amount and nature of the ignition sources, and because the amount of these sources increases as the function of the size of the building, the ignition frequency is often primarily the function of the floor area. Thus the probability of fire starting is

$$P(A) = \frac{n}{N} \frac{v_n(A)}{v_N(A)} \tag{14}$$

where n is the number of fires during the time period, N is the number of buildings at risk in the considered area, $v_n(A)$ is the number density function of the floor area for buildings involved in fires and $v_N(A)$ the number density function of the floor area for buildings at risk. Ramachandran (1979/80) showed that *P(A)* is a power law, if the distributions of the buildings at risk and hit by fire are both either Pareto distributions or logarithmically normal distributions with the same standard deviation. Actually, *P(A)* can have, in principle, very different forms, depending on the functional form of initial distributions (Tillander & Keski-Rahkonen 2002a). If they are both normal, *P(A)* becomes an exponential function of A; if they are smooth functions, within an interval $A_{min} < A < A_{max}$, *P(A)* becomes constant *n/N* in the whole interval. Therefore, it was of interest to generalise Ramachandran's theory and analyse initial distributions $v_n(A)$ and $v_N(A)$ to find out which would be mathematically the most likely functional form of *P(A)*.

The useful floor area distribution, up to an accuracy of visual curve fitting, turned out to be a sum of one Pareto and two lognormal distributions

$$v_k(A) = c_{1k}v_{1k}(A) + c_{2k}v_{2k}(A) + c_{3k}v_{3k}(A), \quad k = n, N \tag{15}$$

where

$$v_{1k}(A) = \lambda_k S_k^{\lambda_k} A^{-\lambda_k - 1}, \quad k = n, N \tag{16}$$

and

$$v_{ik}(A) = \frac{1}{\sqrt{2\pi}\sigma_{ik} A} \exp\left[-\frac{1}{2} \left(\frac{\ln A - \mu_{ik}}{\sigma_{ik}} \right)^2 \right], \quad i = 2,3; \quad k = n, N \tag{17}$$

The values of coefficients c_{ij} are determined in such a way that the distributions v_{ij} become normalized. The function (Equation (15)) is plotted in the same figure with statistical observations of residential buildings in Figure 11.

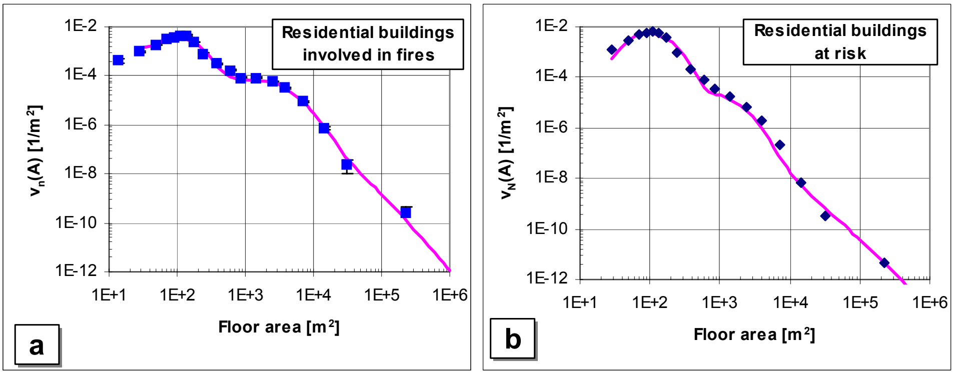


Figure 11. Density functions of the floor area for residential buildings. a) buildings involved in fires and b) buildings at risk. Statistical observations are plotted as dots and the theoretical curve (Equation (15)) as a solid line. The number of observations in figure a) was N = 4 361 and in b) N = 1 086 732. The used class intervals are presented in Appendix E in Table 38. The error bars represent the uncertainty due to the number of observations of each data point (see Section 2.7).

Ignition frequency is the probability of fire starting per floor area. Thus

$$f_m''(A) = \frac{P(A)}{A} \tag{18}$$

where $P(A)$ is obtained from Equation (14). The theoretical ignition frequency in residential buildings calculated using Equations (14)–(18) is presented in Figure 12 with statistical observations (dots) from the years 1996–99.

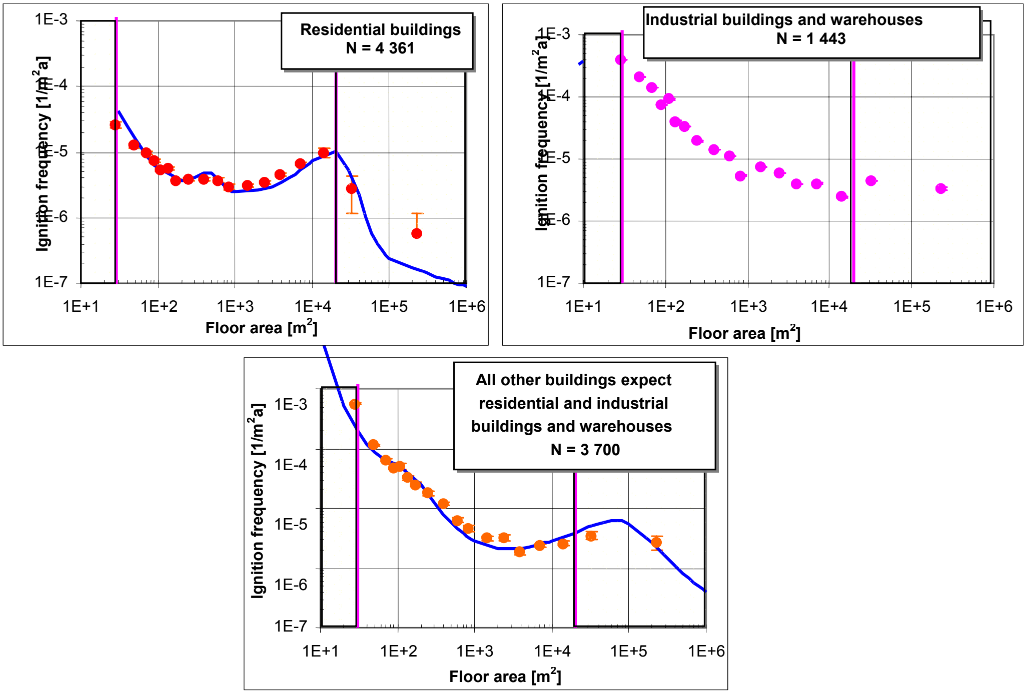


Figure 12. Ignition frequency in different building groups. Statistical observations (dots) and theoretical curve (solid line). In shaded areas, there are not enough observations to support reliable estimation of ignition frequency. The used class intervals are presented in Appendix E in Table 38. The error bars represent the uncertainty due to the number of observations of each data point (see Section 2.7).

Figure 12 shows that in residential buildings the ignition frequency decreases until about 150 m^2 of the floor area, when it settles to a constant level. After about 600 m^2, it starts to increase again, and forms a clear hump around 10 000 m^2 of the floor area. The peak was not caused by statistical inaccuracy, and similar peaks were detected also in other groups. The theoretical curve plotted in Figure 12 acknowledges the increase of ignition frequency in large values of the floor area and explains in a natural way the humps observed in ignition frequency. Because of the limitations of the data available, statistically significant conclusions about the ignition frequency in very large or small buildings (shaded areas) cannot be made with adequate accuracy. In the area between the heavy vertical lines plotted in Figure 12, the model is applicable.

The goodness-of-fit was estimated with a chi-test. When only the observations between the heavy vertical lines were included, the sums of chi-squares ($df = 13$) were

$$\chi^2_{residential} = 37$$

$$\chi^2_{industrial+warehouses} = 14$$

$$\chi^2_{all\ other\ buildings} \quad 27$$

Thus the fits with the observations of the industrial buildings and warehouses ($p = 0.35$) were very good. The p-value for residential buildings was $p = 0.0005$ and for all other buildings (group 3) $p = 0.01$; thus the fits were a little poorer compared to those of industrial buildings and warehouses.

5.3.3 Generalised Barrois model

5.3.3.1 General

The earlier modelling attempt with Finnish data (Rahikainen & Keski-Rahkonen 1998a, b) was totally experimental but inspired by a model presented by Ramachandran (1979/80). By trial and error, a sum of two power law functions was fitted on the statistical data. A more thorough study of literature (Rahikainen & Keski-Rahkonen 1998b) revealed that the function of two power laws is actually a generalization of a theory proposed the first time by Barrois (1835). Following the proposition by Johansen (1979), Rahikainen & Keski-Rahkonen (1998a, b) named this particular application the generalized Barrois model. Accordingly, the ignition frequency f''_m was presented in the form

$$f''_m(A) = c_1 A^r + c_2 A^s \tag{19}$$

where A is the floor area and c_1, c_2, r and s are coefficients, which were determined experimentally from observations for different building categories.

The extension of theory by Ramachandran presented in previous section (Tillander & Keski-Rahkonen 2002a) revealed also the explanation for the sum of two power laws. The generalized Barrois model arises from the nature of the building stock. Residential houses in Finland constitute the great majority of the buildings. They form two natural groups: (a) small houses, starting from single-family houses and ending with multiple units in long-row houses and (b) apartment houses. Both these subgroups show lognormal floor area distributions with rather different averages. This leads roughly to a sum of the two power laws of Equation (19). Still closer examination of the data in the previous section showed that in Finland the density function of the floor area consists of even more subsets.

The fittings of the generalised Barrois model were carried out combining visual curve fitting with fittings carried out by Statistica.

5.3.3.2 All building categories

The generalized Barrois model was fitted on the observations of all building categories in Figure 13. The used floor area classes are presented in Appendix E. Except for residential and other buildings, for other categories, the classes 1–3, 4–6 and 7–9 were combined. The parameters of the Barrois model are presented in Table 7. To each figure is also labelled the number of observations *N* in the considered group. As most of the groups were too small for reliable results, the groups were recombined to four larger categories.

Table 7. Parameters of the generalized Barrois model.

Building category	c_1	c_2	r	s	R^2 [%]
Residential buildings	0.010	5E-6	-1.83	-0.05	84
Commercial buildings	7E-5	6E-6	-0.65	-0.05	26
Office buildings	0.056	3E-6	-2.00	-0.05	74
Transport and fire fighting and rescue-service buildings	7E-5	1E-6	-0.65	-0.05	75
Buildings for institutional care	2E-4	5E-6	-0.61	-0.05	68
Assembly buildings	0.003	2E-6	-1.14	-0.05	85
Educational buildings	0.003	3E-6	-1.26	-0.05	46
Industrial buildings	3E-4	5E-6	-0.61	-0.05	90
Warehouses	3.82	2E-6	-2.08	-0.05	98
Other buildings	1.18	1E-4	-1.87	-0.20	95

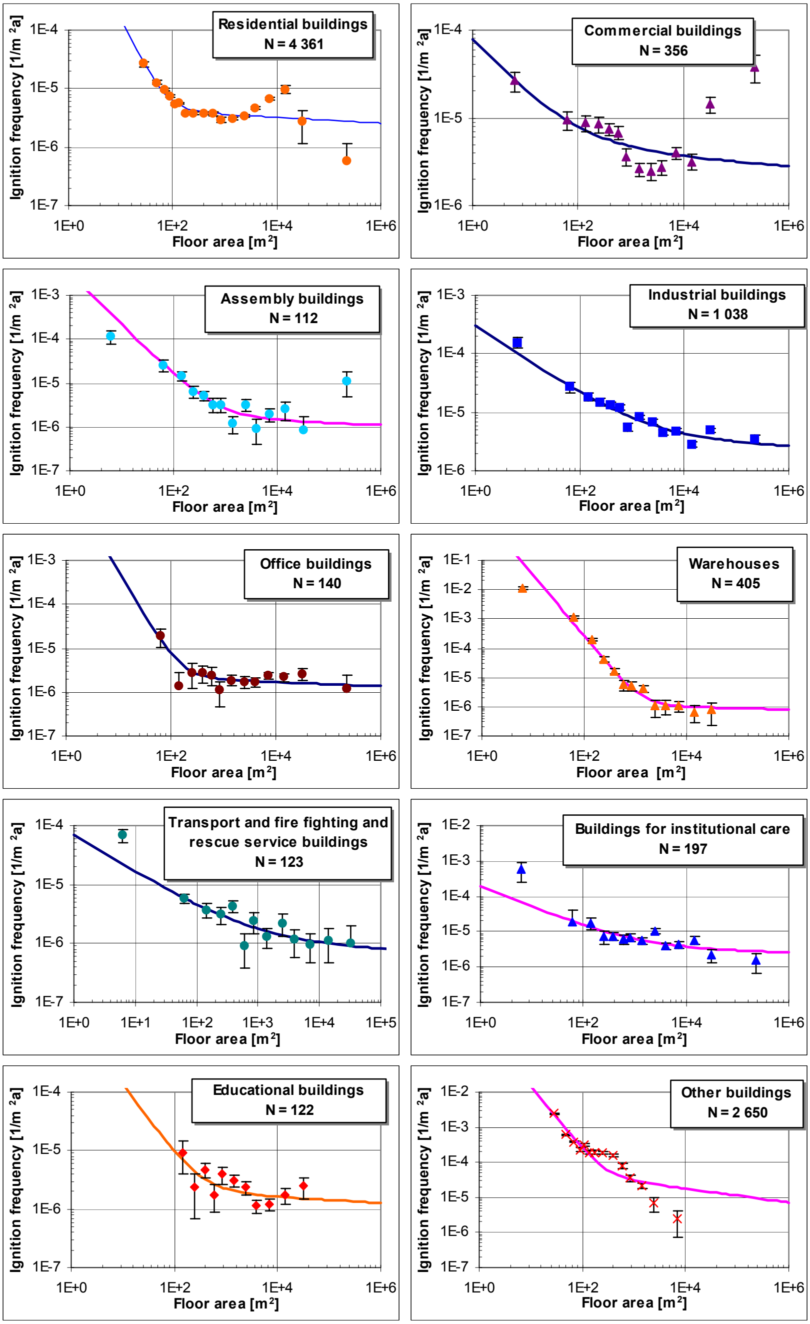


Figure 13. Ignition frequency observations (dots) from the years 1996–99 and theoretical curve (solid line). The error bars represent the uncertainty due to the number of observations of each data point (see Section 2.7).

5.3.3.3 Category groups

Here the building categories of Table 3 were recombined to form just four groups to obtain better statistical accuracy. The groups used were:

1) Residential buildings (A in Table 3)
2) Industrial buildings and warehouses (J and K in Table 3)
3) All buildings except residential and industrial buildings, warehouses and other buildings (C, D, E+L, F, G and H in Table 3)
4) Other buildings (B, M and N in Table 3)

Other buildings (including categories B, M and N in Table 3) were separated from other categories because the information on the building stock concerning these groups was very defective. The fit of the generalized Barrois model on the observations of all buildings, including residential and industrial buildings and warehouses for the years 1996–99, is presented in Figure 14. The parameters of the model are labelled in each figure.

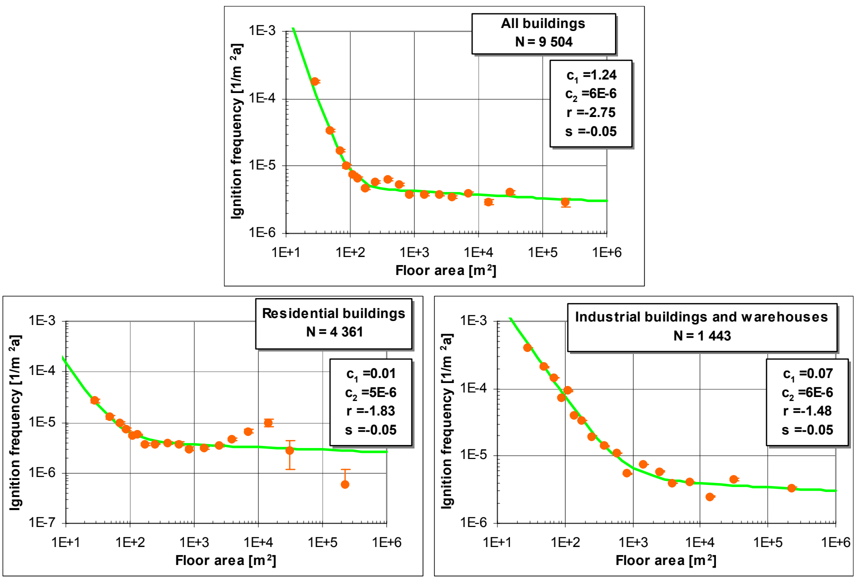


Figure 14. Ignition frequency observations (dots) in different building categories 1996–99 and a generalized Barrois model fitted on the data (solid line). The used floor area classes are presented in Appendix E in Table 38. The error bars represent the uncertainty due to the number of observations of each data point (see Section 2.7).

The ignition frequency observations of the groups 1)–4) in the years 1996–2001 is presented in Figure 15. It transpired that the updating of the data did not influence the results and that the generalized Barrois model with the same parameters could be fitted on the data.

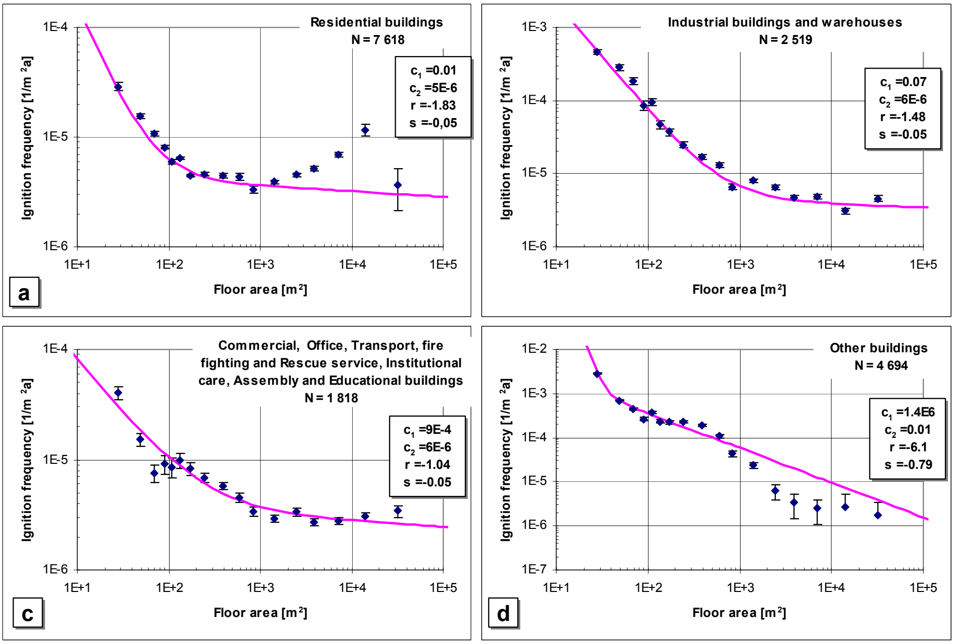


Figure 15. Ignition frequency observations (dots) in different building categories 1996–2001 and a generalized Barrois model fitted on data (solid line). The used floor area classes are presented in Appendix E in Table 38. The error bars represent the uncertainty due to the number of observations of each data point (see Section 2.7).

The model worked fairly well in all buildings, including industrial buildings and warehouses, and would be fully satisfactory for engineering purposes. Since there were only a few observations in two of the largest floor area classes, on the basis of this data, it is not possible to make any conclusions about ignition frequency in buildings with a floor area exceeding 20 000 m^2. However, the amount of buildings with a floor area exceeding 20 000 m^2 is negligible. Based on the information by Statistics Finland, their number is about 400, which is 0.03% of the total number of buildings.

The results of the group ‘other buildings’ cannot be considered statistically reliable (see Sections 5.2 and 9.2), but, just for information, it was nevertheless presented in Figure 15 as were the other groups. The goodness-of-fit was estimated with a chi-test. The sums of chi-squares were

$$\chi^2_{residential} = 91$$

$$\chi^2_{industrial+warehouses} = 23$$

$$\chi^2_{commercial\ etc.} = 7.9$$

Thus the fits with the observations of the industrial buildings and warehouses ($p = 0.05$) and with group 3) ($p = 0.85$) were very good. The fit on data of residential buildings was poorer, because of the ‘hump’ for large floor areas.

5.3.3.4 Partial safety coefficients

For engineering-design purposes, the proper partial safety coefficients must be determined for the Barrois model. In this section, a few known factors causing a systematic error in the results are estimated and partial safety coefficients determined for the different groups of building categories.

A known systematic error was caused by the following facts, which decreased the ignition frequency:

- Floor areas of some buildings in the building stock were unknown. Statistics Finland delivered information on the number of buildings with unknown floor areas. Their share of all buildings in different groups were

Residential buildings	2%
Industrial buildings and warehouses	13%

All buildings except residential and industrial buildings, warehouses and other buildings	14%
Other buildings	22%

- Some floor areas in the accident database were marked as zero ($A = 0\ \mathrm{m}^2$). Their share of all building fires in different groups were

Residential buildings	14%
Industrial buildings and warehouses	20%
All buildings except residential and industrial buildings, warehouses and other buildings	18%
Other buildings	10%

- The fact that buildings that are not populated year-round are not registered in the building stock influences the results of the group 'other buildings'

The following fact had an increasing effect on the ignition frequency:

- Some building fires were incorrectly categorized. Based on a sample ($N = 413$) picked from the accident database, 15% of fires registered as 'other fires' were actually fires in buildings. The annual number of 'other fires' was approximately 3 000.

This examination of systematic errors covered some of the factors influencing the results. Some of the factors were known quite accurately, while others were merely based on assumptions. Not all the factors influencing the results could be identified and taken into account, but all the information available was used and partial safety coefficients were determined on that basis. Estimates of the effect of systematic errors were made for determining the partial safety coefficients γ_f according to the following equation (Tillander & Keski-Rahkonen 2001b):

$$f_s''(A) = \gamma_f f_m''(A) \tag{20}$$

where $f_m''(A)$ is obtained from Equation (19), and $f_s''(A)$ is the design frequency. The partial safety coefficients were determined in such a way that the curve was located above the corrected observations.

The observed ignition frequencies with the corrected values are presented in Figure 16. It was concluded that, for larger buildings (A > 10 000 m^2), $f_m''(A)$ is overestimated due to systematic errors in building stock. Therefore, a value of γ_f = 1 can be used for design purposes for non-residential and γ_f = 3 for residential buildings.

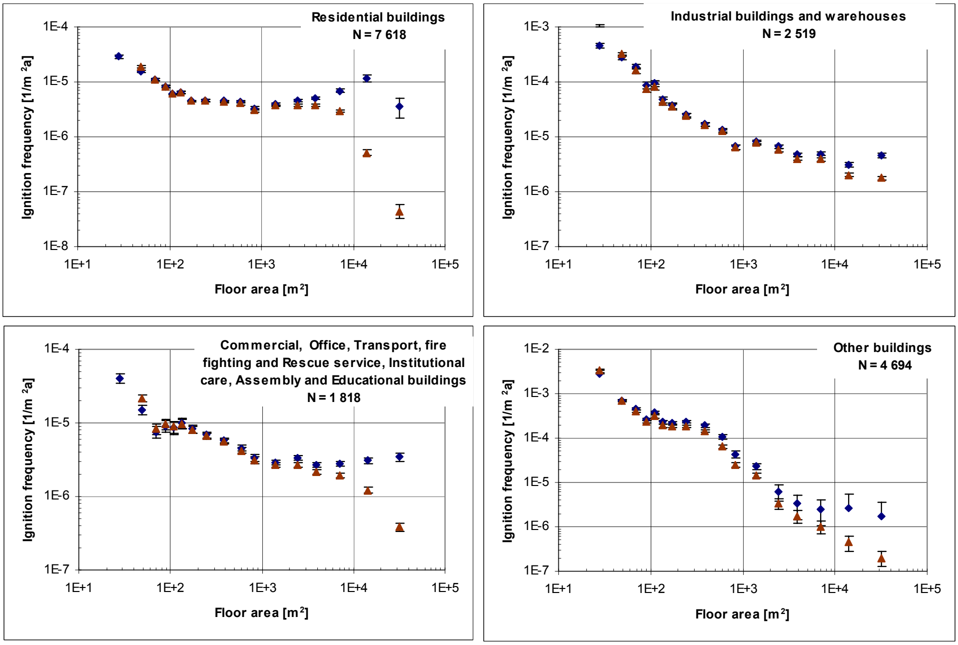


Figure 16. Ignition frequency observations (dots) and corrected values (triangles) in different building categories 1996–2001. The used floor area classes are presented in Appendix E in Table 38. The error bars represent the uncertainty due to the number of observations of each data point (see Section 2.7).

5.4 Time distribution of ignitions

The time distributions of fire alarms of all building fires in Finland during the years 1994–95 were presented in Rahikainen & Keski-Rahkonen (1998b) and during the years 1996–99 in Tillander & Keski-Rahkonen (2001b,c, 2002a). In Figure 17, relative time distributions of the alarms during the years 1996–2001 (N = 19 531) are presented separately for residential buildings, industrial buildings and warehouses, and all other buildings. The periods are: (a) month of the year, (b) day of the week, and (c) hour of the day. The 100% lines represent mean values. Statistix was used to compare differences between the numbers of fires between the time periods. The results are presented in Appendix F. In Appendix F the number of fires is considered, while the relative values are presented in Figure 17.

Figure 17. Periodic variation of relative ignition frequencies of building fires by month of year, day of week and time of day. The 100% line represents the mean value. The error bars represent the uncertainty due to the number of observations of each data point (see Section 2.7).

Figure 17 shows that from periodic variations the clearest was the daily cycle. In studies carried out in China (Lizhong et al. 2002), and Canada (Richardson 2001), the number of fires was observed to be higher during cold winter months, i.e. during the 'heating season' In Finland, the number of fires in residential buildings was highest during January and December and lowest in autumn from August to October. The Kruskal-Wallis Test showed the significant differences between January and the time during August to October. Also, the value in December was significantly higher than the value in August.

The high total number of building fires in summer (May to July) was a result of the high ignition frequency of industrial buildings and warehouses and especially other buildings. The values of industrial buildings and warehouses were significantly above average during May and June and of other buildings during June and July. One explanation of the high value of other buildings is the fires in summer cottages and free-time residential buildings in addition to the saunas related to them, because, naturally, the degree of use of those buildings is the highest during the summer time.

Weekday variation was rather small. The most distinguishable was Saturday for which values were 20% above average in residential and 40% above average in other buildings. In industrial buildings and warehouses, the ignition frequency was significantly lower during the weekends, when the industrial activity is the lowest.

The number of building fires in all categories was lower during nighttime and higher during daytime. Similar behaviour was also observed in studies with the data from China and Canada (Lizhong et al. 2002, Richardson 2001). In Finland, the number of residential fires started to increase after 6 a.m., exceeded the diurnal average after 11 a.m., and remained above average until 11 p.m.

5.4.1 Diurnal variation

Figure 17 indicates a clear diurnal variation of the ignition frequency of building fires. The number of ignitions of building (N = 12 459) and all fires (N = 45 721) per hour during 1996–99 is presented in Figure 18. To the observations was fitted visually the cosine function (Tillander & Keski-Rahkonen 2002a)

$$f_d(t) = a + b\cos\left[\frac{\pi}{12}(t - t_m)\right] \tag{21}$$

where t is the time, [h]. Maximum and minimum of the cosine function is at the point where its derivative equals zero, i.e. $t = t_m$ and $t = 12 + t_m$. The goodness-of-fit was estimated using a chi-test. The sum of chi-square was $\chi^2 = 12$ for building fires and, for all fires, $\chi^2 = 79$, leading to p-values $p_{building} = 0.97$ and $p_{all} = 1.5E-7$. Thus, the cosine function describes well the diurnal variation of the building fires. The fit to all fires was a little poorer but still a good approximation of the phenomenon.

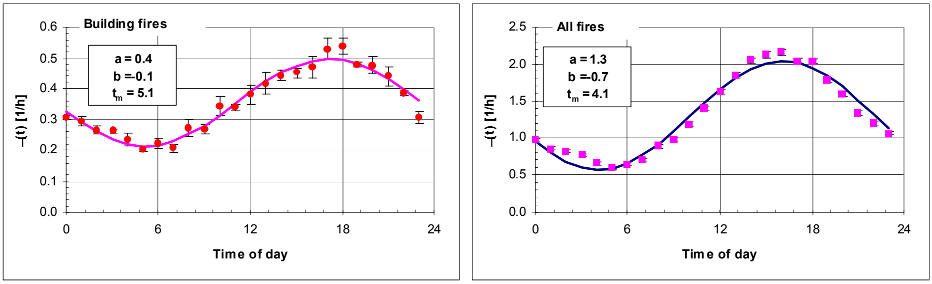


Figure 18. Periodic variation of the ignition frequency by time of day. The error bars represent the uncertainty due to the number of observations of each data point (see Section 2.7).

The same kind of diurnal variation as in building fires was seen in the intensity of all fires, as shown in Figure 18. The number of ignitions of all fires was above average between 11 a.m. and 9 p.m. This is, it would appear, due much to the rhythm of life of people during waking hours in a residential environment, although no specific measured data was observed to show the connection. However, it very clearly indicates the influence of human activity on the ignition frequency.

5.5 Summary

In this study, the data for the ignition frequency of building fires was derived from statistics for different building categories in Finland. Following a model obtained from the literature, the power law function of the total floor area was observed to be at variance with the data, but, working heuristically, it was found that a sum of two power functions led to a fairly good fit to the available statistical data. Since theoretically power law dependence is a special case, a generalized theoretical model was proposed, starting from the initial distributions of the buildings involved in fires and the total stock at risk. Good agreement with the observations was obtained using this approach.

This analysis showed that small local ‘peaks’ of ignition frequency are possible and depend on the form of the floor area distributions. In addition, it was noticed that, in large values of the floor area, ignition frequency does not approach a constant level. However, the used floor area distribution (Equation (17)), which was the sum of three separate distribution functions, was still too simple to describe the actual distributions in great detail. However, the point of the curve fitting was not to find a fitting that was as accurate as possible, but to show in general terms why the ignition frequency varies with floor area. Ignoring minor details, the generalized Barrois model (Equation (19)) is still a good simple calculation form proposed for engineering design purposes, provided partial safety coefficients are calculated in such a way that the curve becomes an upper envelope for the observed data points. The model is useful for determining the ignition frequency of buildings with a floor area of between 100 and 20 000 m^2.

The analysis of the time distributions of ignitions showed that the number of ignitions was clearly dependent on the time of day. The variation could be described fairly well with a cosine function. Thus, the occurrence of ignitions can be treated as a non-homogeneous Poisson process. The knowledge of this kind of diurnal variation is important when the required resources of the fire department are optimised.

6. Fire department intervention in a building fire

6.1 General

A fire department operation is an essential component of the fire-risk assessment process, and so must be considered when the fire risk of a building is being determined. Here simple models were adapted to the operation of the fire department to control the fire risks. On the basis of these models, the quantitative evaluation methods to estimate the influence of the fire department in case of a building fire have been presented. At first, the study concentrated on a comprehensive literary research of the area, after which the statistical data was analysed and the models adapted and valued. For simplification, only the building fires were included. Other duties of the fire department were not taken into account at this phase. Only rough statistical data was collected to estimate their interference to present verification.

In the adopted approach, the operative assignment of the fire department was divided into separate components that were connected again to each other as a fault tree. As a result, the probability of successful intervention of the fire department was evaluated. Another useful feature of the presented models is that the buildings in which a fire department is able to arrive early enough to have a good chance to save the target can be distinguished from those in which the fire safety depends completely on automatic fire extinguishing system. As a demonstration of application of the developed models, a few examples of application to real buildings are presented.

The analysis with the data from the years 1994–97 is published in Finnish in series of VTT Research notes (Tillander & Keski-Rahkonen 2000a) and the matter has been considered briefly in conference papers (Tillander & Keski-Rahkonen 2000b, 2001a). Here the data was updated where necessary.

6.2 Operative time distributions

The **turnout time** is the length of time from the moment the unit is notified until it leaves the fire station. The **total response time** is the length of time from the moment the fire is reported until the unit is at the fire scene. The **fire department response time** is the length of time from the moment the fire unit is notified until it is at the fire scene. Here the latter response time was considered. The **operating time** is the length of time from the moment the unit is notified until it returns to the fire station. A more practical definition of operating time would be the time from the moment the unit is notified until it is again free to serve other calls. However, this information was not available in the used statistical database. The time line from the ignition to the start of the extinguishing actions is presented in Figure 19.

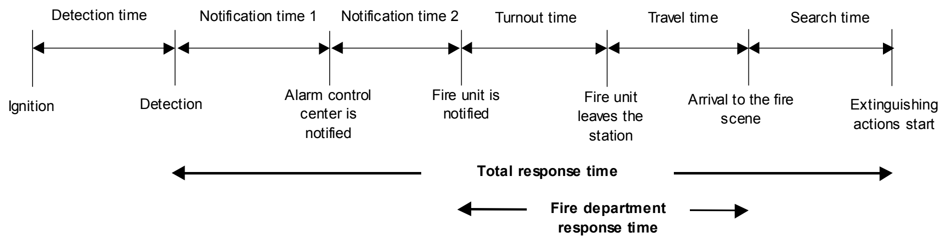


Figure 19. Time line of the response time.

Curve fitting to the time distributions referred to above was attempted using common theoretical distributions. Without any profound modelling, the gamma distribution (Equations (2) and (3)) seemed a plausible fit for all three times. Similarly, the time distributions have been determined for every province of Finland, as well as individually for some major cities with data covering the years 1994–97 (Tillander 1999, Tillander & Keski-Rahkonen 2000a). Here, selected examples from the report, and the same results with updated information from year 2000, are shown.

In Figure 20, the density functions of the turnout, response and operating times of the rescue vehicles with the gamma density functions fitted visually to the observations are presented. The parameters of the gamma function are labelled in each figure.

Years 1994–1997 Year 2000

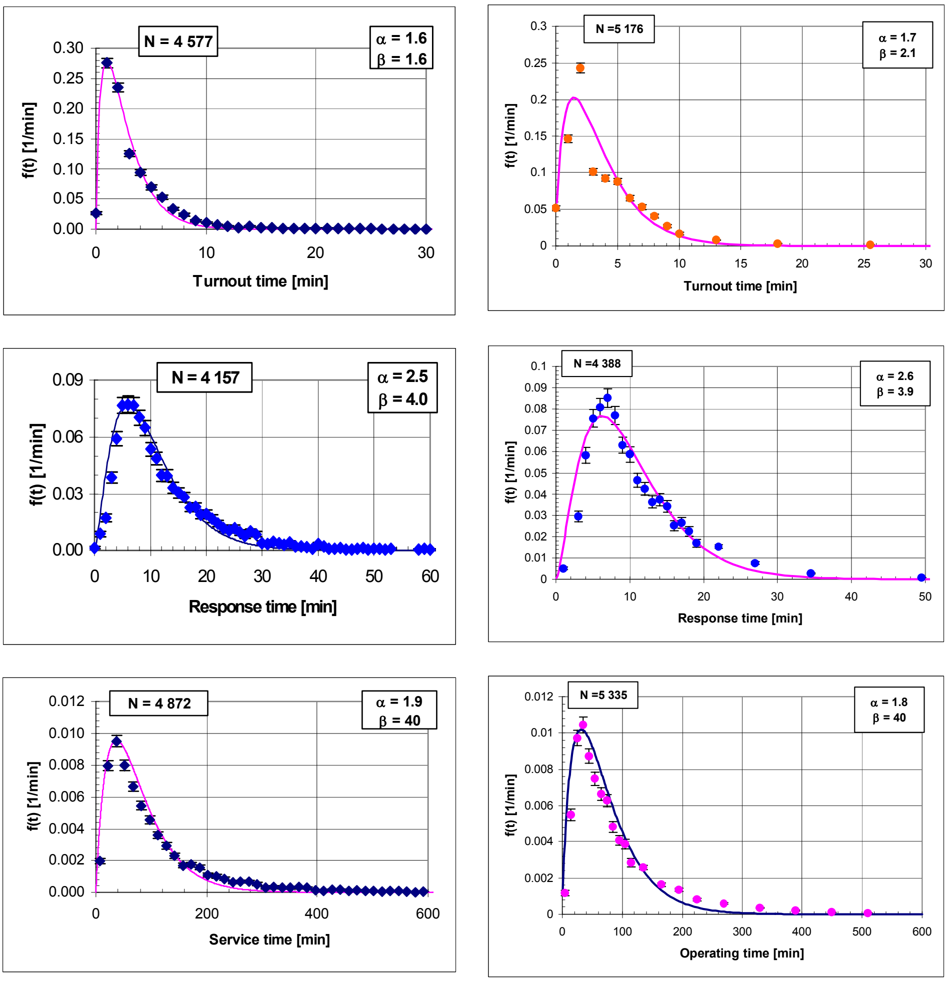


Figure 20. Time distributions of the rescue vehicles in Finland and the gamma density function. The used class intervals are presented in Appendix E in Table 39 and Table 40. The error bars represent the uncertainty due to the number of observations of each data point (see Section 2.7).

Differences between considered time periods were observed only in the distribution of the turnout time. This is probably due to more advanced registration systems, which gradually have become more general over time. Also, the Figure 20 shows that fit of the gamma distribution on the turnout time observations was weaker compared to others. However, all the three distributions have a very long tail, which the fit of a single gamma distribution cannot describe very well. Clearly a better fit was achieved when the sum of two gamma distributions (Equation (4)) were fitted visually on the data, which led also to smaller values of the sums of chi-squares for all time distributions. The fit on the observations of the rescue vehicles from year 2000 is presented in Figure 21 and the used parameters in Table 8.

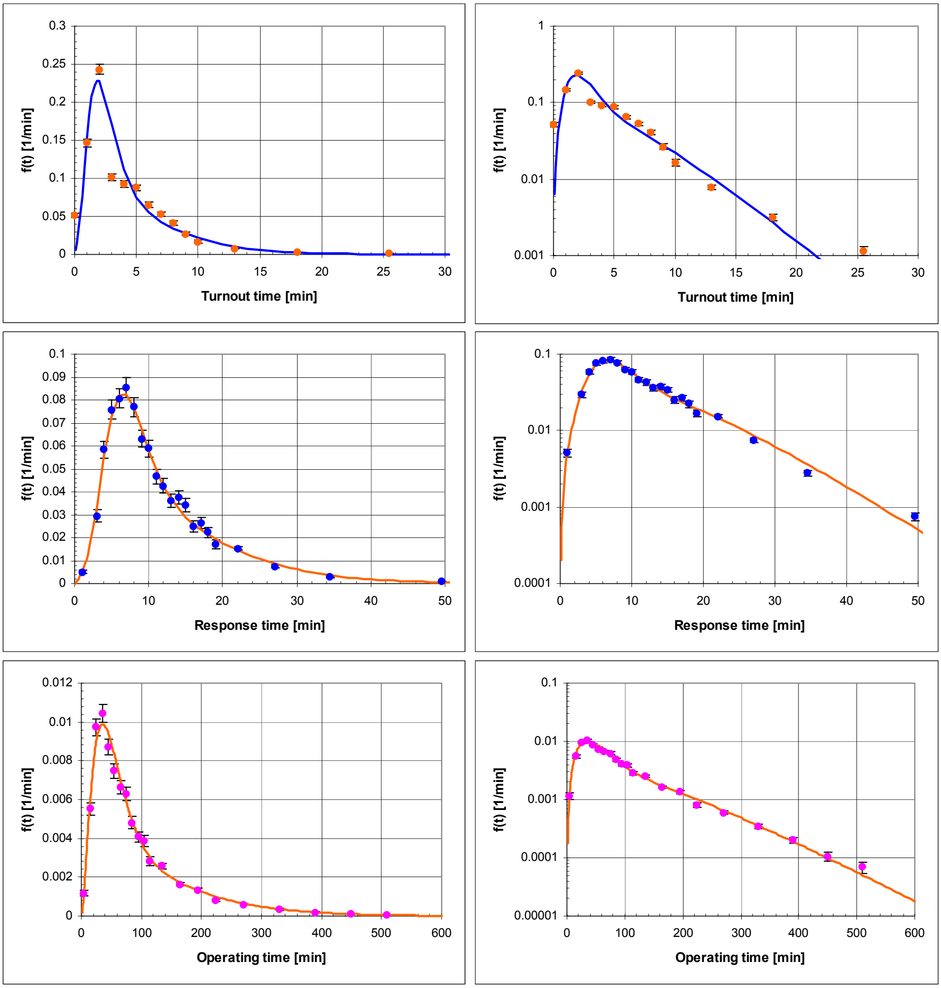


Figure 21. Time distributions of the rescue vehicles in Finland from year 2000 and the gamma density function, a) linear x- and y-axis, b) linear x- and logarithmic y-axis. The used class intervals are presented in Appendix E in Table 40. The error bars represent the uncertainty due to the number of observations of each data point (see Section 2.7).

Table 8. Parameters of the two gamma distributions in Figure 21.

Parameter	Turnout time	Response time	Operating time
a	0.87	0.35	0.5
α_1	1.7	6.6	2.9
β_1	2.1	1.1	17
α_2	1.2	2.5	1.9
β_2	10	6.1	76

The chi-square values of the fits presented in Figure 21 were

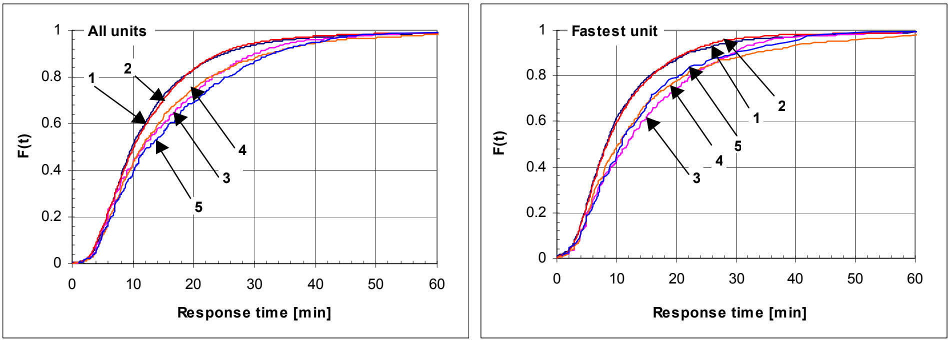
$$\chi^2_{turnout} = 272 \qquad \chi^2_{response} = 38 \qquad \chi^2_{operating} = 36$$

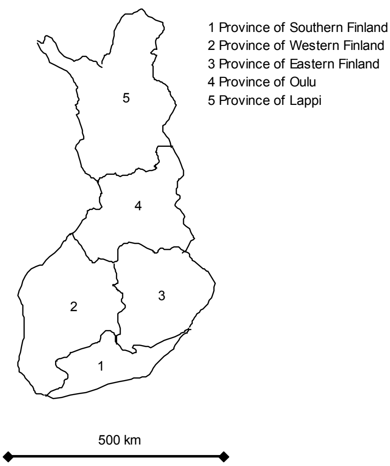
All sums of chi-squares presented above lead to a p-value of under 0.05. The required χ^2-values leading to a p-value 0.05 were for each case:

Turnout time: $\chi^2 = 22$; df = 13
Response time: $\chi^2 = 33$; df = 21
Operating time: $\chi^2 = 31$; df = 20

Thus, the sums of chi-squares of response and operating times were reasonably low and very close to the values presented above leading to p-value under 0.05. Therefore, the fits with those distributions can be considered good under the circumstances where it is very unusual that any theoretical distribution could be fitted perfectly to the real data.

In general, the response time is used to measure the performance of the fire department. In Figure 22, cumulative response times of different provinces of Finland are presented. Figure 22 shows that in provinces with very long travel distances (5 Lappi) or routes fractured by waterways (3 Eastern Finland) the travel time lengthens the response time considerably. Figure 22 shows that 22% of response times of the Southern Finland fell within six minutes. The same value for the province of Lappi (5) was 18%. Nevertheless, for practical work and engineering purposes, a sum of two cumulative gamma distributions can be determined for most provinces. The generality is valid for communities similar to those in Finland, where the population and buildings are concentrated in a small area compared to the total area of the community.





Area	Number of observations	
	All units	Fastest unit
1	4 821	1 816
2	5 765	2 084
3	1 704	718
4	1 212	495
5	516	194

Figure 22. Cumulative response time functions in different provinces of Finland in year 2000.

6.3 Travel time

6.3.1 Theoretical model

Travel time is the elapsed time between when a unit leaves its station and arrives at the fire scene. In addition to travel time, response time includes the turnout time of the fire unit. Travel time was separated from the response time because, with the travel time model parameters verified from statistics, the distance dependency of the travel time can be taken into account. Thus, when the travel distance is known, the travel time to individual destination can be estimated.

A simple travel time model (Kolesar 1975, Chaiken et al. 1975), tested earlier and found practical in New York, was adapted to the Finnish environment. Observed data was used to extract parameters *a*, *b*, *c* and *d* for a model presented in Equation (22) (Tillander 1999, Tillander & Keski-Rahkonen 2000a, b) by using Statistica.

$$t = \begin{cases} a\sqrt{s}, & s \le d \\ bs + c, & s \ge d \end{cases} \tag{22}$$

where t is the travel time [s] and s is the travel distance [km]. In Equation (22), it is assumed that the unit at first accelerates until it reaches its full cruising speed, which it maintains for a period and starts to decelerate as it approaches its destination. This process can be repeated several times during one drive because of road and traffic obstacles but it does not affect to the mathematical shape of the correlation. The square root of the first part of the curve describes the situation in small distances, where the unit never reaches its full cruising speed.

Two additional requirements were set for Equation (22): the functions and their first derivatives should be continuous at $s = d$. This limited the free parameters to b and c to be determined from non-linear equations

$$t = \begin{cases} 2\sqrt{bs}, & s \le \dfrac{c}{b} \\ bs + c, & s \ge \dfrac{c}{b} \end{cases} \tag{23}$$

The travel time model was fitted on the travel time and distance data of different fire unit types collected from three different regions in Finland for a period of one year: i) the City of Helsinki, ii) the City of Tampere and iii) a rural area in the province of Western Finland (see Figure 22). The differences between the test areas were minor and data were therefore pooled and the universal curve was determined to be valid for the whole country. The parameters of the model were determined separately for command and rescue vehicles in Finland and are presented in Equation (24).

$$\begin{aligned} t_{rescue} &= \begin{cases} 3.0\sqrt{s}, & s \le 8.0 \text{ km} \\ 0.5s + 4.2, & s \ge 8.0 \text{ km} \end{cases} \\ t_{command} &= \begin{cases} 2.3\sqrt{s}, & s \le 2.5 \text{ km} \\ 0.7s + 1.8, & s \ge 2.5 \text{ km} \end{cases} \end{aligned} \tag{24}$$

where t is travel time [min]. The proportion of variance explained (R^2) indicates the goodness-of-fit. The values were

$$R^2_{rescue} = 70\ \% \qquad R^2_{command} = 80\ \%$$

The statistical observations of the rescue vehicles and the determined travel time curve (Equation (24)) are presented in Figure 23. The heaviest line lowest represents the average travel time. The middle line represents the upper limit of the average travel time at an 80% confidence level. The travel time of an individual rescue vehicle remains below the uppermost line at an 80% confidence level, which is important when the travel time is estimated for a specific building in a fire-risk analysis.

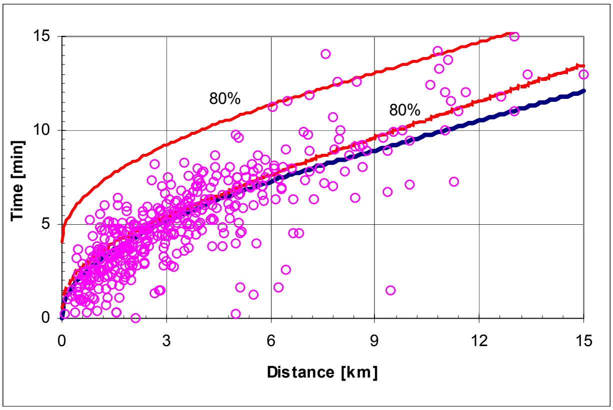


Figure 23. Real travel time and distance observations (circles) of rescue vehicles of three test areas (N = 426) and the travel time curve fitted on the data (heavy line lowest). The middle line represents the upper limit at 80% confidence level of the fitted curve and the uppermost line at 80% confidence level the upper limit of the travel time for a single vehicle.

In Figure 24, the observations shown in Figure 23 are grouped by the travel distance and the average travel time of each group presented. The travel time curve obtained from Equation (24) and presented in Figure 23 is plotted in Figure 24. As may be seen, the correlation between the model and the observations were satisfactory.

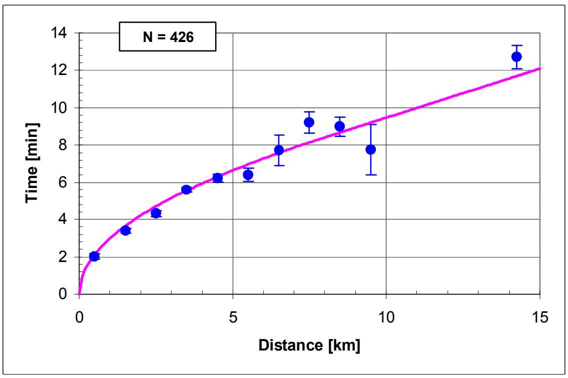


Figure 24. The average travel time as a function of the travel distance (circles) of rescue vehicles of three test areas and the travel time curve (Equation (24)). The used class intervals are presented in Appendix E in Table 41. The error bars represent the standard deviation of the mean (see Section 2.7).

6.3.2 Discussion

Despite discarding the outliers, the scattering of the data was still high. Therefore, the uncertainty of a single travel time grew fairly large compared to the average. This simplest possible model for predicting the travel times of fire units does not consider all the elements affecting the travel time, e.g. weather conditions, volume of traffic or quality of road. The standard errors of parameters of Equation (24) were obtained as a result of the fit carried out using Statistica and are shown in Table 9.

Table 9. Standard errors of the travel time model parameters (i = a, b, c).

i	**Rescue vehicles** $i \pm \sigma_i$	**Command vehicles** $i \pm \sigma_i$
a	3.0±0.4	2.3±0.1
b	0.5±0.1	0.7±0.03
c	4.2±0.9	1.8±0.2

According to Table 9, within a 5 km radius, the deviation of travel time of rescue vehicles is 0.9 min and within a 15 km radius, 2.3 min. However, the scattering was acknowledged when the confidence intervals shown in Figure 23 were determined using Equations (36) and (37), presented in Appendix B.

To obtain more accurate travel time estimates, the number of observations should be increased and the actual distances measured with greater accuracy along the roads. Both the road network and property addresses are registered in Finland in digital databases but were not available in this study. Enlarging the sample sufficiently, more elements affecting the travel time, e.g. the time of day or the features of the road network, could be considered.

6.4 Frequency of blockage

The theories used widely in telecommunication can be applied also to model the operation of the rescue service. Here queuing theory was used to estimate the availability of fire units in case of an alarm. The model parameters were defined from the statistics.

In general, the goal is to model the dependencies between the rate of incoming alarms, the capacity of the rescue service and the quality of the service offered. The theoretical approach aims to assess the quality of service from the user's point of view, taking into account, for example, the probability that the arriving alarm will be blocked or the time spent to serve the call. It can also be assessed how many operating units will be needed with a specific alarm rate to achieve the desired quality of service. The theoretical models form the basis of the assessment of the efficiency of the fire department and the determination of the optimal number of fire units to satisfy the demands in the considered region.

The simplest result is obtained by using Little's method, which describes the intensity of alarms. The arrival process is assumed stationary. Alarms arrive to the system randomly. The average number of alarms in the system at any arbitrary moment is obtained from (Goodman 1988)

$$C = \lambda \tau \tag{25}$$

where λ is the alarm rate (number of alarms (fires) in a time unit) and τ is the average operating time per alarm. With Little's result (Equation (25)), the average number of simultaneous alarms of the fire department was estimated (Table 10).

Table 10. Average number of simultaneous alarms in Helsinki. Results are standardised per million inhabitants. Uncertainties of the parameters are determined as described in Section 2.7.

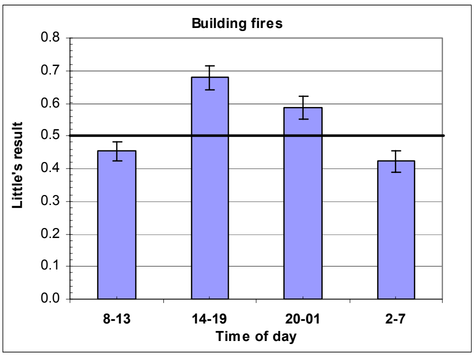
	Average number per year and million inhabitants [1/a]	**Average operating time per alarm [h]**	**Alarm rate [1/h]**	**Average number of customers in the system**
Building fires	432	0.74±0.03	0.049±0.002	0.036±0.002
All alarms	11 696	0.57±0.001	1.335±0.012	0.763±0.007

The number of inhabitants in Helsinki was 555 474 (year 2000/2001). The average number of building fires 1996–2000 and all alarms 1996–2001 registered in Pronto, standardised per million inhabitants, are presented in the second column of Table 10. In the third column of Table 10, the average operating time of alarms during 1996–99 is presented. It may be seen that the average operating time of building fires is longer than the average of all alarms. The alarm rate (alarms per hour) is presented in the fourth column. The average number of alarms in the system at any arbitrary moment is presented in the last column. In this case, it indicates the number of simultaneous building fires or other tasks of the fire department. Thus, in Helsinki, there are 0.04 simultaneous building fires and 0.8 simultaneous tasks of the fire department per million inhabitants.

However, the intensity of alarms varies with different periods of time. In Finland, the diurnal variation of alarms was the only significant variation observed (Section 5.4). Thus in small time interval the arrival process can be determined as Poisson process with intensity λ. Due to diurnal variations, the intensity is not constant but dependent on the time of day $\lambda = \lambda(t)$. It is therefore called the non-homogeneous Poisson process, where the alarms arrive to the system at arbitrary moments following the Poisson process, and the intensity $\lambda(t)$ varies as a function of time. In reality, the intensity of fires $\lambda(t)$ is a stochastic process, which includes a very strong deterministic component related to known predictable variations (diurnal variation). However, the behaviour is not completely deterministic and the intensity varies around the average profile of the diurnal variation. In addition to this, the arrival process may include some variations due to external events, which may be either predictable or unpredictable and regular or irregular.

The effect of the diurnal variation was examined by dividing the day into four time periods in Figure 25. The horizontal line represents the diurnal average. No statistical tests were carried out because the successive time periods the day was divided into cannot be considered independent, and because the analysed data covered only the period of one year. The results were therefore analysed on the basis of the error bars.

Figure 25 showed that the load of the system was the highest during 1400–1900 hours and was below average during 0200–0700 hours. When building fires only were considered, these time periods deviated significantly from the average, when, as a criterion for a significant difference, a difference exceeding three deviations (error bar represents one deviation) was assumed. On the basis of the same criterion, it was found that, for all tasks, the value was significantly above average during 0800–1900 hours and below average during 2000–0700 hours.



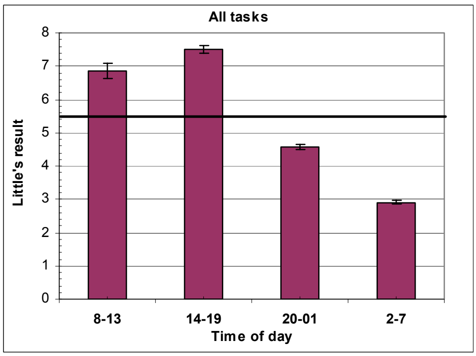


Figure 25. Average number of simultaneous tasks in Finland in year 2000. The error bars represent the uncertainty due to the number of observations of each data point (see Section 2.7).

In Figure 26, the day was divided into two-hour periods before the Little's result was calculated. Because of the limited amount of building fires, the error bars in Figure 26 grew quite large. No statistical tests were carried out, but, on the basis of the error bars only, the low value during 0600–0900 hours and high value during 1800–1900 hours seemed to deviate significantly from the average, when, as a criterion for a significant difference, a difference exceeding three deviations was assumed (one error bar represents one deviation). The number of all tasks was larger and therefore the uncertainty smaller. Close to the average value were only the values between 0800–0900 and 2000–2100 hours. Figure 26 shows that the load of the system was the greatest between 0800 to 2100 hours.

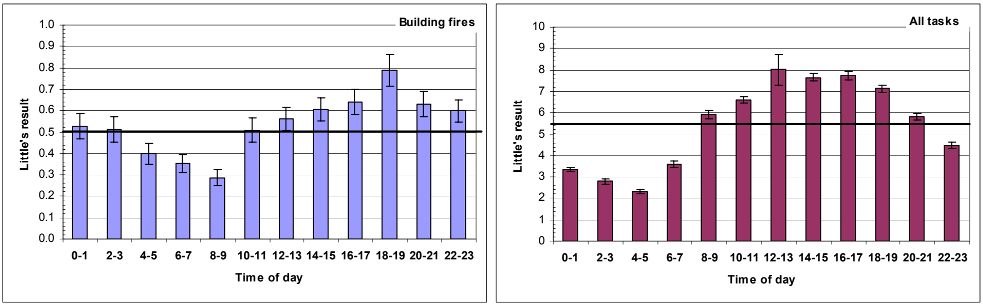


Figure 26. Average number of simultaneous tasks in Finland in year 2000. The error bars represent the uncertainty due to the number of observations of each data point (see Section 2.7).

A simple way to assess the blocking probability is to use Equation (26) known as Erlang's formula (Takács 1962)

$$P_S = E(S,C) = \frac{\dfrac{C^S}{S!}}{\displaystyle\sum_{s=0}^{S} \frac{C^s}{s!}} \tag{26}$$

where C is the intensity of simultaneous fires from Equation (25) and S is the number of units that can be sent to serve the call. Thus it is now assumed that one unit serves one call or alternatively that the S denotes the group of units that will be sent to serve one call. When Equation (26) is used, it is assumed that the blocked alarms will be lost and that they do not return to the system. The arrival process is assumed Poisson distributed. However, Equation (26) is valid in general independently of the shape of the operating time distribution and the blockage depends only on the average duration of the operation.

In Figure 27, the probability of blockage in Helsinki with different number of units *S* as a function of the time of day, determined using Equation (26), is presented.

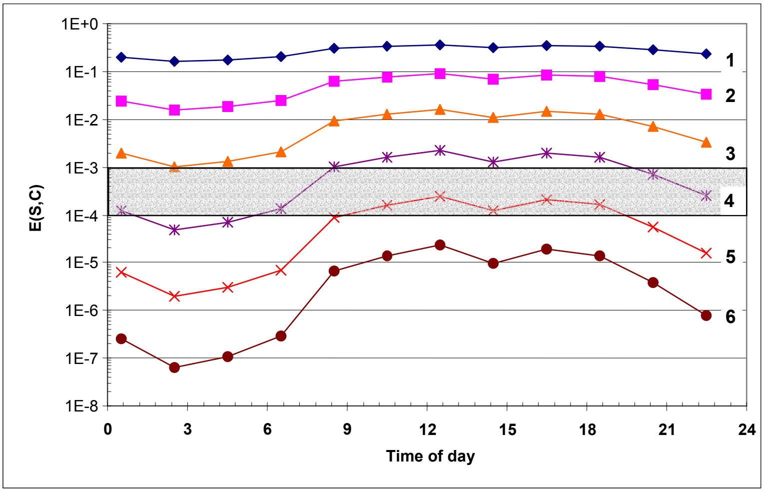


Figure 27. Probability of blockage (Equation (26)) with different values of S as a function of the time of day in Helsinki.

If the acceptable blocking probability is set between 10^{-4}–10^{-3} (grey area in), the required number of units or groups of units needed to serve one call in Helsinki was four during 2000–0700 hours and five during 0800–1900 hours.

This was a very simplified example of the operation of the fire department, but points out how the methods used in telecommunication can be applied to the fire service. A somewhat more advanced approach has been introduced by Brušlinskij (1988). An abridgement of his theory is presented in Appendix B and is illustrated in the example presented in Section 6.6.2. In his approach, the fact that the alarms are dissimilar and require a different number of units and operating time, is acknowledged. In the theory, it is assumed that the alarms arrive randomly, as described mathematically by exponential distribution. This is in agreement with the observations in Finland (Rahikainen 1998a), although periodic diurnal variation causes a slight distortion (Tillander & Keski-Rahkonen 2001b, c, 2002a). This approach does not agree with the observations of the gamma distributed operating time, but it is nevertheless possible to generalise the theory for an arbitrary distribution (Pollaczek 1953) as noted earlier (Tillander & Keski-Rahkonen 2000a).

6.5 Fire suppression

Finnish statistics do not include information on the success of fire suppression. In the accident database, the magnitude of the fire is assessed in relation to how wide it has spread at the moment the fire department arrived and at the end of their operation (see Figure 61). This information is not detailed enough to assess the probability of success of the extinguishing actions. The problem can be solved by determining the critical rate of heat release P_{cr}, such that the probability of successful extinction is estimated to be ≥ 0.8. Then the probabilities of the chain of suppression events would convert to evaluation of the probability of the fire department arriving at the scene ready to start the extinction before the rate of heat release reaches its critical value P_{cr}.

Several results of extinguishing experiments and methods to calculate the fire fighting water requirements (Yu et al. 1994, Särdqvist 1996, 2000, Davis 2000, Torvi et al. 2001) are presented in the literature. One example of such calculation methods is the Barnett methodology, by which the required fire fighting water flow rate is obtained (Davis 2000)

$$FR = \frac{Q_c}{\eta Q_w} \tag{27}$$

where FR is the water flow rate [l/s], Q_c the heat release rate of the fire [MW], η the cooling efficiency of water, equivalent to 0.1–0.4 (Särdqvist 1996) and Q_w the theoretical absorption energy of water going from a liquid at ambient temperature to vapour at 100°C, equivalent to 2.6 MW.

With one hose, the flow rate between 10–50 l/s is achievable. The lower limit is close to the real flow rate achievable even in unfavourable circumstances. If the water flow rate of the first fire-fighting squad at the scene of fire was assumed FR = 15 l/s, and the cooling efficiency of water η = 0.4, it equals the value of the rate of heat release Q_c = 15.6 MW.

On the basis of calculations and recent extinguishing experiments, 15 MW was chosen for a critical rate of heat release value to be used in the event- and fault-tree approaches presented in Section 6.6 (Tillander & Keski-Rahkonen 2000a, b, 2001a). It was considered a limit value at which the fire department is able to extinguish the fire with probability ≥ 0.8.

6.6 Event- and fault-trees

6.6.1 General

The performance of the fire department can be evaluated by comparing the estimated response time of the nearest unit to the fire growth. An alternative approach is to divide the whole operative process into separate operations, which can be distinguished from each other by the physical nature of the task operators or by some formal definition of operative tasks. To be practicable and amenable for quantitative assessment, the statistical data was used as backup. The operative assignment of the fire department, fire alarm, was divided into four parts. It is described as an event tree in Figure 28 (Tillander & Keski-Rahkonen 2000a, b 2001a). This is only one example of an event tree for which the actual selection of the branches was greatly influenced by the data available in the used accident database. From the primary event, the assignment is divided to (S1) turnout, (S2) travel time, (S3) observation at the scene and (S4) fire extinction.

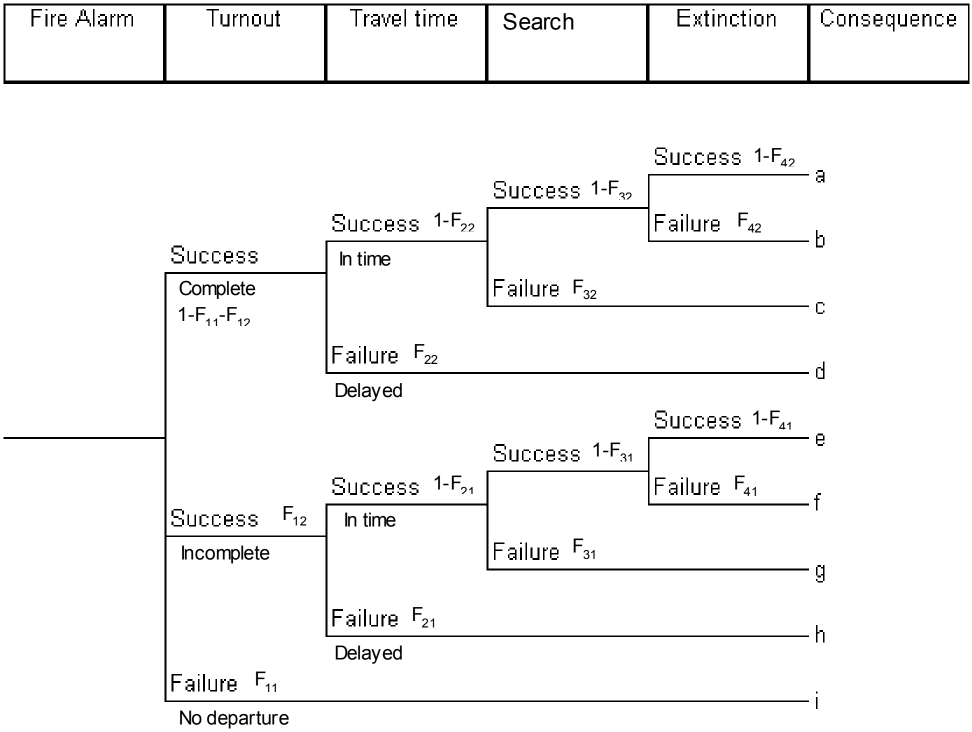


Figure 28. Event tree of the fire department operation.

The probability of successful extinction is the sum of the chains *a* and *e*

$$a + e = (1 - F_{11} - F_{12})(1 - F_{22})(1 - F_{32})(1 - F_{42}) \\ + F_{12}(1 - F_{21})(1 - F_{31})(1 - F_{41}) \tag{28}$$

Because detailed information was not available, the travel time, search time at the scene and the success of an extinction were assumed independent of the turnout such that F_{11}=F_{22}=F_2, F_{31}=F_{32}=F_3 and F_{41}=F_{42}=F_4. Thus, regardless of the completion of the turnout, the probabilities are assumed equal. In this way, the probability of successful extinction is obtained from

$$a + e = (1 - F_{11})(1 - F_2)(1 - F_3)(1 - F_4) \tag{29}$$

This is expressed as a fault tree (or success tree) in Figure 29. The top event is the successful intervention of the fire department to the occurring fire. This means that the first unit arrives in time and is able to locate and control the fire. When the probabilities of every event are known, the probability of the primary event can be calculated. The gates separating the probabilities are either AND-(&) or OR-(≥1) gates. Probabilities distinguished by AND-gate are multiplied and OR-gate summed up.

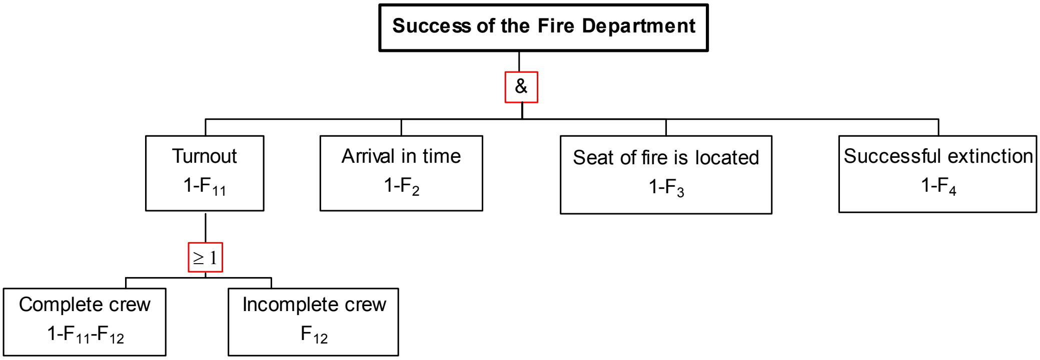


Figure 29. Success/fault tree of the fire department operation.

There was no statistical information available on the probability of locating the seat of the fire. For the time taken for the clearance of equipment and transferring to the seat of fire, the international research results are available from Australia (Australasian Fire Authorities Council 1997). However, in Finland, where the example calculations were made, buildings are generally modest in size, and high-rise constructions are rare. Therefore, the time needed from the fire truck to the fire seat is not as long as it may be in bigger metropolises and locating the seat of fire is generally easier.

After some example calculations for different situations were carried out, it very soon became clear that the success of the fire department in Finland depends strongly on travel time, while other parts included in the fault tree have a much lower significance.

6.6.2 Illustration example: Office block

As an example of the use of the event- and fault-tree methods described in the previous sections, a simple illustration example is presented (Tillander & Keski-

Rahkonen 2000a). The example building is an office block with a large atrium and a high tower located in Helsinki. The building is divided to 18 fire compartments. Firstly, the probability of blockage was estimated. In Helsinki there are approximately 250 building fires and totally 6 500 duties of the fire department yearly. Blocking probabilities were determined using Equations (38)–(48) in Appendix B. The detailed information in this study was available only on building fires. The effect of other duties was estimated using the total number of calls and assuming their number and operating time distributions were similar to those of building fires. This is not precisely true, as can be seen from Table 10, where the average operating time of building fires was longer compared to all calls. Hence, the probability can be considered to be an upper limit. The average alarm rates and operating times are presented in Table 11. The deviations of the values presented in Table 11 were estimated as described in Section 2.7.

The unit is usually sent from the nearest fire station to serve the alarm. If it is not available, another unit arrives from further away. Therefore, all fire units in Helsinki can be sent to incoming calls, but, in this analysis, it affects the travel time estimated later.

Table 11. The average rate and operating time of alarms that required the number of units S presented in first column in Helsinki 2000.

Number of rescue units	**Alarm rate λ [1/h]**		**Operating time τ [h]**	
S	**Building fires**	**All duties**	**Building fires**	**All duties**
1	0.004±0.001	0.464±0.007	0.98±0.15	0.50±0.02
2	0.001±0.0003	0.037±0.002	0.43±0.03	0.66±0.02
3	0.001±0.0004	0.121±0.004	0.71±0.11	0.46±0.02
4	0.001±0.0004	0.014±0.001	1.13±0.26	0.61±0.05
5	0.001±0.0003	0.011±0.001	0.54±0.10	0.38±0.03
6	0.019±0.001	0.109±0.004	0.73±0.05	0.42±0.02
7	0.003±0.001	0.011±0.001	1.16±0.19	0.60±0.06
8		0.001±0.0003		1.26±0.90

For λ_i and τ_j given in Table 11, the frequencies f_{pb} (partial block), f_{tb} (total block) and f_b (block) and the probabilities P_{pb} (partial block), P_{tb} (total block) and P_b (block) were determined and given in Table 12.

The majority of building fires (63%) required six fire units. When all calls were considered, one unit was sent to most of the tasks (60%); the share of alarms requiring three and six units was approximately 15% each. The blocking probability for six units from Table 12 is $P_b = 0.10$ (all alarms).

Table 12. The probability and frequency, P_{pb} and f_{pb}, of a partial block, P_{tb} and f_{tb}, of a total block and their sums, P_b and f_b, in Helsinki.

Building fires						
S	P_b	P_{pb}	P_{tb}	f_b [1/h]	f_{pb} [1/h]	f_{tb} [1/h]
1	0.87	0.85	0.02	0.026	0.025	0.0007
2	0.84	0.82	0.02	0.025	0.025	0.0006
3	0.80	0.78	0.02	0.024	0.023	0.0006
4	0.76	0.74	0.02	0.023	0.022	0.0006
5	0.73	0.72	0.02	0.022	0.021	0.0005
6	0.12	0.10	0.02	0.004	0.003	0.0005
All calls						
S	P_b	P_{pb}	P_{tb}	f_b [1/h]	f_{pb} [1/h]	f_{tb} [1/h]
1	0.58	0.27	0.31	0.45	0.21	0.24
2	0.45	0.30	0.15	0.35	0.23	0.11
3	0.31	0.20	0.11	0.24	0.15	0.09
4	0.25	0.18	0.07	0.19	0.14	0.05
5	0.22	0.16	0.05	0.17	0.13	0.04
6	0.10	0.06	0.05	0.08	0.04	0.04

The probability of ‘arrival-in-time’ box in Figure 29 was estimated on the basis of the design fire located to atrium. Its rate of heat release curve is presented in Figure 30. The distance to the nearest fire station is 4.3 km. When it is assumed that the fire is reported to the fire station immediately after ignition, the response time of the first rescue unit, including turnout time based on statistics and travel time based on the model presented in Equation (24), was on average six minutes. The rate of heat release reaches the critical value $P_{cr} = 15$ MW after 9.3 min. Calculating backward from the travel time model, the probability of arrival within 9.3 min was 0.7. Then the probability of successful extinction would be 0.8. As mentioned above, no research results were available; only expert opinions existed for the probability of locating the seat of fire. Value $F_3 = 0.95$ was suggested here.

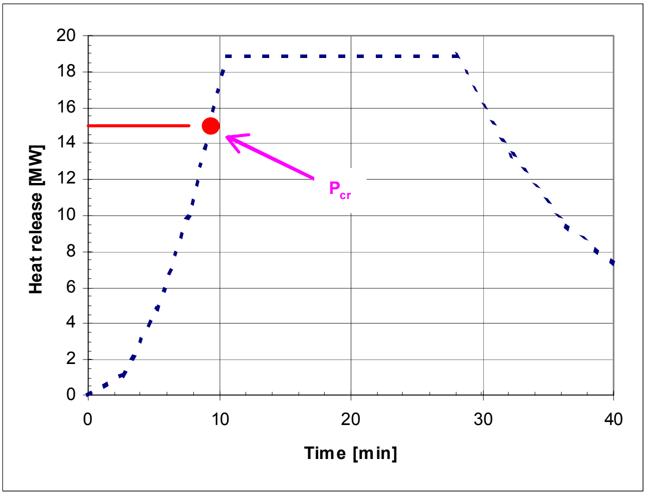


Figure 30. Rate of heat release of the design fire and fire department response times.

After all probabilities of the fault tree in Figure 29 were determined, the probability of successful intervention could be calculated from

$$P_{success} \approx (1 - 0.10) \cdot 0.7 \cdot 0.95 \cdot 0.8 = 0.48 \pm 0.09 \tag{30}$$

The level of uncertainty associated with blocking probability was estimated as described in Section 2.7 in Equations (8)–(10) and with travel time by using the standard errors presented in Table 9. For suppression and locating the seat of fire, the level of uncertainty was estimated to be 5%.

This probability value can be used as guidance in the design process when the required fire safety measures are planned. In this example case, fire safety of the considered building cannot rely on the fire department extinguishing actions because, based on the calculations, the intervention is successful only five times out of ten. Thus, the fire safety must be secured with other actions.

6.7 Application examples

6.7.1 General

In Finland, the successful intervention of the fire department depends primarily on travel time. Another and more practical approach in these circumstances is to evaluate the performance of the fire department by comparing the estimated response time of the nearest unit to the fire growth. This approach is demonstrated here through two examples of real building constructions and the results are compared with each other. The examples are not exhaustive, but represent typical objects designed nowadays using performance-based principles.

6.7.2 Design example 1: Community centre

6.7.2.1 Description of the target building

A target building was a virtual community centre from which a lobby area was chosen for closer examination. The most hazardous areas were found by comparing the probabilities of ignition and extinguishing failure in addition to severity of the designed fires in different premises. Basic information on the building is presented in Table 13.

Table 13. Basic information on the example building.

Building:	Community centre
Location:	Espoo
Premises chosen for closer examination:	Lobby area
Area [m^2]	2 900
Distance from the nearest fire station [km]:	4
Fire prevention systems in the lobby:	No automatic extinguishing system

As a fire safety strategy, the probability of large fires is kept below a tolerable level. The path of fire development is described as a fault tree in Figure 31. The form of it was chosen such that branching ratios could be derived from fire statistics. The values shown in Figure 31 are preliminary, but show the order of magnitude.

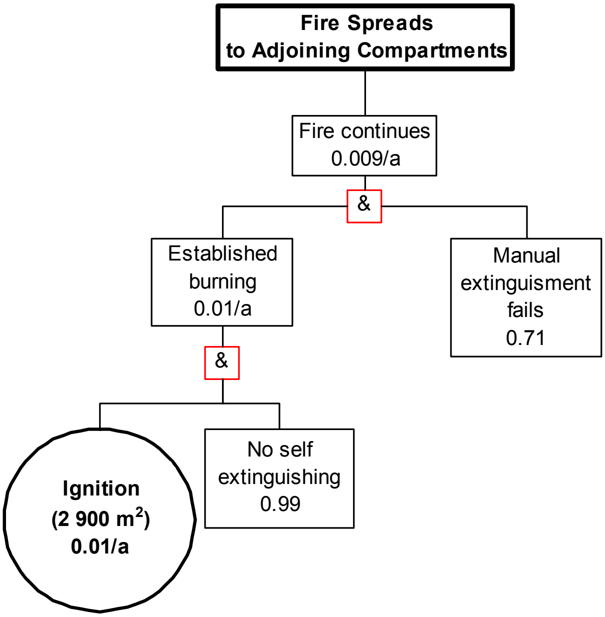


Figure 31. Fault tree of extinguishing failure of a fire in a lobby. The principle fault tree presented in CIB W14 Workshop (1983) is quantified and reformed to risk analysis tool (Tillander & Keski-Rahkonen 2000a, 2001a) (1/a denotes probability per annum).

The probability of ignition presented in Figure 31 was obtained using the generalized Barrois model (Equation (19)) with parameters labelled as in Figure 15 c). When the probability of self-termination of the fire is estimated to be 0.01 (Fitzgerald 1985, 1991), the probability of established burning equals to $0.012 \cdot 0.99 = 0.012/a \approx 0.01$ /a. From Table 14, it can be seen that the expected average number of ignitions during the life span of the building is 0.6, and an ignition requiring an intervention of the fire department occurs in the lobby once in 80 years.

Table 14. Frequency of established burning.

Established burning [1/a]	Length of life span [a]	Number of ignitions during life span	Occurrence interval [a]
0.01	50	0.6	80

The premises are not sprinkled. Based on information for the years 1996–2001 in the accident database Pronto, in public buildings (including building categories C, D, E+L, F, G and H presented in Table 3) in 52% of the fires the available manual fire extinguisher was not used and in 19% of the fires it was used but did not extinguish the fire. Thus, in Figure 31, their sum, 71%, was used as the probability of a manual extinguishing failure. Furthermore, the probability of the fire continuing and threatening other compartments is $0.012 \cdot 0.71 = 0.0085/a \approx 0.009/a$. This happens once in 120 years.

6.7.2.2 Design fire

The design fire was assumed to ignite in the kiosk booth placed in the lobby. The rate of the heat release in Figure 32 (dashed line) was determined from the fire load using the technique depicted by Keski-Rahkonen (1993) and t^2-fire growth model (Heskestad & Delichatsios 1978) (see Appendix C). The distance from the nearest fire station is 4 km. The total time to which the fire growth is later compared includes detection time, notification time 1 and 2, turnout and travel times, in addition to the time from the arrival to the start of the extinguishing actions (see Figure 19). Often it is not known when the fire started, in which case assumptions must be made on the basis of other information available on the specific fire. Here it was assumed that the fire is reported to the fire department immediately after ignition. If the premises are equipped with a fire detector system, its activation time can be determined using suitable programs (Baroudi et al. 1998), in which the rate of heat release of the design fire must be given as input.

The total time from the moment the fire unit is notified until it is ready to start extinguishing actions is presented in Table 15 at probability levels of 50% and 80%. The 50% value was obtained by summing the median of the turnout time and the average travel time determined from the travel-time model adjusted to the rescue units (Equation (24)). The median of the turnout time can be assumed to represent the average value more closely than the mean value, because the mean is distorted by the extremely long and short time observations, which most probably are erroneous. However, compared to the turnout time, the travel time is clearly longer and its deviation larger. It is therefore assumed that the result corresponds to the average value with reasonable accuracy and is taken as having a 50% probability level.

The total time at 80% probability level was obtained by summing the 80% fractal of the turnout time and the travel time at an 80% confidence level. For the same reasons as mentioned above, the method was estimated to be acceptable.

To these values were then added the time from the arrival to the start of the extinguishing actions (Australasian Fire Authorities Council 1997) presented in the fourth column of Table 15. The total time is plotted in Figure 32 at a probability level of 50% as the solid line and at 80% level as the dashed.

Table 15. Average time from the moment the fire unit is notified until it is ready to start extinguishing actions in community centre located in Espoo.

Probability level [%]	**Turnout time [min]**	**Travel time [min]**	**Time from arrival until start of fire extinction [min]**	**Total [min]**
50	1.4	5.9	1.1	8.4
80	2.0	9.3	1.1	12.4

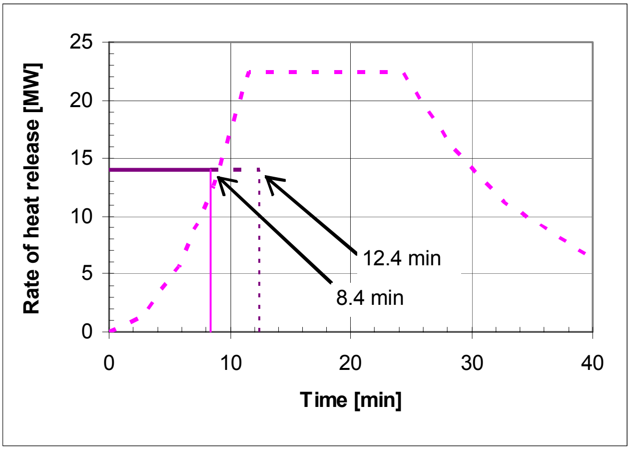


Figure 32. Rate of heat release of the design fire in the kiosk booth and response time of the first rescue unit.

Using Figure 32, the response time can be compared to the fire growth (Tillander & Keski-Rahkonen 2000a, b, 2001a). The results are also summarised in Table 16.

Table 16. Comparison of the fire department response time to the fire growth.

Fire department arrival probability	Time [min]	RHR [MW]
50%	8.4	12
80%	12.4	22

The average response time of the first unit is 8.4 min when the rate of heat release is 12 MW. With a probability of 0.8, the first unit is on the scene at earliest after 12.4 min. Then the rate of heat release has reached its maximum 22 MW. To be able to get control of the fire, the first unit should start extinguishing before the RHR reaches the critical value 15 MW.

Figure 32 shows that in this case the average response time fulfilled the condition and, on that basis, it maybe said that the fire department has a good chance to save the building. However, the detection time was excluded above. If the detection and thus the reporting of the fire are delayed, the total time grows and influences the results significantly. For example, a delay of only three minutes gives time to the fire to grow and reach its maximum rate of heat release 22 MW. Furthermore, the time from arrival until the fire fighting operation becomes effective can easily be prolonged from the estimated 1.1 min. All these prolongations decrease the chances of the fire department to successfully control and extinguish the fire. These elements should be reduced, therefore, to the lowest possible level with precautions such as improved fire detection and other actions.

6.7.3 Design example 2: Shopping centre

6.7.3.1 Description of the target building

The target building is a shopping centre located in Central Finland. Its fire compartment size is over 15 000 m^2. The basic information on the building is presented in Table 17.

Table 17. Basic information on the example building.

Building:	Shopping centre
Location:	Central Finland
Area [m^2]	15 000
Distance from the nearest fire station [km]:	3.1
Fire prevention systems in the lobby:	Automatic extinguishing system

The building is equipped with a sprinkler system and thus the fault tree in Figure 33 also includes the branch of the automatic extinguishing failure (Tillander & Keski-Rahkonen 2000a, 2001a).

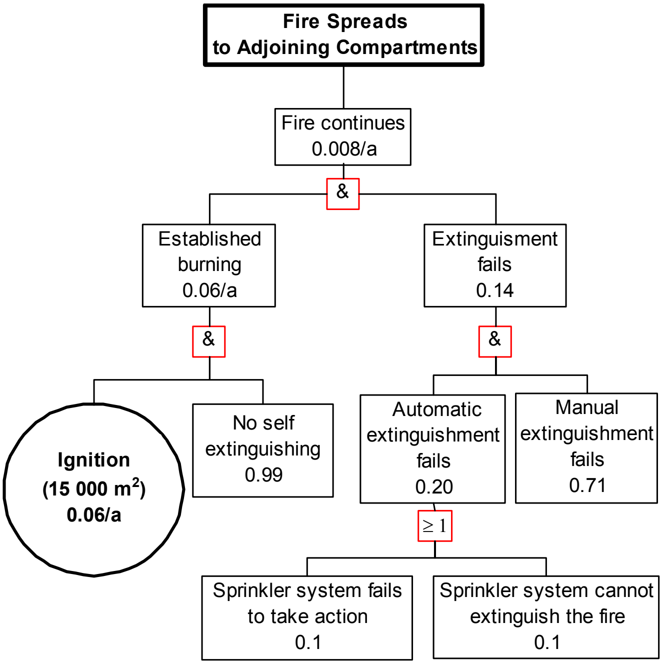


Figure 33. Fault tree of extinguishing failure of a fire in a shopping centre. The principle fault tree presented in CIB W14 Workshop (1983) is quantified and reformed to risk analysis tool (Tillander & Keski-Rahkonen 2000a, 2001a).

The fault-tree approach shows that the established burning is generated once in 17 years (1/0.06a) (Table 18) and the extinguishing failure with the established burning occurs once in 130 years (1/0.008a).

Table 18. Frequency of established burning.

Established burning [1/a]	Length of the life span [a]	Number of ignitions during the life span	Occurrence interval [a]
0.06	50	3	17

6.7.3.2 Design fire

The response times of the fire department were compared to the time scale set by the rate of heat release curve of the design fire, which was based on an Australian test (Bennets et al. 1998). This test illustrated a fire in a shoe storage shelves; it achieved a peak rate of heat release of 40 MW. This fire can be considered as one of the most severe design fires likely to be encountered in a shopping centre like this.

The time dependence of rate of heat release (RHR) after the sprinklers had activated was taken exponential following the experimental evidence of Madrzykowski and Vettori (1992) (Tillander & Keski-Rahkonen 2000a)

$$Q_c(t) = Q_{akt} \exp(-\frac{t}{435s}), \tag{31}$$

where Q_{act} was the value of RHR [MW] at the moment sprinklers activated and t the time from the moment of activation [s].

Sprinklers are not assumed to put out the fire but they are assumed to at least limit it. Until better statistical evidence is available, a model where RHR settles to 20% of the initial level is used following the Nordic guideline (Nordic Committee on Building Regulations, NKB Fire Safety Committee 1995). The fire growth is compared to the response time of the first unit in Figure 34. The higher heat release curve (circles) presents the unsprinkled circumstances, while the lower (triangles) the sprinkled.

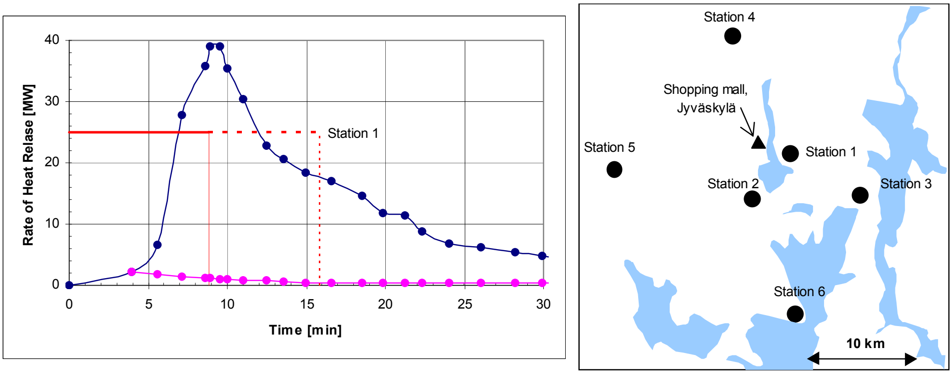


Figure 34. Rate of heat release of the design fire, and the response time of rescue unit starting from the closest station 1. Shopping centre is located in the Lake District of Finland. The routes are fractured by waters much more than could be inferred from the map. On the right are shown the approximate locations of example building and six of the nearest fire stations, shaded areas indicate lakes (Tillander & Keski-Rahkonen 2000a, b).

The rate of heat release achieves its peak value after nine minutes, and the first fire unit arrives at the scene with 50% probability after 8.9 min. With an 80% probability, the response time is 15.9 min. The critical rate of heat release, P_{cr} = 15 MW, is reached after 6.2 minutes. The results are also summarised in Table 19.

Table 19. Comparison of the fire department response time to the fire growth.

Fire department arrival probability	**Time [min]**	**RHR [MW]**
50%	8.9	P_{max} = 39
80%	15.9	$\geq P_{max}$

The example indicates that if the sprinklers operate, the fire remains small and local, and the fire department can extinguish it finally. In case the sprinklers do not operate, the fire department arrives at the scene probably slightly too late, as the rate of heat release has already achieved its maximum. At this phase, it is likely that the fire spreads from the ignition point to neighbouring shelves. Then the fire probably spreads very rapidly and it is unlikely that the fire department gains control of it. The delays discussed in the context of the first example would make the situation even worse for the fire department. Therefore, acceptability of the fire safety design of this building depends completely on the reliability of the sprinkler system.

6.8 Summary

The time distributions describing the operation of the fire department were determined. The skew nature of these distributions should be recognised when the performance of the rescue force is assessed. A simple travel time model was adapted for estimation of the travel times of the fire units with reasonable accuracy. The time distributions based on statistical data and the travel time model were used to estimate the fire department response times. Integrating the result with time-dependent fire growth, the probability that the first unit arrives at the scene in time to be able to get control of the fire can be estimated. In the presented technique, the response time of the first unit is compared to the time in which the chosen design fire reaches the specified critical value of RHR.

In areas with high alarm rates, the blocking probability is one factor limiting the success of the fire department operation. This effect was estimated despite the data available covering only fires in buildings. The number of all tasks was known but the shapes of the time distributions were unclear. When all operative duties of the fire department are taken into account, the alarm rate grows by an order of magnitude. However, the model is more sensitive to alarm rate changes than to changes in operating time and the real alarm rates can be accurately determined from the statistics. The analysis showed that the simultaneous calls are not too frequent and do not contribute much to the success probability of the rescue team. In a country with large area and small population, in most of the cases, the limiting factor is the response time.

The presented results indicate that the operation of the fire department can be evaluated with simple fault-tree technique. When the whole operative process is divided into separate operations and reformed to a fault tree, quantitative estimates of the success probability of the fire department operation can be made for a particular building anywhere in the country.

The use of the techniques to evaluate the performance of the fire department was demonstrated by three examples. The first illustration example was a simple demonstration of the fault-tree technique used in the evaluation process. The construction of the fault tree and the results obtained from it are greatly influenced by the presence and quality of the statistical information needed. The travel time turned out to be the most significant part in most cases in Finland. Hence, another approach, which compares the fire department response time to fire growth, was presented through two example calculations. The examples represent objects typical of those designed currently according to performance-based principles.

By comparing the risk of ignition and the possible consequences of fire in different areas of the building, the substantial premises were chosen for closer examination. In the community centre example, the ignition occurs at the chosen area once in the life span of the building. However, in case of an established fire, the fire department has a good chance to save the building. The situation is worse in the shopping centre, in which the ignition occurs once in seventeen years. In case of the extinguishing failure, the consequences are disastrous. The automatic extinguishing system failure is rare but, in this building, fire safety depends completely on its reliability. The examples showed the importance of rapid fire detection and the reliability of automatic extinguishing systems.

In the presented approach, the buildings in which the fire safety depends completely on automatic extinguishing systems can be distinguished from those in which the fire department is able to arrive at the fire scene early enough to have a good chance of saving the building. To make the task easier for the fire department, special attention must be paid to rapid fire detection and locating of the fire seat. Delays in these actions lengthen the total response time and reduce significantly the chances of the fire department successfully interfering with the progress of the fire.

The presented techniques can be used in risk assessment in performance-based design; a number of buildings have, in fact, been designed, approved by local authorities and constructed along these lines in Finland. In future, these models could build a theoretical basis on which some part of the operative performance of fire departments could be monitored and possibly assessed.

7. Consequences of fires

7.1 Economic fire losses

7.1.1 General

The main features of the first component of fire risk, i.e. ignition frequency, were considered in Section 5. The information concerning the other component, i.e. consequences has been previously restricted to fire deaths (Rahikainen 1998b, Rahikainen & Keski-Rahkonen 1998c, 1999a, b, 2001). Until now, detailed information on the economic losses has not been publicly available.

The available fire loss data covered fires in buildings in Finland during 1996–99. At first, the top down analysis method was adopted and the data analysed as one group. Later the data was divided into smaller groups as far as the statistical accuracy allowed. The analysis of losses of different building categories and fatal fires is published in Finnish in a series of VTT Research notes (Tillander et al. 2002b). The effect of the load-bearing member material is considered in an unpublished report by Tillander & Keski-Rahkonen.

The fire loss distribution is known to be skewed and can be described fairly well with a lognormal distribution. Here, a substantial amount of data was analysed and the first focus was the characteristic features of the fire loss in the middle part of the distribution. The data showed that at its tails the distribution differs considerably from lognormal. Variation at the lower tail could be regarded as statistical uncertainty. The upper tail of the distribution probably differs from lognormal systematically.

The behaviour and dependencies of the fire loss were examined and different statistical methods were applied to the data. The fire losses in buildings with different load-bearing structure materials were also compared.

7.1.2 Fire loss distribution

In the Finnish database, the losses are divided to three categories: building, property and consequential losses. The loss of the building includes the damages to building structures caused by fire, when the property loss indicates the damages to the movable belongings in the building. The loss caused when the normal operation in the building is interrupted because of the fire is called consequential loss.

Over half of the total sum of the fire losses was accumulated through damages to the building structures. The total fire loss in Finland during 1996–99 was 376 900 000 €, of which 14% covered consequential loss. The percentual division of the loss is presented in Figure 35.

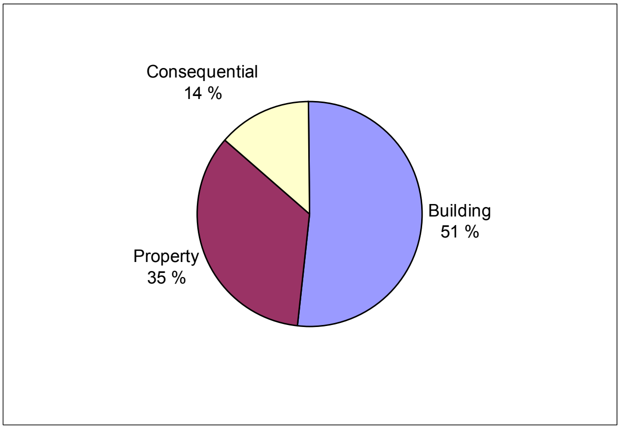


Figure 35. Percentual division of the total sum of the fire loss 1996–99.

Unfortunately, the data of consequential loss is not completely reliable. Most of it (86%) accrued in industrial buildings and warehouses in which the nature of the operation is such that the possibility of consequential loss is considerable and, in the case of residential buildings, it is seldom given.

Formerly, (Ramachandran 1979/80, 1982) verified that, except for the tails, the fire loss is well described with the lognormal distribution (density distribution presented in Section 2.3.4 (Equation (5)). Nevertheless, extensive data in the open literature is rare. The lognormal distribution was fitted to the cumulative distribution of the statistical observations of the total, property and consequential loss, in addition to loss of the building in Figure 36. On the basis of the visual estimation, the fit presented in Figure 36 seemed quite good, particularly in the central part of the distribution. However, differences between the distributions exist, which can be seen from the Figure 36 and on the basis of the large values of the chi-squares, which were for each fit (*df* = 17):

$$\chi^2_{total} = 126 \qquad \chi^2_{building} = 627$$

$$\chi^2_{property} = 579 \qquad \chi^2_{consequential} = 131$$

The chi-squared values were estimated on the assumption that if the loss is logarithmically distributed, the logarithm of loss must be normally distributed. Losses under 1 € were excluded. The required chi-squared value leading to a p-value under 0.05 would have been $\chi^2 = 28$.

The total loss in Figure 36 includes losses of the building and property in addition to the consequential loss. The shape of the distribution remained the same when the losses were considered individually. The fittings were carried out using Statistica.

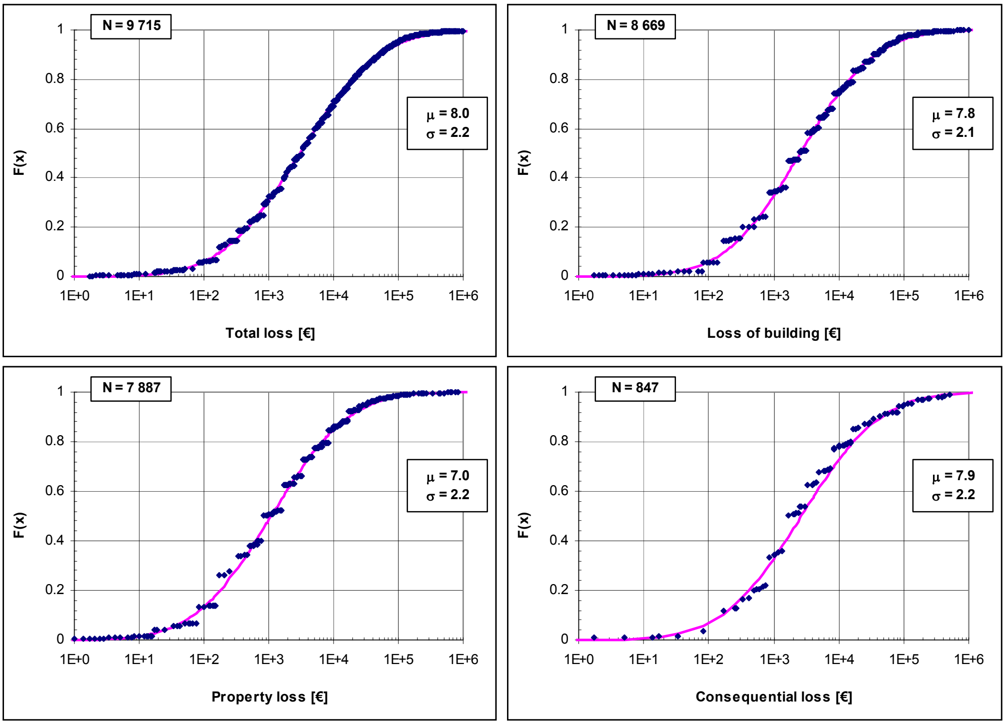


Figure 36. Cumulative fire losses in Finland during 1996–99 (dots) and lognormal distribution.

7.1.3 Value-at-risk

For every building fire, information on the value-at-risk of both the building and property involved in the fire is registered in the accident database. The value-at-risk is estimated by the fire officials concerned. In some regions, a guide by The Federation of Finnish Insurance Companies (2002) is used to estimate the value-at-risk on the basis of the floor area of the building. However, no nationwide regulations on the estimation exist; the quality of the data in the database is therefore dependent on the expertise and evaluation methods used by the individual evaluators. In general, in the building fires registered in the database, the value-at-risk comprises the value of the whole building instead of only the ignition compartment or the compartments the fire actually has threatened. In one-fire-compartment buildings, such as detached houses are simplistically said to be, this causes no problems. However, in fires in apartment houses, for example, the value-at-risk is the value of the whole apartment building, instead of just the ignition flat, floor or part of the building. This complicates the analysis in some parts, especially in the comparison of the results of different types of buildings. For most of the cases, the floor area, or the value-at-risk of the fire compartment, would be a more appropriate descriptor and should be added to the database.

In Figure 37 the data is divided into groups on the basis of the value-at-risk (building and property). The number of observations in each class were:

N_{V1} = 2 081 N_{V4} =563

N_{V2} =1 369 N_{V5} =1 156

N_{V3} =1 507 N_{V6} =242

N_{V7} =245

In Figure 37 the cumulative distribution of the observations is plotted together with the lognormal distribution, the parameters of which are presented in Table 20.

Table 20. Parameters of the lognormal distributions plotted in Figure 37.

Group	μ	σ
1	8.4	1.9
2	8.5	2.2
3	8.5	2.5
4	7.9	2.5
5	7.8	2.3
6	7.8	2.3
7	7.8	2.5

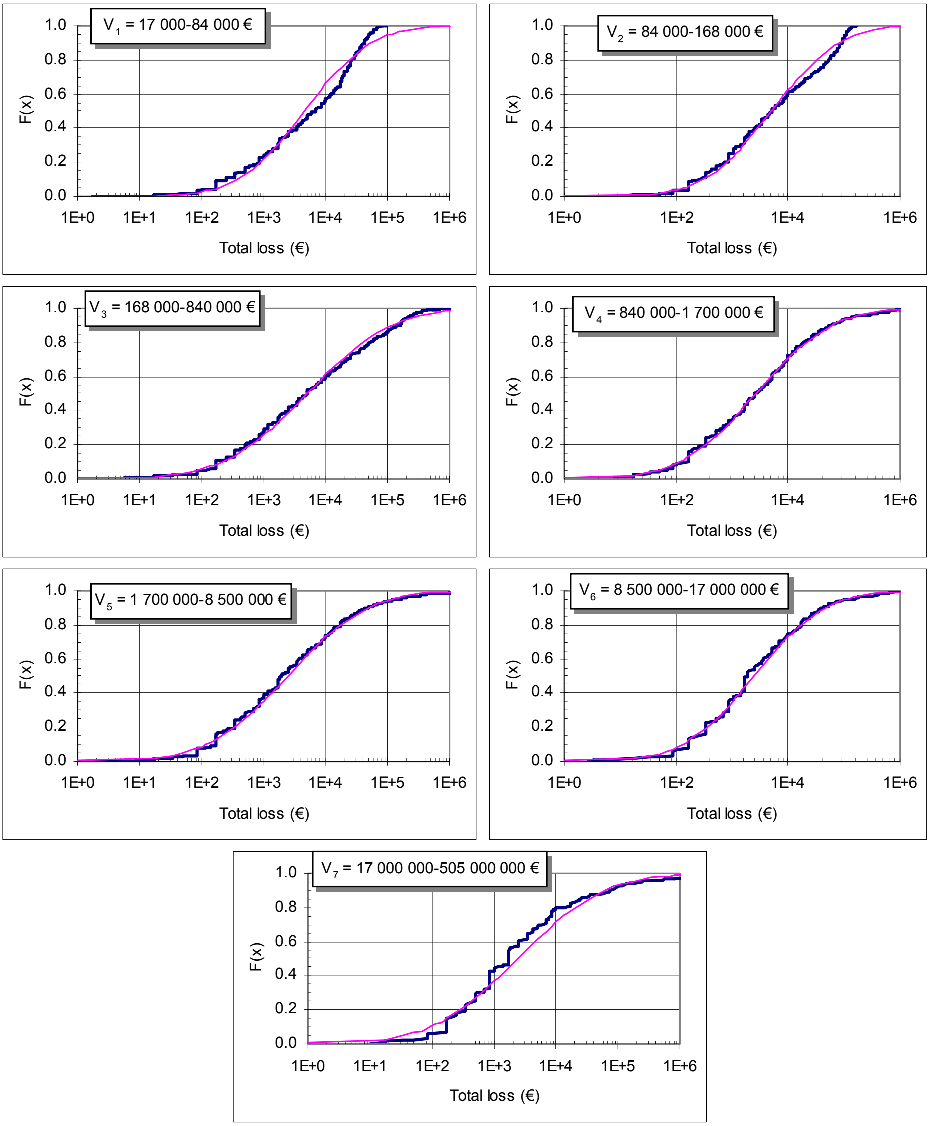


Figure 37. Cumulative distribution of the fire loss and the lognormal distribution (years 1996–99). Limits of the categories are labelled in each figure. Fitting was carried out using statistical software Statistica.

Figure 37 in addition to the values of the chi-squares showed that the fire-loss distributions, especially in groups V_1, V_2, V_3 and V_7, differed considerably from the lognormal, which gave a hint that the distribution of the fire loss was not necessarily unambiguously lognormal. The p-value of group V_4 was over 0.05

and the p-value of V_6 was close to it, which shows that the fit was quite good in these groups. The chi-squared values were estimated on the assumption that, if the loss is logarithmically distributed, the logarithm of loss must be normally distributed. The values for each of the groups were:

$\chi^2_{v1} = 361$; p-value = 0.0000

$\chi^2_{v2} = 166$; p-value = 0.0000

$\chi^2_{v3} = 88$; p-value = 0.0000

$\chi^2_{v4} = 16$; p-value = 0.2133

$\chi^2_{v5} = 53$; p-value = 0.0000

$\chi^2_{v6} = 26$; p-value = 0.02983

$\chi^2_{v7} = 86$; p-value = 0.0000

The deviation of the loss distribution at low and high values-at-risk probably reflects the population at risk. As that distribution including the total building stock was not available, it could only be determined for the burned buildings (See Figure 43).

In Figure 38, the burned buildings were divided according to their values-at-risk to find out the majority building types in each class. As can be seen from Figure 38, most of the buildings in classes V_1 and V_2 were residential buildings and mostly detached houses. In class V_3, all building types were equally represented. Apartment houses dominated the classes V_4 and V_5; industrial and storage in addition to group of other buildings, covered approximately 20% each. In class V_6, the share of both industrial buildings and warehouses and other buildings approached 40%; the share of apartment houses remained 25%. The class with largest values-at-risk was dominated by the industrial and storage buildings. The behaviour of the fire losses in different building types is considered in later sections.

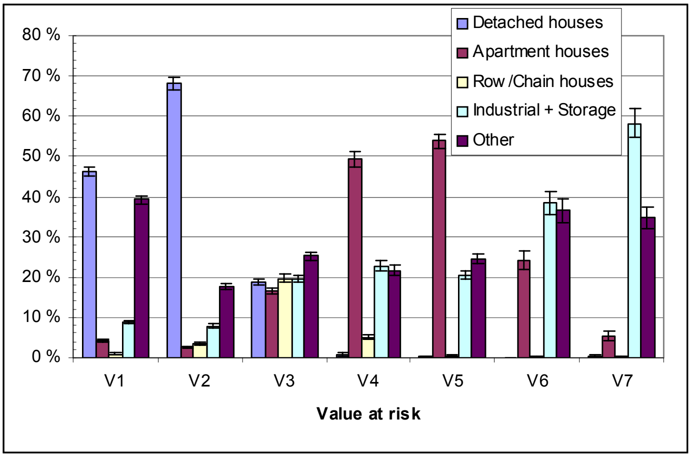


Figure 38. Division of different building types to seven classes of the value-at-risk.

7.1.4 Correlation between floor area and value-at-risk

In Figure 39, the observed values of loss of building and property are plotted as a function of the floor area. The values-at-risk are plotted respectively in Figure 40. The lowest frame presents the consequential loss, the value-at-risk of which is not estimated in the accident database.

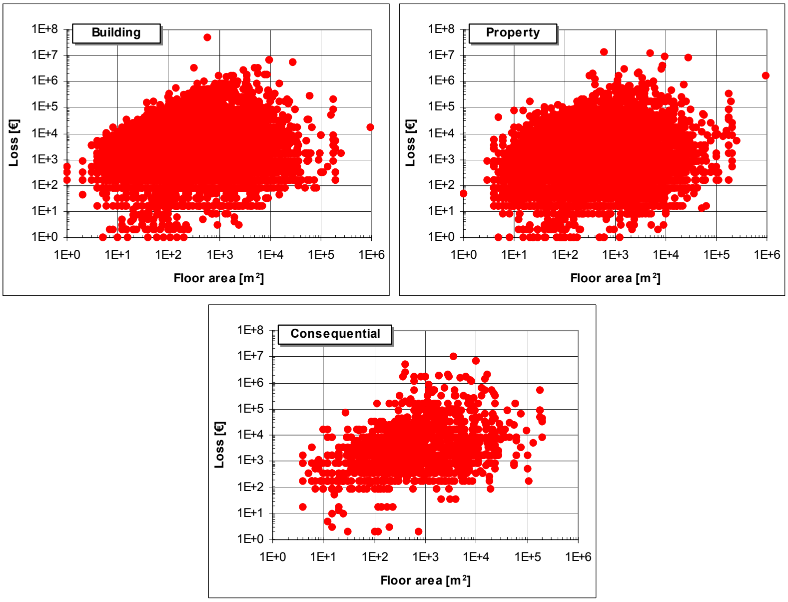


Figure 39. Losses of building and property and consequential loss as a function of the total floor area of the building during 1996–2001 (N_{total} = 16 752).

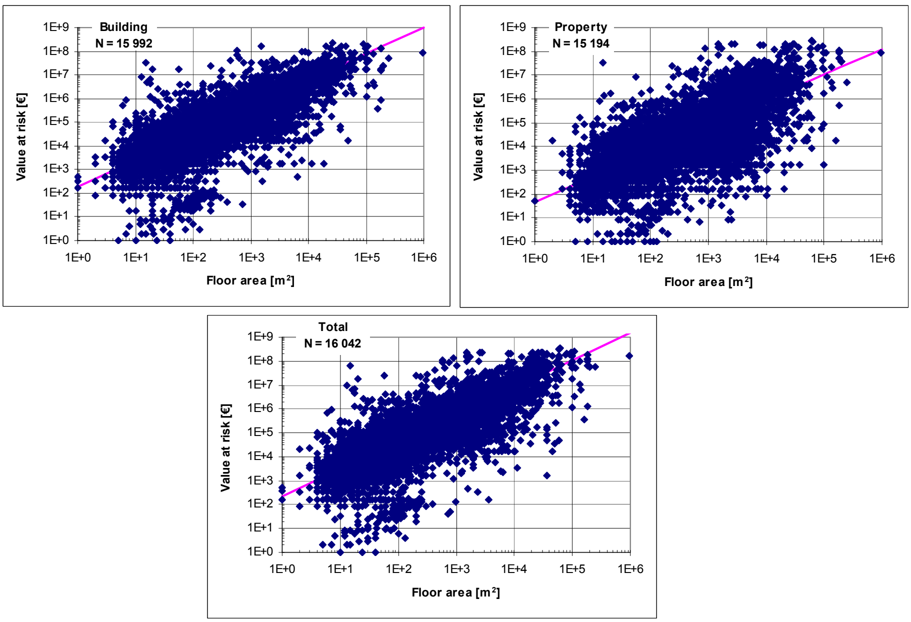


Figure 40. Value of building and property at risk as a function of the total floor area of the building (years 1996–2001).

In the accident database the value-at-risk is estimated by the fire officials. One basis of the estimate is floor area. Superficial examination of the data presented in Figure 40 showed that the dependency of the value-at-risk V [€] on the floor area of the building A [m^2] may be described with (Tillander et al. 2002b)

$$V = V_0 A^q \tag{32}$$

The fitting was carried out using Statistica. The values of the parameters are presented in Table 21 with the value of the proportion of the variance explained. The values of q were close to one, which also indicates that a straight line could be fitted to the observations. The power-law function in Equation (32), however, gave a somewhat better proportion of the variance explained. The p-values for all r-squared were under 0.05, which indicated that those were significant in each case. The fit of the function in Equation (32) is plotted in Figure 40.

Table 21. Values of parameters of Equation (32) and the proportion of the variance explained.

	q	**V_0**	**R^2 [%]**
Building	1.12	188	74
Property	1.07	48	57
Total	1.14	229	74

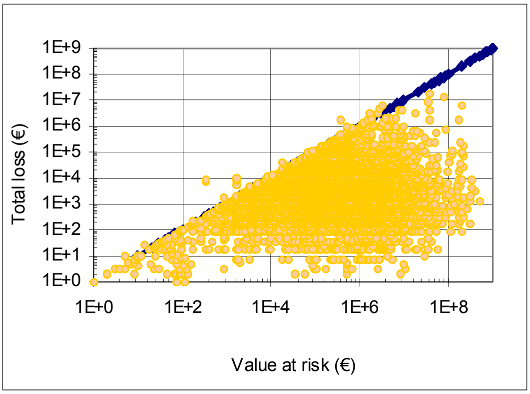


Figure 41. Total loss as a function of the value-at-risk.

The total loss is presented in Figure 41 as a function of the value-at-risk. On the solid line, the total loss and value-at-risk are equal. Occasional values of loss above the line are caused by the consequential losses, which are not included in value-at-risk.

7.1.5 Expected loss

The theoretical approach to estimate the expected loss by Ramachandran (1979/80, 1982, 1998) is presented briefly in Appendix D. The basic assumption of the theory is that the fire loss distribution $f(x)$ is lognormal. In Figure 42, the expected loss as a function of a) the value-at-risk and b) floor area is presented. Statistical observations are plotted as dots and a theoretical curve (Equation (58) in Appendix D) as a solid line. If the parameters of the lognormal distribution were determined from the fire loss data, the theoretical curve differed considerably from observations (Tillander et al. 2002b). By changing the lognormal distribution parameters, a better fit was obtained. The lower of the two theoretical curves was obtained with the lognormal distribution parameters determined from the loss data, while the higher curve was obtained with the parameters adjusted by minimising the residual sum of squares. For Figure 42a) the r-squared value improved from 0.41 (lower curve) to 0.98 (higher curve), when the largest value-at-risk category was excluded as the r-squared was determined and the higher curve fitted. For Figure 42b) the r-squared values were 0.60 (lower curve) and 0.87 (higher curve), when all floor area classes were included.

In Figure 42 b), the theoretical curve was at first determined as a function of the value-at-risk, which was then transformed to floor area by using Equation (32). No transformation was made to the observed values, the expected loss was determined straight from the data set.

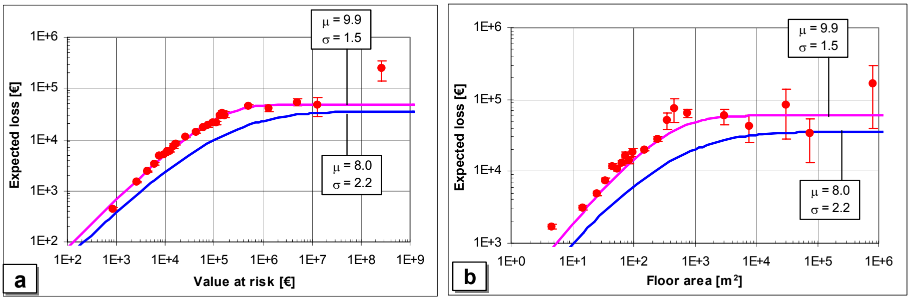


Figure 42. The expected loss during 1996–99 as a function of a) the value-at-risk and b) the total floor area of the building. The number of observations in figure a) was N = 9 314 and in b) N = 8 739. The used class intervals are presented in Appendix E in Table 42. The error bars represent the standard deviation of the mean (see Section 2.7).

The analysis showed that the model was capable of estimating the average loss in Finland (Tillander et al. 2002b). However, the problem was that the distribution of the value-at-risk of the total building stock was unknown. However, for burned buildings, it could be determined and is presented in Figure 43. Because the distribution of the total stock was not available, presumably the better result and parameters are obtained by fitting the model to the observations. The matter is discussed closer in Section 9.5.

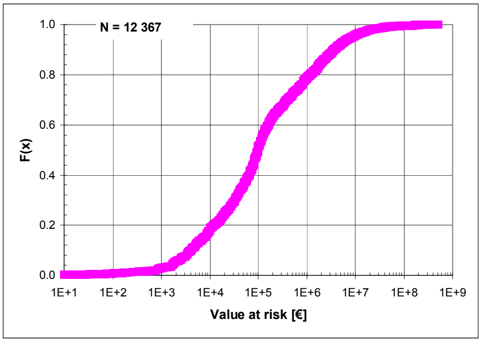


Figure 43. Cumulative distribution of the value-at-risk of the burned buildings (1996–99).

7.1.6 Loss probability

Furthermore, when the fire loss distribution is assumed lognormal, the probability of the loss amount exceeding x [€] can be determined following the theory of Ramachandran presented in Appendix D. In Figure 44, the probability curves with different values at risk V are plotted. The assumption of the theory is that the maximum loss cannot exceed the value-at-risk V. The numerical results in Figure 44 are preliminary but show that, after about 1 000 000 €, the increase of the value-at-risk does not affect to the probability of loss x.

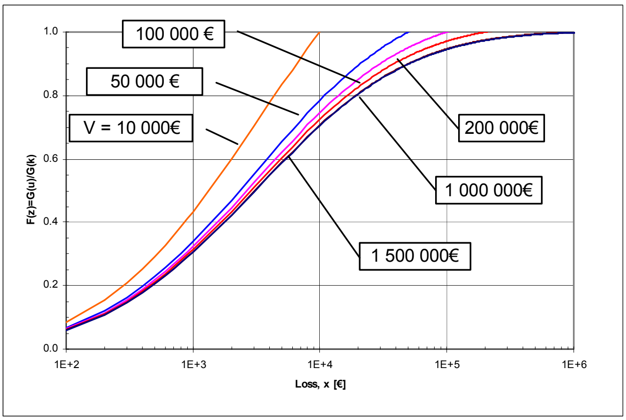


Figure 44. Probability of loss x with different values-at-risk V.

7.1.7 Building categories

7.1.7.1 General

In Figure 45, losses and values-at-risk between different building categories are compared. Figures 45 a) and c) show that the largest portion of the loss and the value-at-risk was associated with the industrial buildings. The portion of residential buildings was also quite large. Furthermore, on the basis of the visual observations of Figure 45 b) and d), the average loss is evidently larger in industrial buildings, compared to other categories.

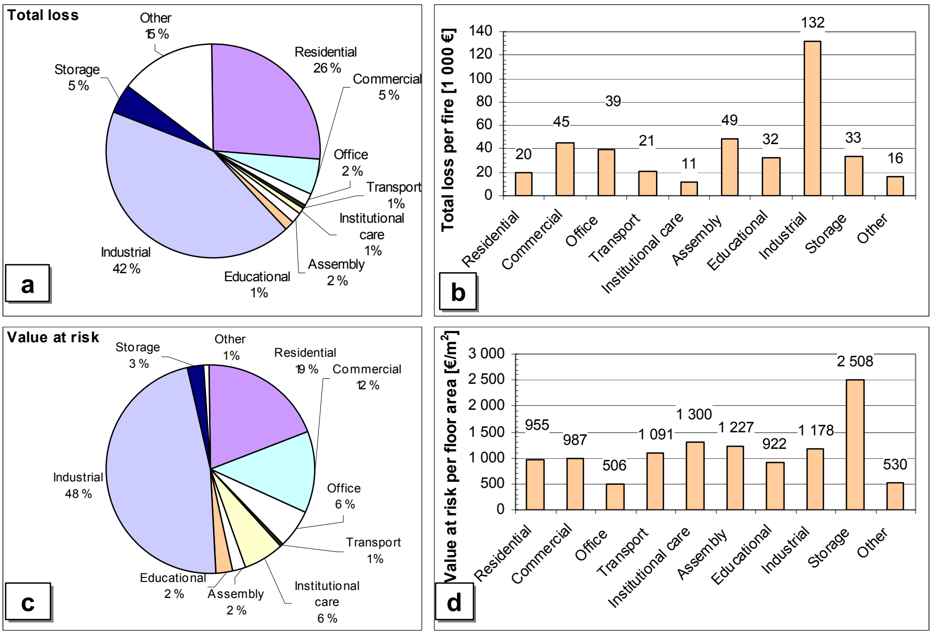


Figure 45. a) Percentual division of the total sum of fire loss between building categories, b) average loss per fire in different building categories (N_{total} = 8 754), c) percentual division of the value-at-risk and d) average value-at-risk per floor area in different building categories.

7.1.7.2 Three building groups

To obtain better statistical accuracy, the buildings were divided into three groups according to building category: 1) residential buildings, 2) industrial buildings and warehouses and 3) all other buildings, which included commercial, office, transport and fire fighting and rescue service buildings as well as buildings of institutional care, assembly, educational and other buildings (B, M and N).

The cumulative fire loss in different groups is presented in Figure 46. This figure shows that there were differences between the observed data and the lognormal distribution, especially in the upper tail of the distribution for residential buildings and in the middle part for industrial buildings and warehouses. The parameters of lognormal distributions were calculated from the observations and are presented in Table 22. Estimated visually, the fit seemed quite good in the group of all other buildings, in which the structure and features were the most heterogeneous of these three groups.

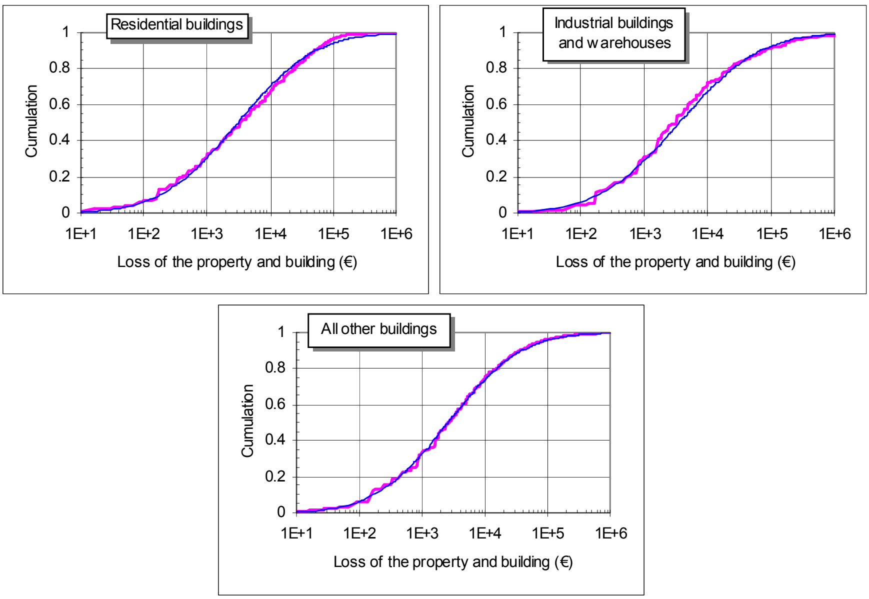


Figure 46. Cumulative distribution of the fire loss and the lognormal distribution in three different building categories ($N_{residential}$ = 4 165, $N_{ind+warehouses}$ = 1 371, N_{other} = 3 739).

Table 22. Parameters of the lognormal distributions plotted in Figure 46.

Building group	μ	σ
Residential buildings	8.0	2.2
Industrial buildings and warehouses	8.2	2.3
All other buildings	7.9	2.1

The goodness-of-fit was estimated using the chi-test. If the loss is assumed logarithmically distributed, then the logarithm of loss must be normally distributed. When the chi-values were calculated for the logarithm of loss and normal distribution, and the losses under 1 € ($N = 8$) were excluded, the values were:

		One distribution		**Sum of two distributions**	
	df	χ^2	**p-value**	χ^2	**p-value**
Residential	14	182	0.0000	39	0.0003
Industrial and warehouses	16	78	0.0000	48	0.0000
All other	14	52	0.0000	31	0.0052

The thought that the distribution of the fire loss could be more complex was strengthened further when the observations of residential buildings were divided into smaller groups by the value-at-risk. In cases of small values at risk especially, the distributions differed from lognormal considerably. The sum of the two lognormal distributions gave somewhat lower values of the chi-squares and thus a better fit to the statistical data in all groups. Because the finding of a perfect fit was not the main interest, more complex alternatives were not tried during this phase.

In Figure 47, the average loss of building and property is plotted as the function of the value-at-risk and floor area. Especially in the cases of large values-at-risk and floor areas, the amount of observations was rather small and thus the error bars grew quite large. However, the same kind of behaviour as in Figure 42 was detected; with small values, the loss increases and settles approximately to a constant level with large values. In Figure 47, an obvious ‘peak’ was also detected, especially in other buildings around floor area of 1 000 m^2 and, most distinctly, in residential buildings around floor area of 600 m^2.

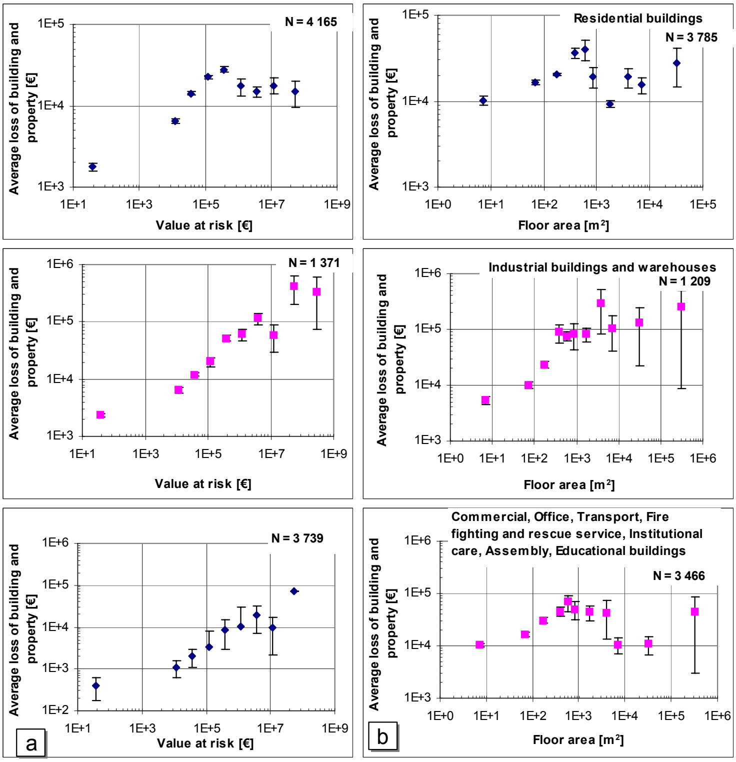


Figure 47. The average loss of building and property as a function of the a) value-at-risk and b) floor area in three building groups. The used class intervals are presented in Appendix E in Table 43 and Table 44. The error bars represent the standard deviation of the mean (see Section 2.7).

7.2 Effect of material of load-bearing structures on economic fire loss

7.2.1 General

To examine more closely the dependencies of the loss on the floor area and other features of the buildings, the effect of material of the load-bearing structure on the fire loss was considered. The data of building fires during 1996–2001 included 9 697 fires, in which the material of the load-bearing structure of a building was entered to the database. This was 50% of all building fires registered.

The percentual division of the building fires, number of buildings and the floor area in the building stock between different materials of load-bearing structures is presented in Figure 48. The information on the building stock was delivered by Statistics Finland. The category ‘other’ includes steel, brick, lightweight aggregate concrete and other materials. Lightweight concrete is included in the category ‘concrete’.

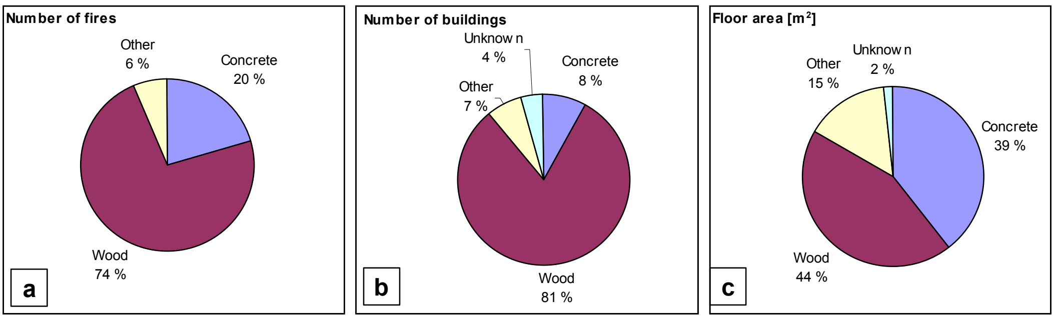


Figure 48. Percentual division of the structural fires picked out from Pronto, the number of buildings and the floor area of the building stock delivered by Statistics Finland.

As shown in Figure 48, the number of wood-framed buildings in Finland is greater in comparison to other materials of load-bearing structures. Naturally, also the number of ignitions in wood-framed buildings was the largest. However, Figure 48 shows the difference between the floor area distributions of wood and concrete-framed buildings. The 81% numerical share of wood-framed buildings covered only 44% of the total floor area of the building stock. The floor area portion of the concrete-framed buildings was almost equal to that.

In Figure 49, the buildings are grouped on the basis of their floor area. In this figure, a) the number of buildings and b) the total sum of the floor area in each group as a function of the floor area[2] is presented. The sizes of the floor area groups differ and thus Figure 49 does not represent the density distribution of the buildings. It was simply plotted to illustrate the division of different load-bearing structures in specific floor area classes.

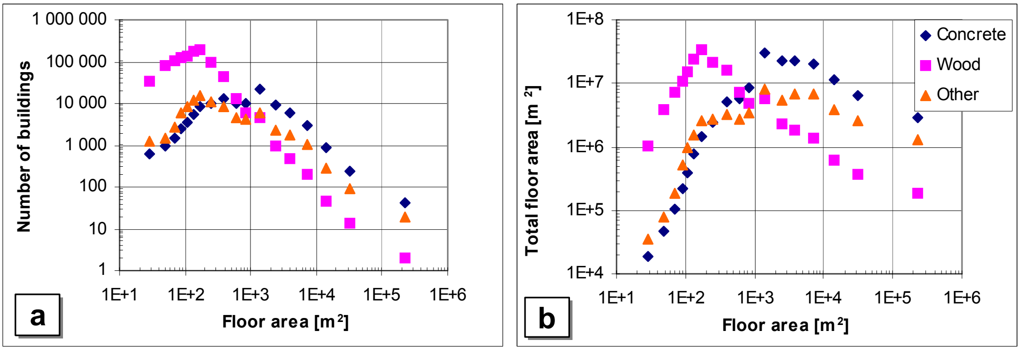


Figure 49. a) Number of buildings and b) total floor area as a function of the floor area. The sizes of the floor area classes are not equal, the class intervals are presented in Appendix E in Table 38.

Figure 49 shows that with small floor areas wood framed-buildings were dominant. In the case of buildings with a floor area of about 600 m^2, the difference between wood-framed and concrete-framed buildings was very small. With larger floor areas, the number of concrete-framed buildings, in addition to their sum of the floor area was the greatest.

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[2] Based on electronic data on building stock on 31.12.1999 delivered by Statistics Finland.

The average loss and value-at-risk per fire and floor area is presented in Figure 50. Because the data included all buildings, their size and use may substantially vary from one building to another. As the group was in many ways non-homogeneous, the comparison of the average values must be made carefully. The error bars plotted in Figure 50 represent the standard error of mean. No statistical tests were carried out to compare the differences but as Figure 50 a) shows that the values of average loss were at the same level beyond the error bars. Because of the different types of floor area distributions, the differences in the value-at-risk per fire grew large in Figure 50 b) and Figure 50 c).

Figure 49 shows that the concrete-framed buildings are, in general, much larger compared to wood-framed, and so their combined floor area is considerably larger. The average loss per floor area is therefore not useful in measuring the differences. The value-at-risk per floor area in Figure 50 d) is at the same level in concrete- and wood-framed buildings. With other materials, the value is lower.

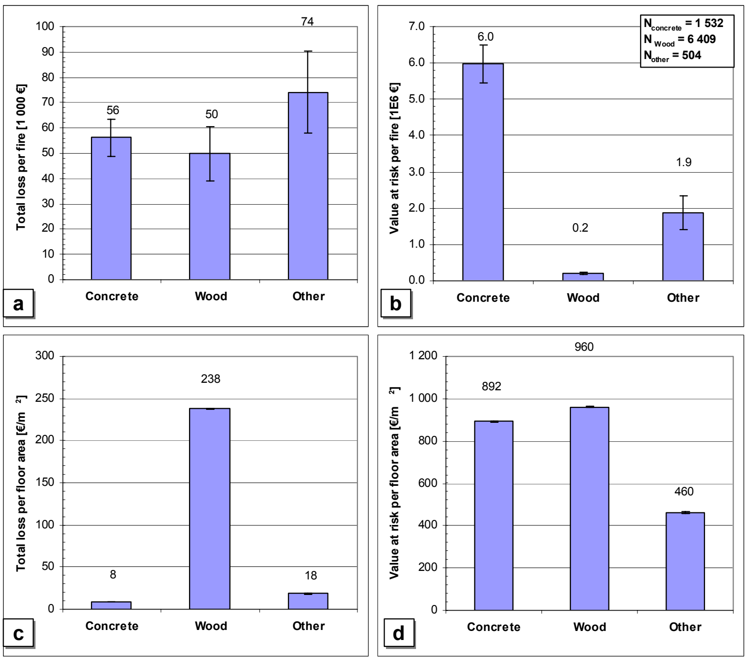

Figure 50. a) Average loss per fire, b) average value-at-risk per fire, c) average loss per floor area, d) average value-at-risk per floor area. The error bars represent the standard deviation of the mean.

7.2.2 Dependency on the floor area

To get a better view of the actual differences between the materials, the values were determined as a function of the floor area. In Figure 51 a) the cumulative fire loss distribution of buildings with different load -bearing structures is presented. The differences were analysed using Kruskal-Wallis Test, which was carried out using Statistix. The results are presented in Appendix F. The Figure 51 a) showed that the differences between materials were rather small. However, the Kruskal-Wallis test showed that the loss of concrete-framed buildings was lower compared to others.

Figure 51 b) shows large differences between the values-at-risk and, on the basis of the Kruskal-Wallis test, the differences between the materials were significant. The ratio of medians of the value-at-risk of concrete- and wood-framed buildings is 40.

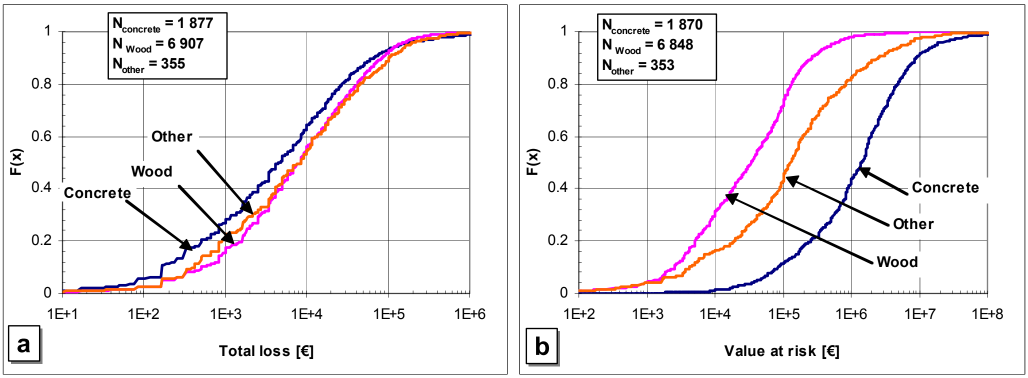

Figure 51. Cumulative distributions of the fire loss and value-at-risk of buildings with different load-bearing structures.

The large differences between the sizes of the buildings distort the result shown in Figure 50. The differences decreased, as the observations were divided into groups on the basis of the floor area in Figure 52.

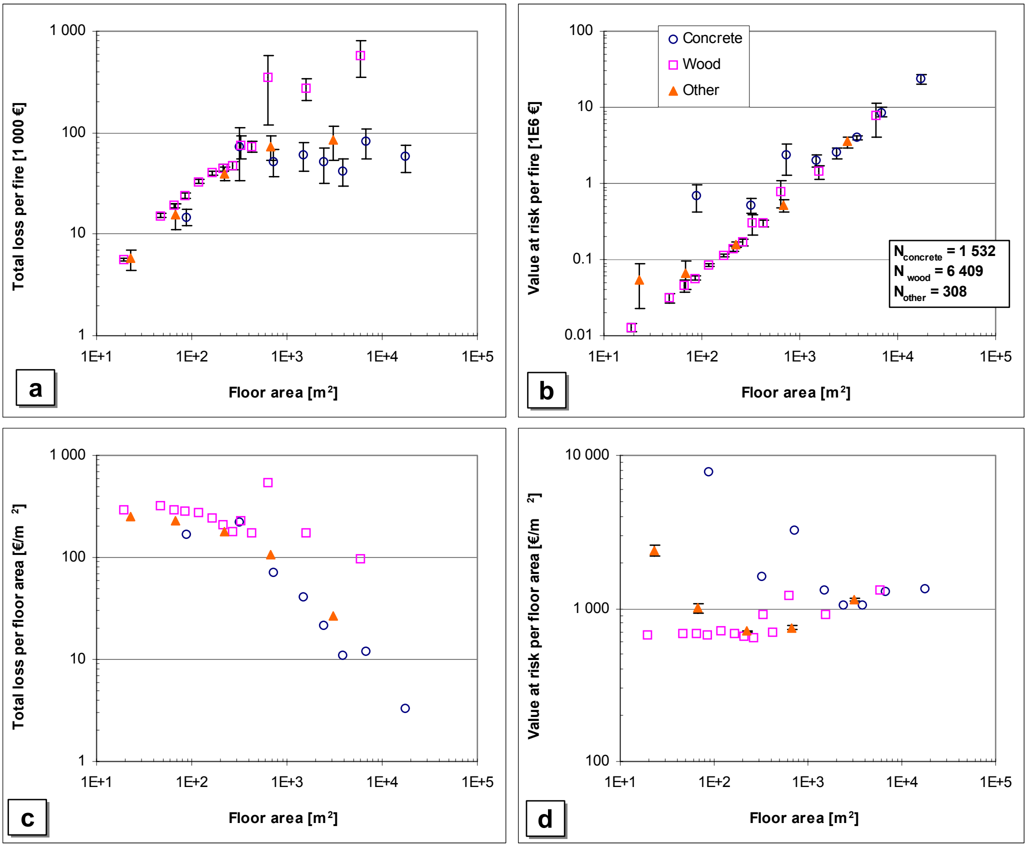

Figure 52. a) Average loss per fire, b) average value-at-risk per fire, c) average loss per floor area, d) average value-at-risk per floor area. The used class intervals are presented in Appendix E in Table 45. The error bars represent the standard deviation of the mean (see Section 2.7).

Because of the limited number of observations, the class division was not very dense. Due to the small number of fires in steel-framed buildings, they were excluded from the analysis. In spite of the sparse classification, it may be seen in Figure 52 a) that the average loss per fire increased as a function of the floor area up to 600 m^2. After that, it remained constant. The value-at-risk shown in Figure 52 b) increased steeply as a function of the floor area. When the loss is normalised by the floor area, the value of the wood-framed buildings remained at around same level, while the value of concrete-framed and other materials started to decrease after about 500–600 m^2. The value-at-risk per floor area in wood-framed buildings remained at the same level until after 500 m^2, when a slight increase was observed. In concrete-framed buildings it settled to a constant value around floor area of 1 000 m^2.

7.3 Residential buildings

7.3.1 Residential building types

To get a clearer view of the area dependency of the loss, the residential buildings were considered more closely (Tillander et al. 2002b). They were the largest and most homogeneous group and could be logically divided further into apartment, row and detached houses. In Figure 53, the structure of the Finnish building stock is presented. Of residential buildings, 89% were detached houses, 6% row or chain houses and 5% apartment houses. Associated with the detached houses was 54% of the total floor area, to the row and chain houses 12% and to apartment houses 34%. Of building fires, 64% occurred in detached houses during the observed time, 10% in row and chain houses and 26% in apartment houses. The fire-loss data showed that the floor area of detached houses where the fire had ignited were under 1 000 m^2, whereas 80% of apartment houses were over 1 000 m^2. The floor area distribution of ignited residential buildings is presented in Figure 54b) and the cumulative distributions of loss in these three categories in Figure 54a). The differences between the building types were analysed with the Kruskal-Wallis test and the results are presented in Appendix F.

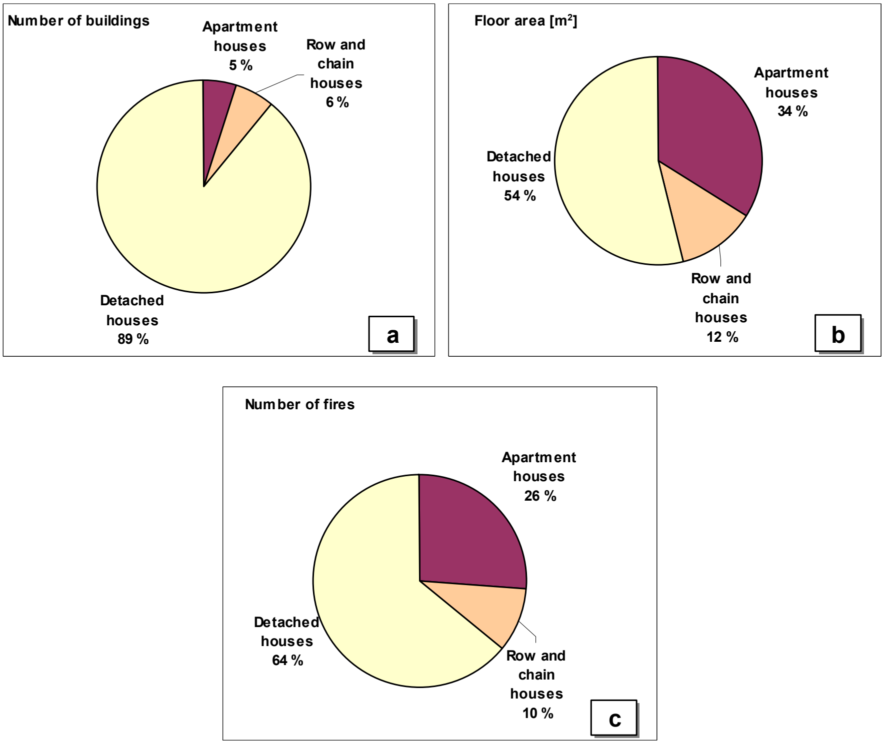

Figure 53. Percentual division of a) number and b) floor area of residential buildings c) number of fires in residential buildings.

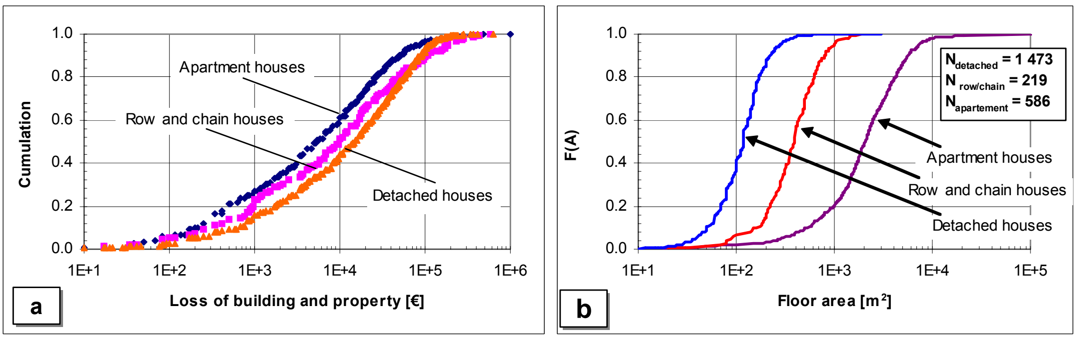

Figure 54. The cumulative loss of building and property in different residential building categories.

In Figure 55, the average loss in different types of residential buildings is plotted. In detached houses, the average loss appears to be growing quite steeply as a function of the floor area. In apartment houses, the growth appears to be substantially slower, remaining almost at constant value. The number of observations in row and chain houses was too small for detailed conclusions. With the data available, the loss seems to remain at the same level beyond the error bars. The loss values of apartment and row houses were a little lower than the peak value of the detached houses. A rough conclusion from this is that the residential buildings form two groups, small, detached houses where the average loss grows steeply as a function of the floor area. These buildings dominate the first part of the floor area distribution of all residential buildings. Around 600 m^2 the dominant group shifts to apartment houses. Simultaneously, the average loss drops a little, the area-dependent growth settles down and remains nearly constant after that. This causes the ’peak’ of average loss to occur around 600 m^2 floor area in residential buildings. The reason for the behaviour of the average loss in different types of residential buildings is presumably that, in general, the detached houses form one fire compartment in which the fire can spread quite freely. In apartment houses, the fire usually remains only in one flat (i.e. in one fire compartment). So, the area dependence is not that significant and the average losses are approximately at the same level in every case regardless of the whole area of the apartment house.

It would be logical to examine the behaviour further and to plot the fire losses as a function of the fire compartment area. Unfortunately, such data on buildings with multiple fire compartments was not available at the time. The data set included information on compartment size only with very coarse class division, which was too inaccurate for more detailed study.

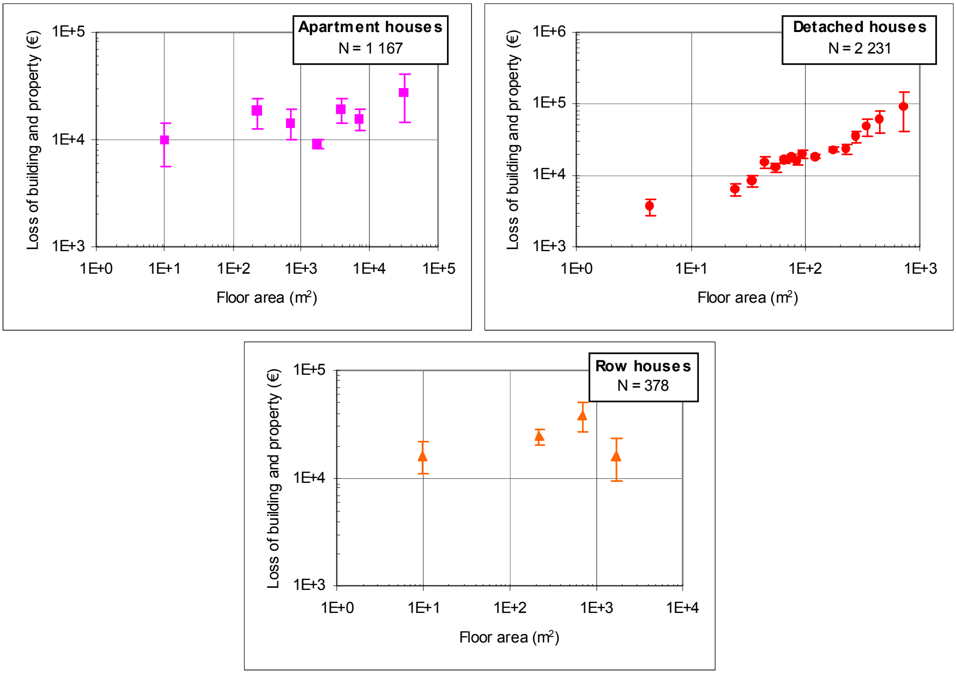

Figure 55. The average loss of building and property as a function of the floor area in three different residential building categories. The used class intervals are presented in Appendix E in Table 46. The error bars represent the standard deviation of the mean (see Section 2.7).

7.3.2 Materials of load-bearing structures

The explanation of the peak that appears in observations of the residential buildings around floor area of 600 m^2 in Figure 47 was found to lie in the differences between the features of the residential building types. Here the materials of the load-bearing structures of residential buildings were studied in relation to the building type. In Figure 56, the percentual division of building fires and number of buildings in the building stock between different materials of the load-bearing structures in apartment, row and chain and detached houses is presented. All building fires are included in Figure 56. However, as mentioned in Section 7.2.1, the material of the load-bearing member was registered in the accident database in only 50% of all cases of building fires. The proportion of unknowns is therefore quite large in Figure 56.

Figure 56 shows that most apartment houses are concrete framed while most row, chain and detached houses are wood framed. The building fires were similarly distributed. Thus, a rough generalization is that in Figure 55 apartment houses correspond to concrete buildings and detached, row and chain houses to wood-framed buildings.

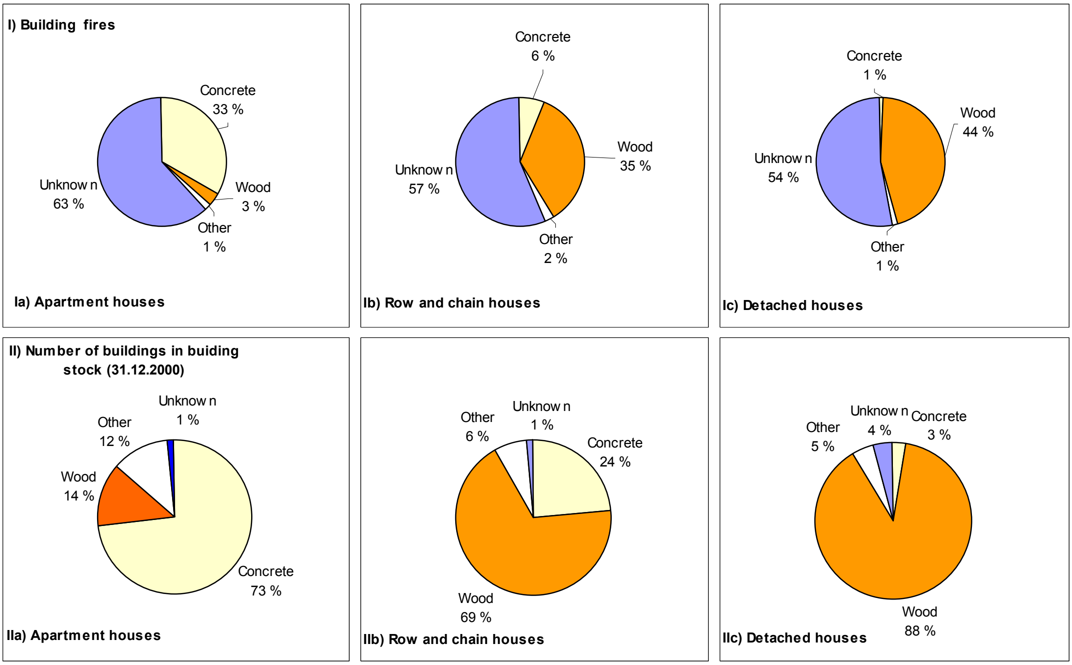

Figure 56. I a)–c) Percentual division of the building fires and II a)–c)number of buildings in the building stock between different load-bearing structure materials in apartment, row and chain and detached houses.

The distribution in Figure 56 supported the assumption that the division based on load-bearing structure material is not necessarily appropriate and the other features of the building can be as, or even more, dominant. Thus, the problem reverts to the subject of the different building types. The residential building groups were therefore divided further by type and load-bearing structure.

In Figure 57, the cumulative distributions of fire loss and value-at-risk in apartment and detached houses are presented. The differences between the values at risk seemed smaller compared to the difference shown in Figure 51. The ratio of medians of concrete- and wood-framed houses was 6 in apartment and 2 in detached houses. The differences between the materials were analysed with the Kruskal-Wallis test and the results are presented in Appendix F.

On the basis of Figure 57, the losses in wood-framed buildings seem larger compared to other materials in both residential building types. On the basis of the Kruskal-Wallis Test, in apartment houses, the difference between concrete and wood-framed buildings was significant. In detached houses, the losses of wood-framed buildings were larger compared to those of other materials.

In both residential building types, the value-at-risk of wood-framed buildings was significantly larger compared to those of other materials.

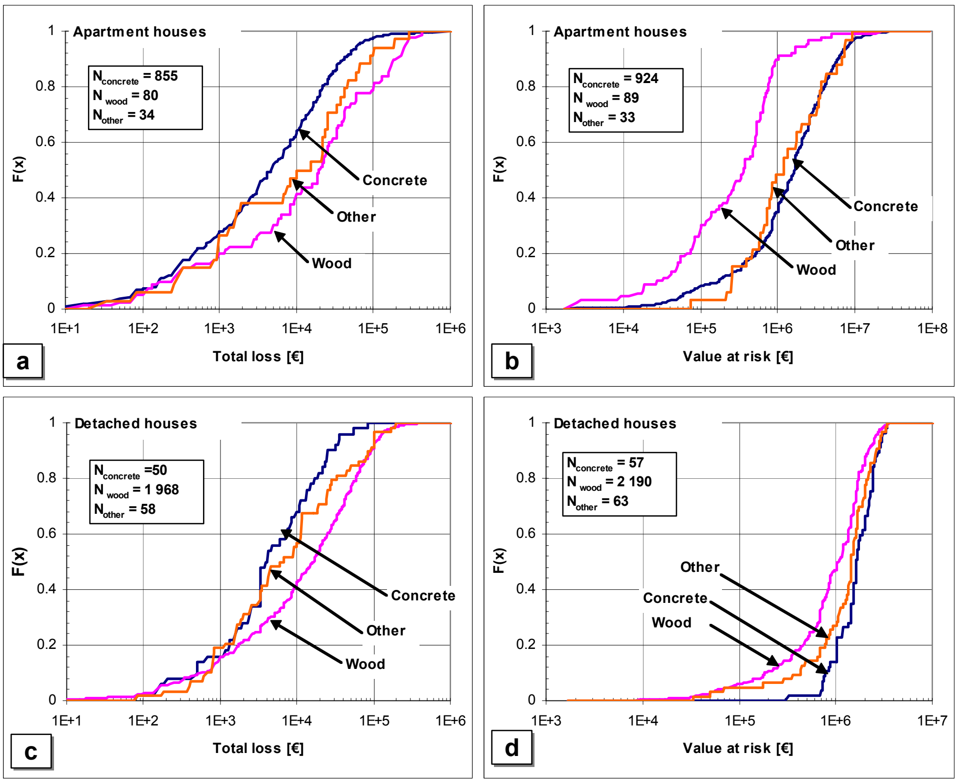

Figure 57. Cumulative distributions of a) total loss and b) value-at-risk in apartment houses and c) total loss and d) value-at-risk in detached houses.

7.3.3 Damage degree

The damage degree is the ratio of the fire loss and value-at-risk. It is known to decrease as a function of the size of the building (Berge 1937, Eklund 1932). Here, the effect of the material of the load-bearing structure on the mean damage degree was examined. In Figure 58, the mean damage degree as a function of the floor area is shown. In Figure 58, all building categories were included.

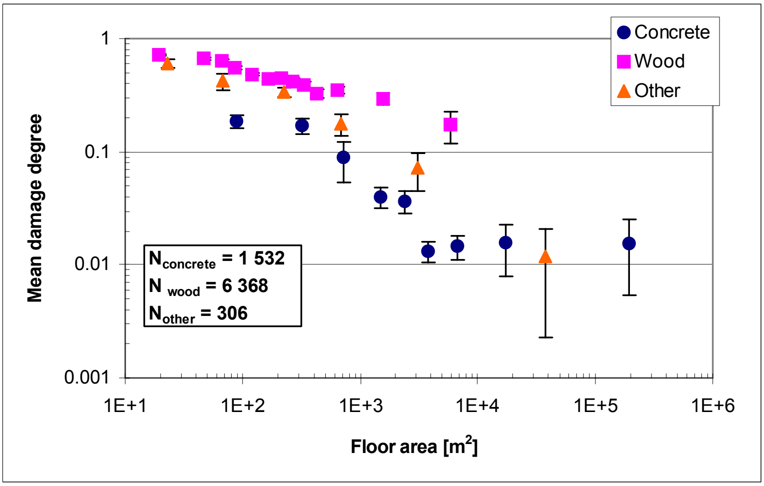

Figure 58. Mean damage degree as a function of the floor area in all building categories. The used class intervals are presented in Appendix E in Table 47. The error bars represent the standard deviation of the mean (see Section 2.7).

Figure 58 shows that in concrete-framed buildings the decrease of the mean damage degree settled to a constant level with large floor areas, when with other materials it continued to decrease. Based on Figure 58, it seems that the mean damage degree was higher in wood-framed buildings compared to other load-bearing structure materials. However, the categorisation in Figure 58 is not at all homogeneous because all building categories were included. Therefore, only residential buildings were considered when the phenomenon was examined in detail. The number of observations and buildings of this type are the largest and the type of use very similar.

Detached and apartment houses were considered separately due to the different estimation of the value-at-risk. As mentioned before, the value-at-risk comprises the value of the whole building also in apartment houses, instead of just the flat or flats the fire actually has threatened. The separation of detached and apartment houses to individual groups decreased the number of observations and so the level of uncertainty grew large. However, the groups were as homogeneous as possible, which was essential in order to make the results comparable. Row and chain houses were excluded from the analysis because of the small number of observations. In Figure 59, the mean damage degree in apartment and detached houses with different load-bearing structure materials is presented.

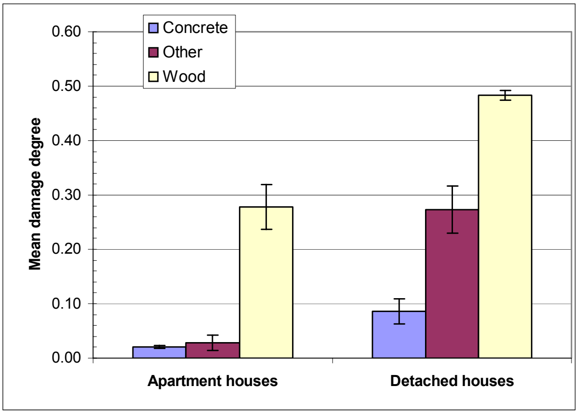

Figure 59. Mean damage degree in apartment and detached houses. The numbers of observations are similar to Figure 60. The error bars represent the standard deviation of the mean (see Section 2.7).

The differences between materials were analysed using statistical software Statistix. The results of the used Kruskal-Wallis tests are presented in Appendix F. As the analysis showed and can also be seen from Figure 59, the mean damage degree was higher in wood-framed buildings. The difference between concrete and other materials was not as significant.

The difference between different materials in apartment houses is partly explained by the different floor area distributions shown in Figure 60. It showed that the wood-framed apartment houses are generally smaller compared to others, which was confirmed also by the Kruskal-Wallis Test (Appendix F). Because the value-at-risk in the accident database is the value of the whole building, but the fire is usually limited only to one apartment, this leads to a lower damage degree in large apartment houses. However, the floor area distributions of the detached houses were more similar, while the mean damage degree of wood-framed houses remained higher. Although the floor area distributions of detached houses in Figure 60 are close to each other, the Kruskal-Wallis Test showed that the difference between wood-framed houses and other materials was nevertheless significant.

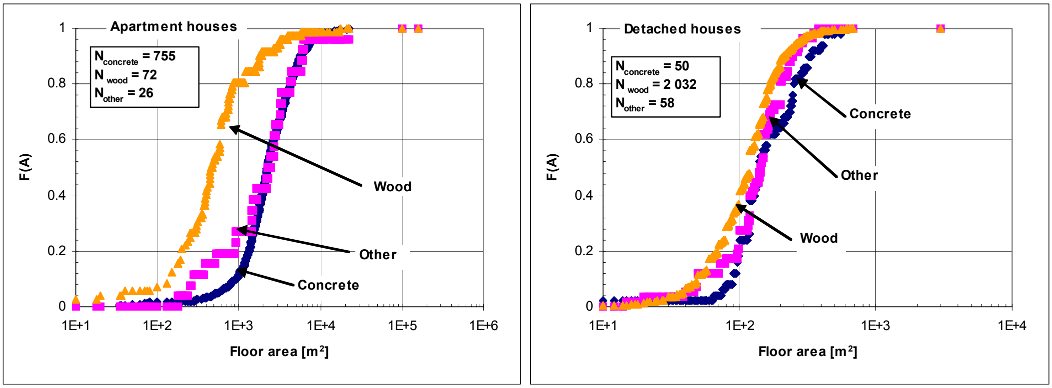

Figure 60. Floor area distributions of apartment and detached houses.

Figure 61 shows that the fire spread wider more often in wood-framed buildings compared to other material framed buildings. The differences between materials were analysed using statistical software Statistix. The results of the used Kruskal-Wallis tests are presented in Appendix F. Figure 61 included all buildings, but for apartment and detached houses the trend was the same. Because the level of uncertainty grew rather large, that is not presented here. The wider spread is probably one of the reasons for the higher damage degree in wood-framed buildings and for the larger losses seen in Figure 57. Furthermore, Figure 62 shows that in wood-framed buildings the surface layer of the flat in most of the fires boosted the fire rather than slowed it down and vice versa in concrete-framed buildings. These observations at least partly explain the differences between materials but, unfortunately, the other possible reasons behind the wider spread of the fire could not be examined in detail with the data available.

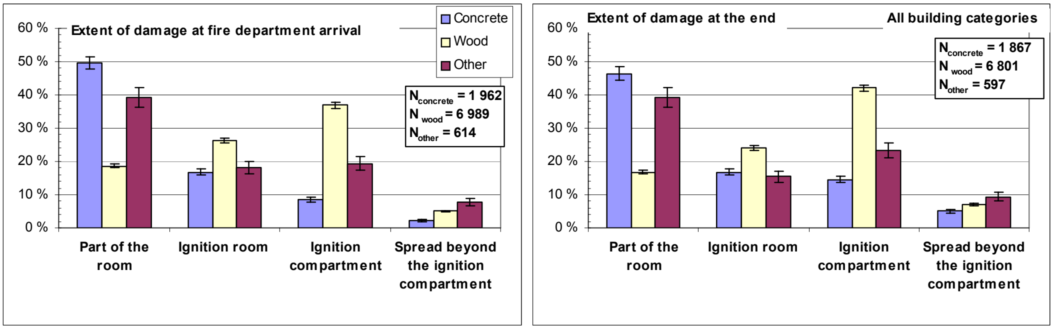

Figure 61. Extent of damage at fire department arrival and at the end. The error bars represent the uncertainty due to the number of observations of each data point (see Section 2.7).

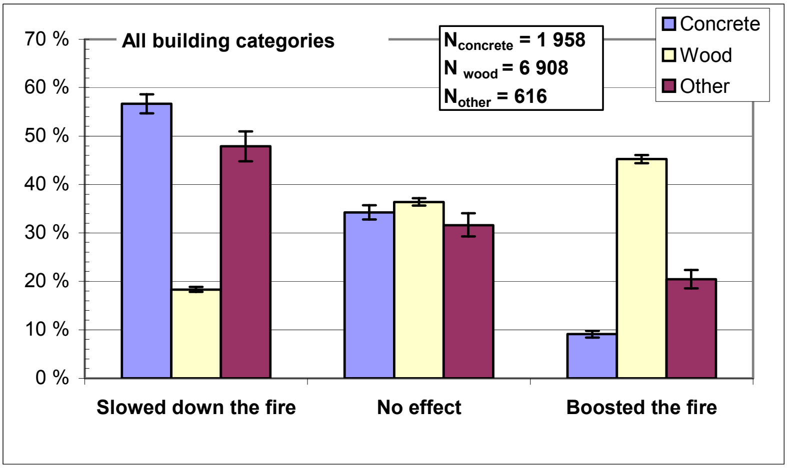

Figure 62. The effect of the surface layer of the ignition flat to the fire. The error bars represent the uncertainty due to the number of observations of each data point (see Section 2.7).

7.4 All other buildings

7.4.1 Material of the load-bearing structure

Category 'all other buildings' includes commercial, office, transport, fire fighting and rescue service, assembly, educational and other buildings, in addition to buildings for institutional care. Following the same approach as in the residential category, the buildings were divided into groups by the material of the load-bearing structure. In Figure 63, the average loss in concrete- and wood-framed buildings, the two largest groups, is presented. Regardless of the large standard deviation of the mean values in Figure 63 a), the same kind of behaviour as in residential houses was discovered. The material of the load-bearing structure of large houses was concrete, in which the average loss increased slowly as a function of the size of the building levelling off almost to a constant value with large floor areas. The behaviour is similar to apartment houses. The floor area of wood-framed buildings was, in general, under 1 000 m^2, while the average loss increased steeply as a function of the size of the building, which is similar to the behaviour of the loss in detached houses.

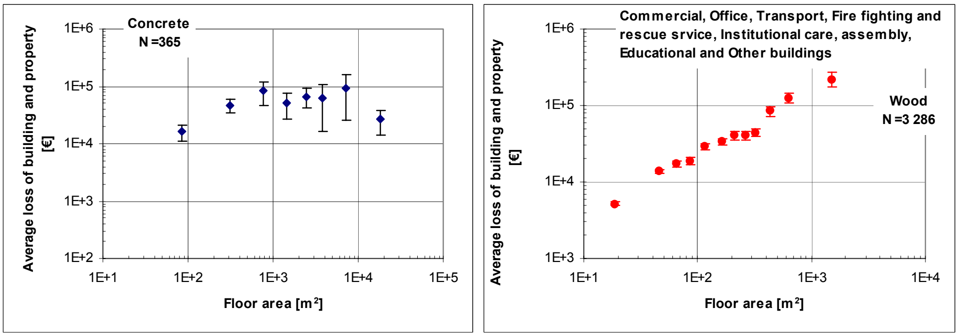

Figure 63. Average loss of building and property as a function of the floor area in 'all other buildings'. The used class intervals are presented in Appendix E in Table 48. The error bars represent the standard deviation of the mean (see Section 2.7).

The explanation of the 'peak' of loss seemed to be similar to residential buildings. However, in both cases it turned out that the main issue was not the material of the load-bearing member but the features of the buildings such as different methods of compartmentation or usages.

7.5 Fire deaths

7.5.1 General

Because of the small number of observations on fire deaths, no statistical tests to compare the differences in this section were carried out and the results were interpreted on the basis of the error bars. A difference exceeding three deviations (one error bar represents one deviation) was set as the criterion for a significant difference.

7.5.2 Financial losses in fatal fires

The fire deaths are the most important measure of fire safety and should be included in fire-risk determination. A recent study on fire deaths in Finland (Rahikainen 1998b, Rahikainen & Keski-Rahkonen 2001) quantifies the major characteristics of human loss. However, in that study, the fire loss data was not available. Here, the economic losses in fatal fires were compared to losses of all building fires (Tillander et al. 2002b). The used data on fire deaths was not complete, covering 67% of all fire deaths during 1996–2001. The data was collected by combining the information on the accident database Pronto and the fire death statistics updated by the Finnish Fire Protection Association (SPEK 2001). Here, only deaths in buildings were included; deaths in fires occurring in cars, boats and trash containers were excluded. The real coverage was therefore somewhat higher than 67%. For instance, during 1999–2001, 10% of fire deaths occurred in places other than buildings. In Figure 64a), the cumulative distributions of fire loss in fatal fires and all building fires are plotted. Because 86% of fire deaths took place in residential buildings, that cumulative loss distribution was also plotted in Figure 64. The sizes of the data sets are given in inserts in Figure 64.

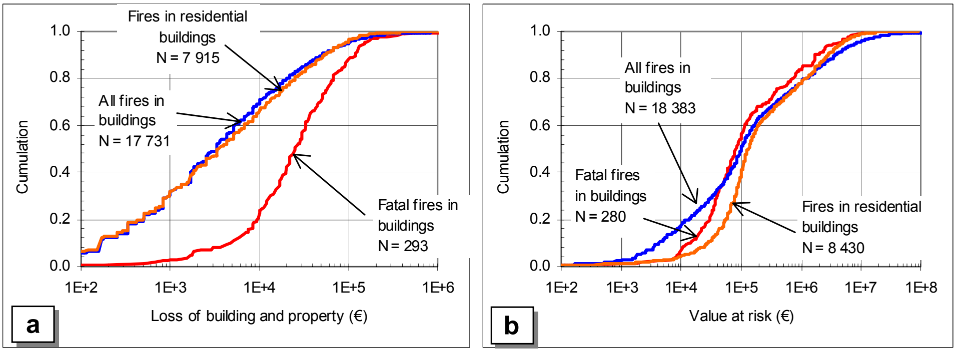

Figure 64. a) Cumulative distribution of loss of building and property and b) value-at-risk in all building fires, fires in residential buildings and fatal fires.

The cumulative distributions showed that the loss was generally larger in fatal fires compared to all or residential building fires. No major differences were observed between the distributions of the value-at-risk in Figure 64 b). The analysis pointed out the same fact as detected in the earlier study (Rahikainen 1998b, Rahikainen & Keski-Rahkonen 2001), i.e. that the fatal fires have spread wider than average fires when the fire department arrives at the scene. The analysis showed that this is not a result of delay in the fire department's arrival, because the response time distributions were similar in fatal and all building fires.

7.5.3 Average frequency of fire death

In Figure 65, the percentual share of fires involving deaths in all structural fires during 1996–2001 is presented. As can be seen, the fire deaths occur generally in residential buildings. The differences between the different load-bearing structure materials or residential building categories did not exceed three deviations, which in this context was assumed as a criterion for a significant difference.

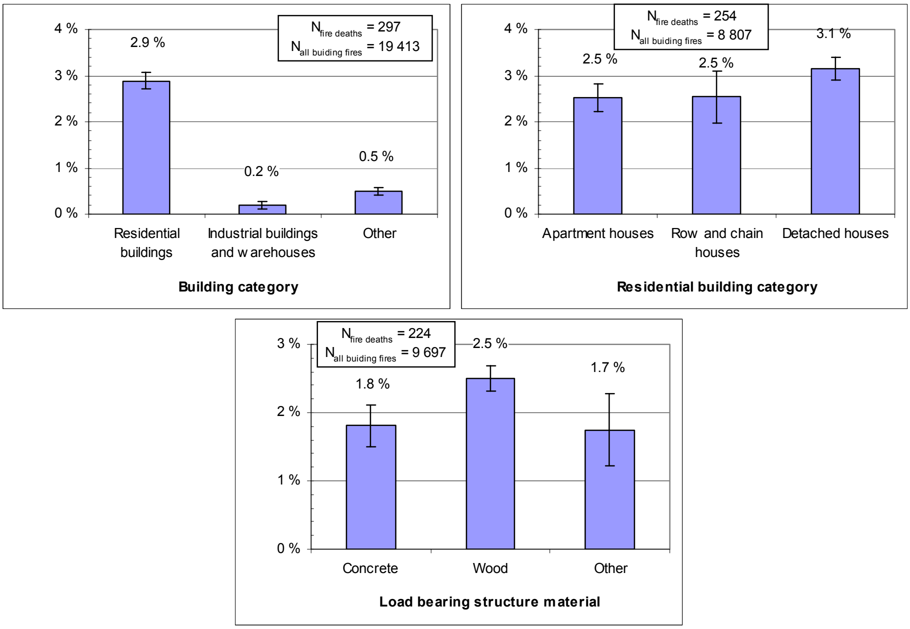

Figure 65. Percentual share of fires involving deaths of all fires in buildings. The error bars represent the uncertainty due to the number of observations of each data point (see Section 2.7).

7.5.4 Average frequency of fire death in different types of residential buildings

Incidents that had taken place in apartment, row or chain and detached houses during the years 1999–2001 were treated separately from the fire death statistics (SPEK 2001). The size of the data set was small (N = 257), which affected the reliability of the analysis. It was nevertheless carried out because better information, including the required elements, will not be available until collecting methods are improved and the amount of data increased in the course of time. The number of deaths in different building types is presented in Table 23.

Table 23. Number of fire deaths in different building types in Finland 1999-2001.

Building type	**Fire deaths 1999–2001**
Apartment houses	50
Row and chain houses	17
Detached houses	115
Summer cottages or free-time residential buildings	9
Not known	8
Other than residential building	58
Total	**257**

Statistics Finland delivered the information on the floor area and inhabitants in residential buildings presented in Table 24.

Table 24. Floor area and number of buildings and inhabitants in residential buildings 1999.

Building type	**Buildings**	**Floor area [m^2]**	**Inhabitants**
Apartment houses	51 645	78 730 420	1 715 812
Row or chain houses	65 799	27 537 733	681 075
Detached houses	994 251	125 237 006	2 553 689
Total	**1 111 695**	**231 505 159**	**4 950 576**

The average frequency of fire death per floor area and inhabitant is presented in Figure 66 a) and b). The floor area per flat and inhabitant in different building types is plotted in Figure 66 c) and d).

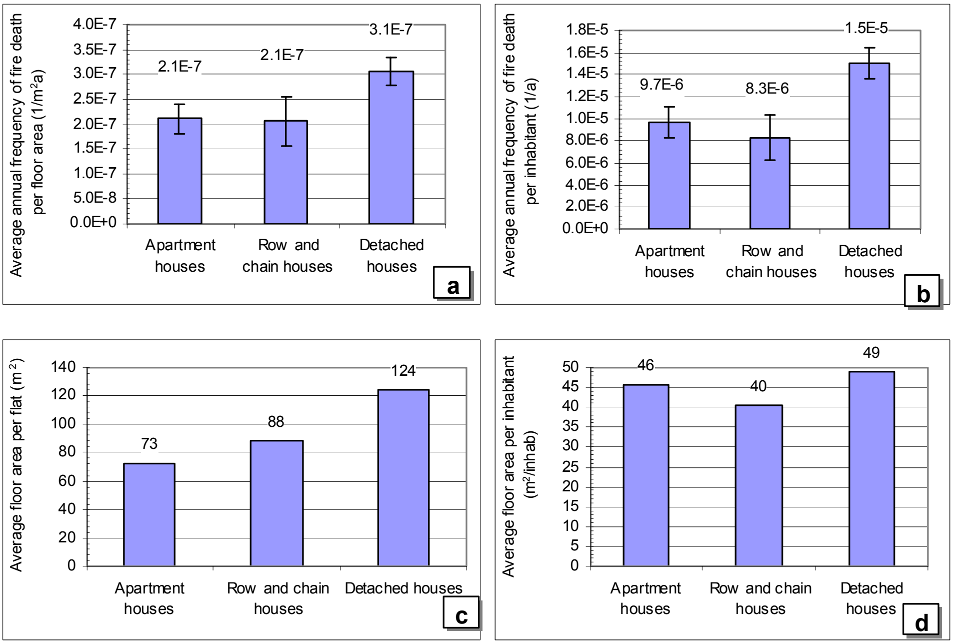

Figure 66. a) Average annual frequency of fire death per floor area, b) per inhabitant, c) average floor area per one flat, d) average floor area per inhabitant. The error bars represent the uncertainty due to the number of observations of each data point (see Section 2.7).

Figures 66 a) and b) showed that the differences in fire death frequencies between residential building types were small. Only the average annual fire death frequency per inhabitant in detached houses was somewhat higher compared to others, although, as stated above, the amount of data was rather small. The difference did not exceed three deviations, which was regarded as the limiting value for significant difference. Figure 66 c) showed that the floor area per flat was larger in detached houses, from which follows a higher probability of ignition, because a considerable portion of ignitions are still independent of human actions. Figure 66 d) showed that average floor area per inhabitant was at the same level in different building types. However, before any final conclusions can be made, more data should be collected in the course of time and the analysis repeated.

7.6 Summary

The distribution of the fire loss is known to be skewed. The tails of the distribution differed considerably from lognormal distribution. This became apparent especially in smaller classes when the observations were divided into groups by the value-at-risk of the building. When the observations were divided into groups on the basis of the building categories, the fit of the lognormal distribution was the best in the group including all other buildings except residential and industrial and warehouses. A somewhat better fit was achieved with the sum of two lognormal distributions for all category groups. When the assumption of the lognormality was considered correct, the expected loss in individual building could be determined using the method introduced by Ramachandran (1979/80, 1982). When the parameters for the model were determined from the data set, the compatibility of the theoretical curve with the observations was still weak for quantitative work. The sum of two lognormal distributions added to the theory did not improve the agreement. By fitting the curve visually to the data set, a good fit was obtained. This was presumably a better way to determine the parameters because the actual distribution of the value-at-risk of the total building stock was not known. Also, the definitions of the value-at-risk were different in the Finnish database compared to assumptions of the theory. Based on the results obtained from the theory and real observations, it became evident that the increase of loss levels off to near a constant value with the large values at risk or floor area. The theoretical approach followed overall more the perspective of the insurance industry. The loss data in the Finnish accident database was based on assessments made by the rescue service at the scene of the fire.

The data confirmed the dependency between the value-at-risk and the floor area. Either the floor area or monetary value can therefore be used to express the size of the building. A peak of loss appeared around 600 m^2 floor areas, especially in residential buildings. Furthermore, the residential buildings in which 47% of the fires ignited were divided into apartment, row and detached houses. The data showed that the majority of the observations of buildings with floor areas under 600 m^2 were fires in detached houses. After 600 m^2, the majority of buildings changed to apartment houses. The peak appeared in the floor area region where the majority of buildings in the building stock changed from detached houses to apartment houses and the loss dropped little from the peak value of detached houses to the slightly lower level of the apartment houses.

The more detailed analysis of the loss data of residential buildings revealed that the loss grew rapidly as a function of the floor area in the detached houses while in row and apartment houses the growth was substantially slower. A natural explanation for this is that generally in detached houses the compartment size is equal to the whole floor area of the building, while in apartment houses one flat corresponds to one fire compartment. An average fire generally remains in the ignition flat, damaging only that. Thus, the average loss does not vary as a function of the total floor area of the building but of the size of the fire compartment (flat). Similar behaviour would probably be observed in other building categories where large buildings are separated in different fire compartments or zones. However, with only the data available, this could not be examined in detail. Overall, it became evident that the fire compartment size would be a more proper descriptor than the whole floor area of the building and so the information should also be collected for the accident database.

In this connection, the effect of the material of the load-bearing structure on the fire losses was examined closer. It was observed that generally the losses in wood-framed buildings were larger compared to other load-bearing materials, while their values at risk were significantly lower. The analysis of the damage degree showed that generally the spread of fire in those buildings was wider. However, the reasons behind the wider fire spread could not be examined in detail. Overall, the main conclusion of the analysis was that the approach was wrong. The analysis of the data available showed that the material of load-bearing structures was not the main factor when the fire risk of a building is assessed. A more important factor seemed to be the type of a building. However, the materials of the load-bearing structures seemed to be divided characteristic to the type of building. Probably even a more important element, if not the most important, is compartmentation, which unfortunately could not be examined more closely because the necessary detailed information was not available, as mentioned above.

All building fires were compared to fires in which at least one person had died. In contrast to earlier studies, now the information on economic losses was also available. The analysis showed that the losses were in general larger in fatal fires. However, it became evident that the fatal fires had usually spread wider than the average building fires before the fire department reached the scene. Most of the fatal fires occurred in residential buildings, but the differences between materials of load-bearing structures or types of building (detached, row, chain or apartment house) were very small. The results of earlier study (Rahikainen 1998b, Rahikainen & Keski-Rahkonen 1998c, 1999a, b, 2001) indicated that the main cause of fire deaths is the victims' own behaviour. It therefore seems that any technical fire safety measure might not have extensive influence in reducing the human fire losses in Finland.

8. Examples of utilisation of gathered information on fire-risk assessment

8.1 General

In this section, the utilisation of the results presented earlier will be illustrated through a few examples. Residential buildings, being the largest group in the building stock, were selected for consideration.

At its simplest, a fire risk can be expressed as a product of the probability of ignition and the probable consequences. This approach to determining average fire risks was adopted in this section. As the purpose of this section was to demonstrate the utilisation of the information gathered in this work in a simple way, it was assumed that the approach adopted would yield sufficiently accurate results.

Following the approach presented earlier, the ignition frequency and fire losses are assessed in Section 8.2 together with the average fire risk for detached, row and chain and apartment houses, as well as for concrete- and wood-framed residential buildings. Earlier, it was observed that the division of residential buildings by the material of the load-bearing structure was irrelevant and that the division to different building types was more appropriate. However, detailed information on the whole building stock was not available with the building type division and therefore only average values could be determined. For the concrete- and wood-framed residential buildings, the available data allowed the determination of the average values as the function of the total floor area. The results were expressed as monetary value.

In Section 8.3, the risk analysis was carried out for an individual flat in a large apartment house using the time-dependent event-tree approach (Hietaniemi et al. 2002, Korhonen et al. 2002). In the example, the development of the design fires was modelled with CFAST (Consolidated Compartment Fire and Smoke Transport Model) and the inherent variations of the processes using the Monte Carlo simulation. The design fires were also simulated with FDS3 (Fire Dynamics Simulator, version 3) to which the obtained results were compared.

As the result, the fire risk of the specific building was obtained as monetary-value dependent on the duration of the fire.

8.2 Average fire risk in residential buildings

8.2.1 Detached houses, row and chain houses and apartment houses

8.2.1.1 Ignition frequency

The average ignition frequency, i.e. the annual number of ignitions per floor area in different types of residential buildings, is presented in Figure 67a). The differences between the residential building types were analysed using Statistix. The results of the Kruskal-Wallis tests are presented in Appendix F. The differences between the building types were small, the ignition frequency of detached houses was somewhat larger compared to row and chain houses.

In addition to size of the building, human activity influences ignition frequency. Thus it was determined per inhabitant in Figure 67b). The floor area per inhabitant was a little higher in detached houses, so the value of ignition frequency was also higher compared to others. However, based on the Kruskal-Wallis test, only the difference between row and chain and detached houses was significant.

In Figure 67c), the ignition frequency per flat, which was higher in detached houses compared to other categories, is shown. In detached houses, the floor area and number of inhabitants per flat were higher, which indicates that the number of ignition sources was also larger.

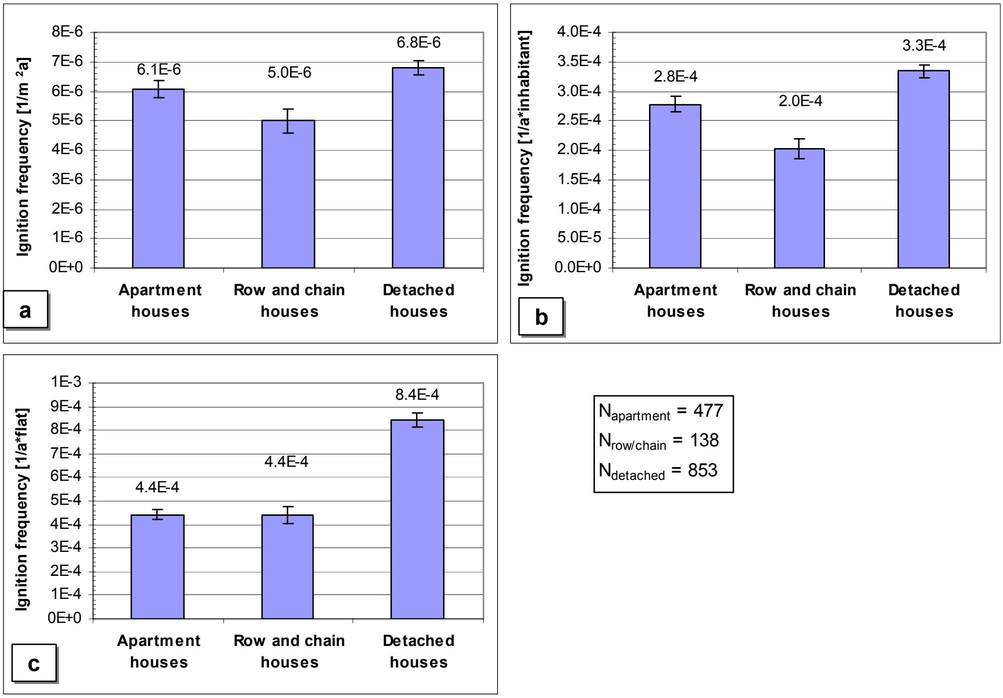

Figure 67. Average annual ignition frequency per a) floor area, b) inhabitant and c) flat in apartment, row and chain and detached houses. The error bars represent the uncertainty due to the number of observations of each data point (see Section 2.7).

8.2.1.2 Economic consequences

The consequences of fires are presented as the average financial loss per fire in Figure 68. The number of observations of row and chain houses was rather small and thus the level of uncertainty grew quite large. The average value of detached houses was a little higher compared to apartment houses as has become evident already from Figure 54. The differences between building types were analysed using statistical software Statistix. The results of the used Kruskal-Wallis tests are presented in Appendix F.

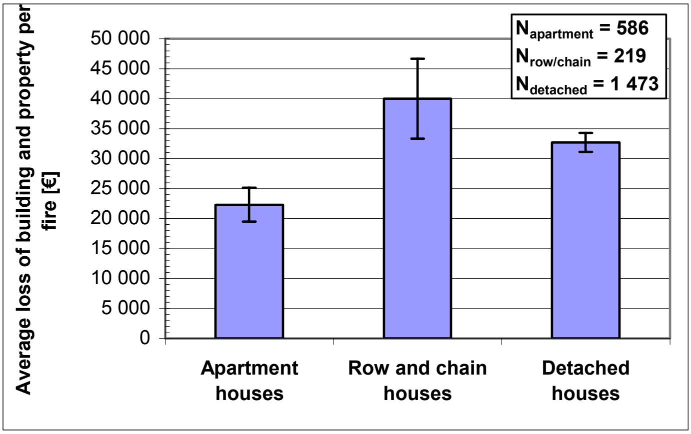

Figure 68. Average loss of building and property. The error bars represent the standard error of mean (see Section 2.7).

8.2.1.3 Average fire risk

The average risk presented in Figure 69 was determined by multiplying the average ignition frequency in Figure 67, by the average loss in Figure 68.

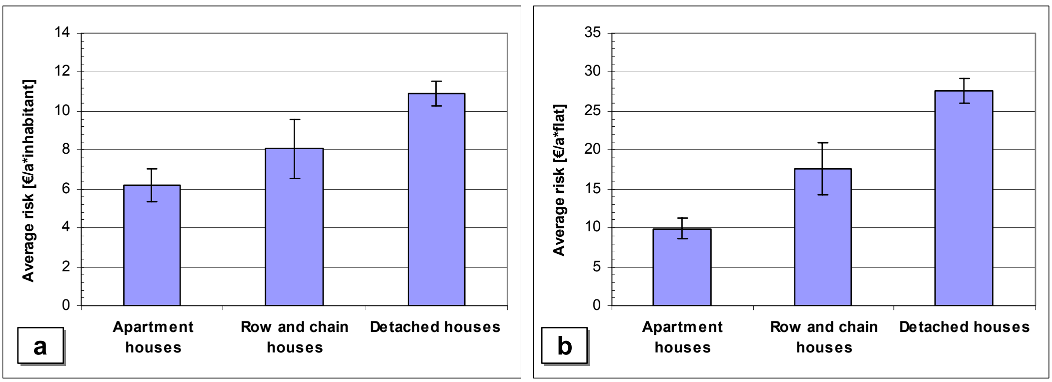

Figure 69. Average annual fire risk in residential buildings a) per inhabitant and b) per flat. The error bars represent the uncertainty due to the number of observations of each group (see Section 2.7).

No statistical tests were carried out in this context and the differences were estimated on the basis of the error bars. Because of the small number of observations, the level of uncertainty of row and chain houses grew rather large and thus no detailed conclusions could be made of the fire risk in that category. However, the difference between detached and apartment houses was significant when a difference exceeding three deviations (one error bar represents one deviation) was assumed as a criterion for a significant difference. The ratio between fire risk per inhabitant in detached and apartment houses was 1.8 and per flat 2.8. The average loss shown in Figure 68 was a little higher in detached houses. The error bars indicate a large standard deviation of the mean, which however was taken into account when the error bars in Figure 69 were determined. The higher average risk in detached houses is caused by its higher value of ignition frequency and somewhat higher average losses.

8.2.2 Concrete- and wood-framed residential buildings

8.2.2.1 Ignition frequency

In Figure 70, the ignition frequency as a function of the floor area of the concrete- and wood-framed residential buildings is presented. The fires in which the floor area or the material of the load-bearing structure was unknown were assumed to be distributed with the same proportion as the known fires and are included in Figure 70.

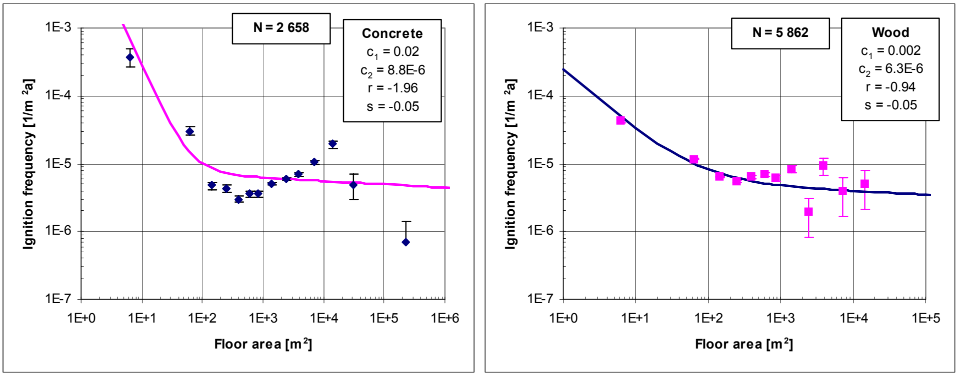

Figure 70. The ignition frequency as a function of the floor area in concrete and wood framed residential buildings. The used floor area class intervals are presented in Appendix E in Table 38. The error bars represent the uncertainty due to the number of observations of each data point (see Section 2.7).

In Figure 70, the generalised Barrois model (Equation (19)) was also fitted to the observations, by combining a visual curve fitting with the fitting carried out with Statistica. The model parameters are labelled in Figure 70. The 'peak' similar to that in Figure 14 or Figure 15 was detected around 10 000 m^2 in the ignition frequency of the concrete-framed buildings. This supported the reasoning that the peak is due to the features of the buildings stock. The peak seemed to appear around the neighbourhood where the majority of buildings were apartment houses. When the number of flats and thus ignition sources increase as a function of the floor area, the ignition frequency also increases considerably. The two largest floor area groups in Figure 70 included only a few observations and so no reliable conclusions could be drawn from the ignition frequency with floor areas over 20 000 m^2. The applicable partial safety co-efficients were determined similarly both for concrete-framed buildings $\gamma_f = 3$ and for wood-framed $\gamma_f = 1$, as shown in Section 5.3.3.4.

8.2.2.2 Economic consequences

In Figure 71, the average loss of building and property is shown as a function of the floor area in wood- and concrete-framed residential buildings. In Figure 71, a power-law function was fitted to the observations using statistical software Statistica.

$$X = bA^k \tag{33}$$

where X is loss [€], A floor area [m^2] and b and k are constants presented in Table 25 together with the proportion of variance explained. As the power-law function in Equation (33) was fitted to the data of the wood-framed buildings, only the floor area classes less than 600 m^2 were included. The Cooke's distance of larger categories exceeded one, which can be considered a limiting value for the observation that deviates from the rest of the data and may therefore be excluded from the analysis on that basis.

Table 25. Parameters of Equation (33) and the proportion of the variance explained (R^2).

	Wood	**Concrete**
b	1 650	7 770
k	0.62	0.14
R^2	0.99	0.73

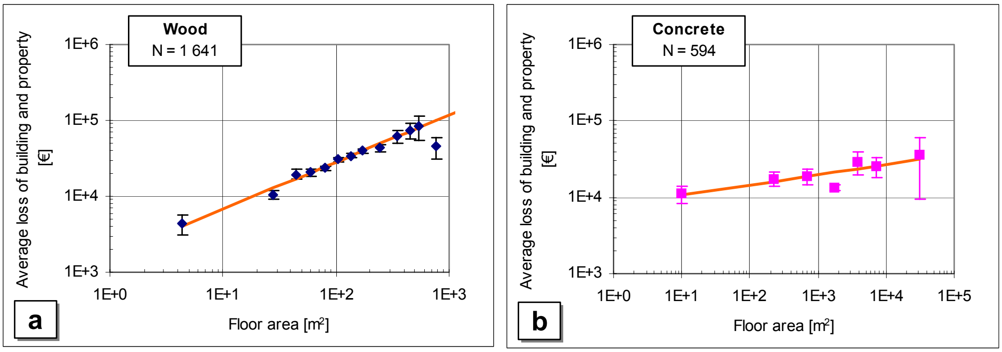

Figure 71. Average loss of building and property in residential buildings in which the load-bearing structure material is a) wood and b) concrete. The error bars represent standard error of mean (see Section 2.7).

In the used loss data, the buildings of which the floor area was 1–300 m^2 and the load-bearing structure material, wood, were mostly detached houses. Most of the wood-framed buildings between 300–1 000 m^2 were row or chain houses. Over 500 m^2 concrete framed buildings were apartment houses. The average loss presented in Figure 71 is similar to the average loss of residential buildings in Figure 47, where the wood-framed buildings were placed at the first part of the curve, where the growth of the average loss was steep, and the concrete buildings at the end part, where the growth was substantially slower. Similarly, the average loss of apartment houses presented in Figure 55 corresponds to concrete-framed buildings in Figure 71b) and detached houses to wood-framed buildings. The differences between the concrete framed and apartment houses, as well as wood framed and detached houses, were rather small.

The average loss as a function of the floor area presented in Figure 71 can be used as a guideline when the amount of critical loss is estimated. The probability of loss can be determined using the theory introduced by Ramachandran and presented in Appendix D or straight from observations using, for example, appropriate cumulative distributions.

8.2.2.3 Average fire risk

At simplest, the average fire risk can be expressed as a product of the average ignition frequency and average losses

$$R = \gamma_f (c_1 A^{r+1} + c_2 A^{s+1}) b A^k \tag{34}$$

The result is plotted in Figure 72 a) for wood-framed residential buildings between floor areas of 1–600 m^2 and in Figure 72 b) for concrete-framed residential buildings between floor areas of 600–100 000 m^2. The fire risk is expressed as annual monetary value per whole building.

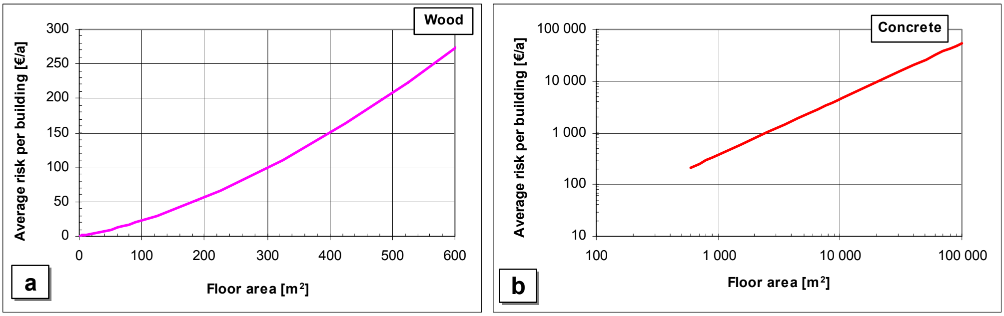

Figure 72. Average fire risk in residential buildings which load-bearing structure material is a) wood and b) concrete.

8.3 Example of risk analysis of an individual building using the time-dependent event-tree approach

8.3.1 General

To illustrate how the gathered statistical information can be utilised in risk determination of an individual building, a simple example case considering one flat in a five-storey apartment house was calculated through using the time-dependent event-tree method depicted in Hietaniemi et al. (2002) and Korhonen et al. (2002).

The flow chart of the risk analysis of a chosen building and fire scenario is presented in Figure 73 (Hietaniemi et al. 2002).

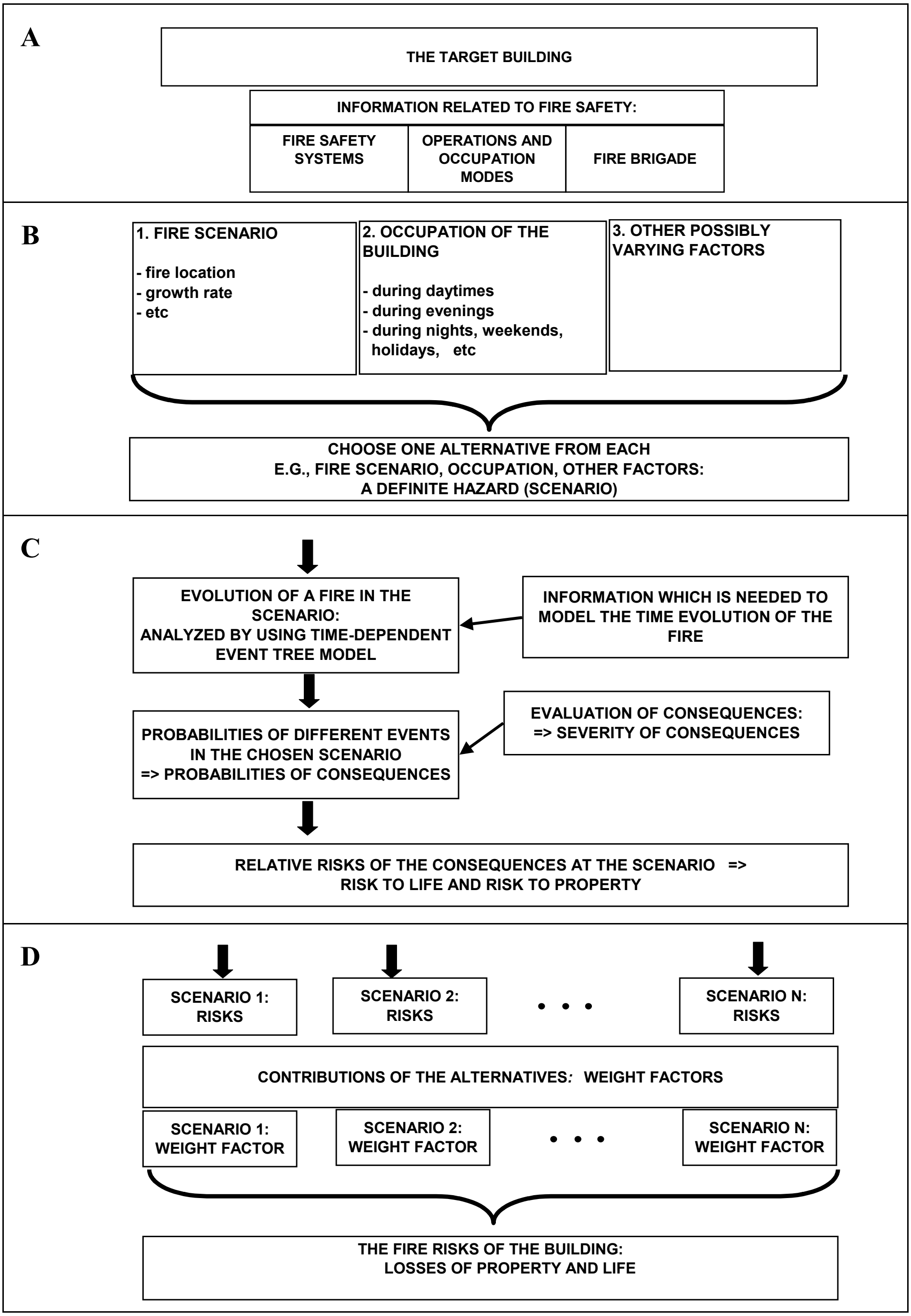

Figure 73. The flow chart of the risk analysis of a target building (Hietaniemi et al. 2002).

The risk analysis process starts with the collection of the information related to the target building (phase A). Required information includes, for example, knowledge of the size, location and the type of use of the building, in addition to the information on its fire safety prevention systems and occupancy. The objectives of the analysis should be acknowledged at this first phase.

In phase B, the appropriate fire scenarios are chosen. The location of the design fire and the occupation of the building at all hours, in addition to other varying factors, must be acknowledged. Often consideration of several parallel fire scenarios is appropriate; these should include the major threats connected to the fire.

In phase C, the risk analysis of different scenarios is carried out. In the time-dependent event-tree approach, the fire incident is divided into discrete time intervals. At each time interval, an event tree is constructed to describe the evolution of the fire and potential detection and fire fighting actions. The time development of the whole process is obtained by connecting the separate time intervals to each other. The basic event tree used in this example case is presented in Figure 74. Because the considered building was residential, the branches of the automatic extinguishing systems were left out.

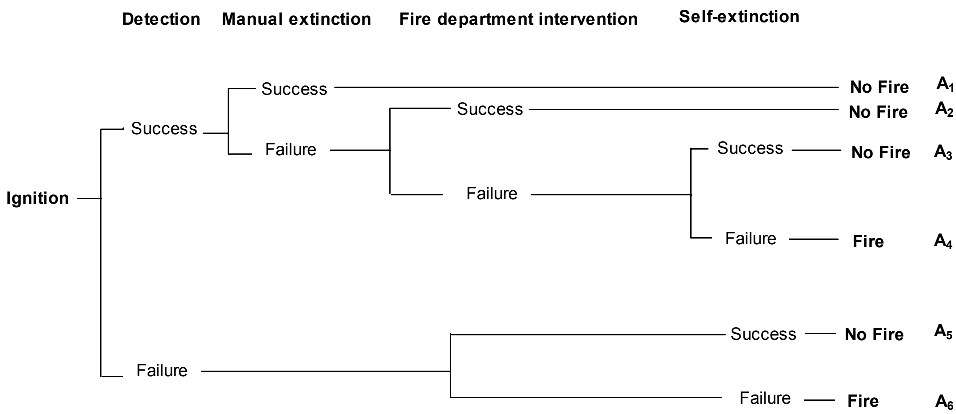

Figure 74. The event tree used to analyse the fire incident at a specific time interval. The upper branches correspond to a successful operation and the lower ones to a failure, e.g., the 'self-extinction' upper branch means that the fire is self-terminated due to the fact that the fuel load has burnt out. The labels A_1-A_6 refer to different states of the system.

The branches in Figure 74 correspond to the success of detection and manual extinction of the fire in addition to intervention of the fire department and burning out of the fire load. The system can be in six different states labelled with A_i at each time interval:

A_1	No fire →	Detected, Extinguished manually
A_2	No fire →	Detected, Extinguished by the fire department
A_3	No fire →	Detected, Fire load burned out
A_4	Fire →	Detected
A_5	No fire →	Not detected, Fire load burned out
A_6	Fire →	Not detected

The information on the manual extinguishing was available in the accident database, unlike the information on the fire detection or burning out the fire load, which needed to be estimated in other ways. The technique used to predict the success of the fire department intervention was presented in Section 6.

In the example case, the development of the design fires were analysed with CFAST. The inherent variations of the processes were modelled using the Monte Carlo simulation, where new input variables were repeatedly and randomly chosen beyond the limits set for each variable. However, some processes were described without variability to obtain a simple description.

With every set of input variables, the development of the fire was simulated with CFAST. The process was continued until the changes in the output variables decreased to an acceptable level. In this example, the simulations were continued until the changes in the 10% and 90% fractals and the mean values and standard deviations of the output variables were less than 1.5%. As a result, the probability distributions for the chosen outputs such as the success of the fire department, the breaking of the window, the occurrence of a flashover etc. were obtained. The detailed description of the approach is presented in Hostikka & Keski-Rahkonen (2003).

The model explicitly incorporates the time dependence of the fire and its consequences in the analysis. In the example, the consequences were considered in terms of financial loss discussed in detail in Section 7. The determination of the time evolution of the fire can be carried out either by using conditional probabilities or by a state transition process description of the system, which can be described as the Markov process (Hietaniemi et al. 2002, Korhonen et al. 2002).

In last phase D, the considered scenarios are added together and as a result the total fire risk of the building is obtained. The total risk is calculated as a weighted average of the risk values of each scenario. The weight factors are the probabilities of each scenario. The absolute fire risk level is obtained by multiplying the calculated risk value by the corresponding ignition frequency discussed in detail in Section 5.

8.3.2 Description of the target building and flat of initial fire

The target was one flat in a five-storey apartment building of 60 flats with a total floor area of 13 200 m^2. The distance to the nearest fire station was 7 km. Because the building was in residential use, it was not equipped with an automatic extinguishing system. The floor layout of the target flat is presented in Figure 75.

The sizes of the rooms of the ignition flat were:

Room 1	3.9 x 3.2 x 2.6 m
Room 2	3.9 x 3.2 x 2.6 m
Room 3	5.5 x 4.2 x 2.6 m

The material of the ceiling was concrete and walls plasterboard. The rooms were separated by 0.9 m wide and 2.05 m high doors. The rooms 1 and 2 had 1.75 wide and 1.35 m high windows. The window in room 3 was 2.0 m wide and 1.60 m high. The sills of the windows were at 0.9 m.

The breaking of the window of the ignition room was simulated by opening a 1.75 m wide and 1.35 high (room 1) or 2.00 m and 1.60 high (room 3) vent to the outside when the upper layer temperature exceeded 350°C. Shields et al.

(2001, 2002) concluded in their experimental work that the failure occurred when the exposed glass bulk and surface temperatures were in the region of 110°C. This was assumed to correspond roughly the upper hot gas layer temperature in the range 300–400°C.

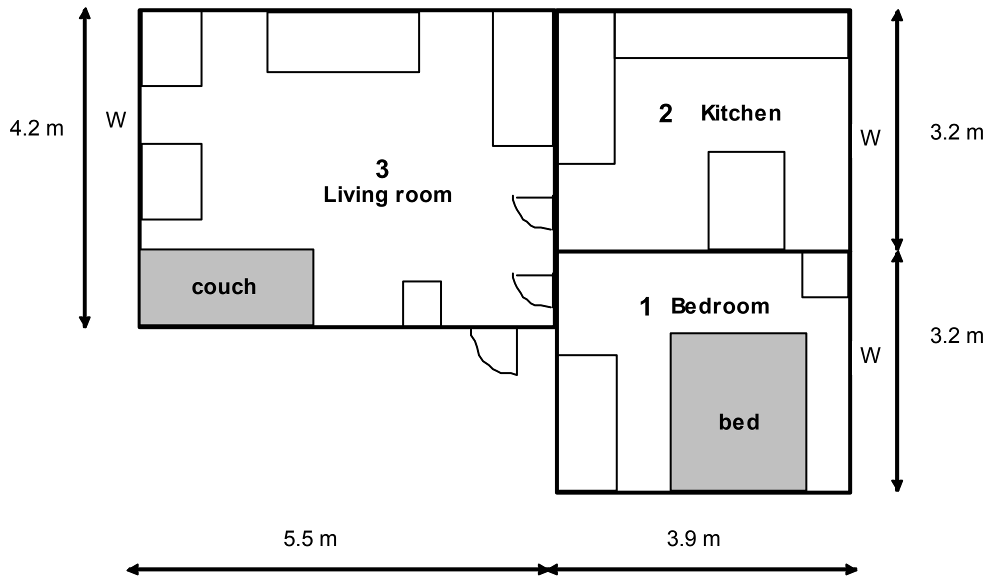

Figure 75. Floor layout of the target flat. W:s indicate the places of the windows.

In Figure 75, the outlines of the furniture are also plotted. In the analysis, two separate design fires were considered: 1) the bedroom fire where the first igniting item was the bed and 2) fire in the living room with the couch as the first igniting item. In Figure 75, room 1 indicates the bedroom and the grey area the igniting bed, the room 2 indicates the kitchen and room 3 the living room, where the igniting sofa is coloured grey.

8.3.3 Objectives

The example target was one flat in the apartment house. The main consequences of interest were damages to people and property. An acute damage to people is assumed to be caused by smoke. Because the simulated premises were quite small, smoke filled the ignition room almost instantly after the ignition. In apartment houses, the safety of occupants is strongly dependent on the detection time of the fire. However, the detection time was very unpredictable and strongly dependent on the characteristics of the occupants and circumstances and could not be described accurately with this approach. Also, the statistical data was insufficient. Normally, the occupants of the ignition flat are able to escape if they are awake and able to move. Thus, in this example case, it was not reasonable to include human losses in the analysis, so only economic losses were considered.

8.3.4 Design fires

In Figure 76, the ignition spaces in the apartment house fires are presented on the basis of the information on the accident database. It shows that 25% of the fires ignited in kitchens, 23% in living rooms and 10% in bedrooms. On the basis of this information, the two design fires were located to the bedroom and the living room. The kitchen fire scenario was excluded because those fires are not the most hazardous and are less likely to spread beyond the room of origin (FCRC 1996b). The Australian analysis (FCRC 1996b) including fire data from Australia, United Kingdom and United States also indicated that the most hazardous fire scenarios in apartments are the fires started by smokers' materials in soft furnishings in living rooms or sleeping areas.

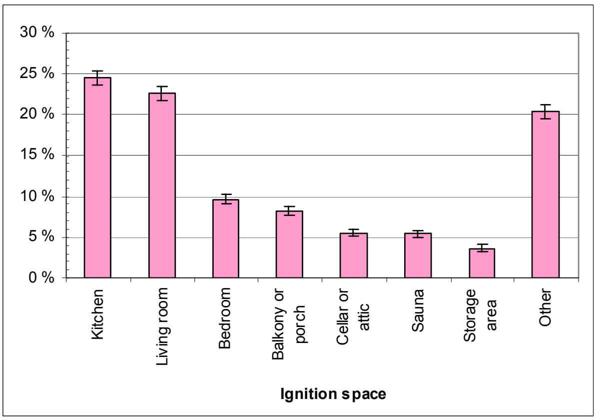

Figure 76. Ignition space in apartment fires during 1996–2002 (N = 2 959) based on the information on the accident database.

The results from a large number of fire tests presented by Särdqvist (1993) were used as a guideline for choosing the average and the limiting values of the RHR as well as for estimation of the growth time and the decay rate. In Figure 77, the RHR curves of several tests including beds and sofas are presented.

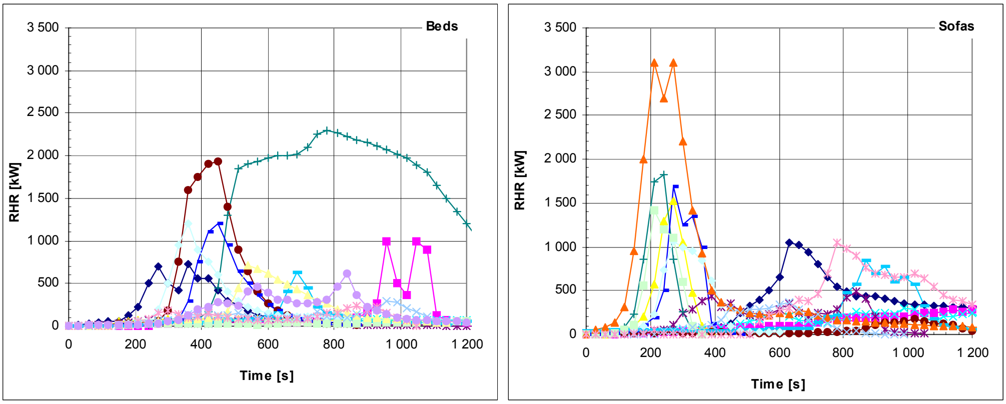

Figure 77. Rate of heat releases in the fire tests including beds and sofas (Särdqvist 1993).

8.3.4.1 Design fire 1: Bedroom fire

The fire source (bed) was located in room 1 (bedroom) and the rate of heat release (RHR) was assumed to follow analytical t^2-curve presented in Appendix C with a predefined maximum level Q_{max}. The RHR based on the bedroom fire test (Särdqvist 1993) and the analytical t^2-curve with growth time t_0 = 300 s, and decay rate τ = 100 s are presented in Figure 78.

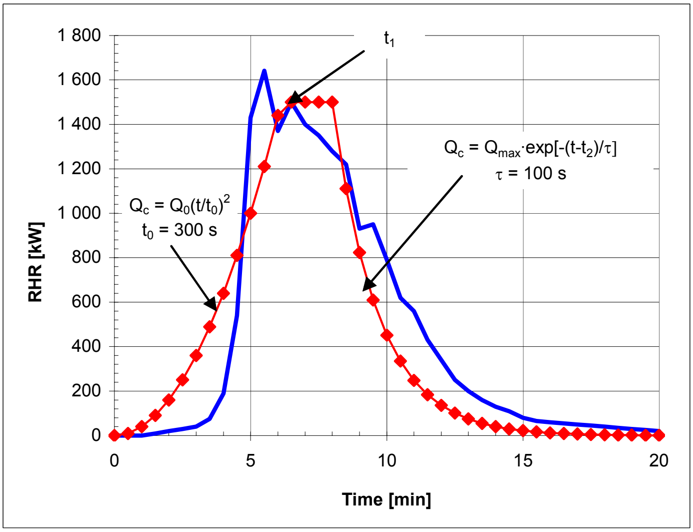

Figure 78. RHR from a bedroom fire test (Särdqvist 1993) and analytical t^2-curve (see Appendix C).

For the design fire, the fire growth rate $t_0 = 300$ s proposed for residential buildings (BSI 1997, Eurocode 1 2002) was used. The decay rate $\tau = 100$ s was estimated from Figure 78. However, the RHR curves of the real fire tests in Figure 77 showed that the growth and decay rates are varying factors and the fire growth rate, for example, varied from fast to very slow. Notwithstanding that, it was assumed that the consideration of the case with the medium growth rate recommended in design guides (BSI 1997, Eurocode 1 2002, FCRC 1996a) was adequate and the stochastic nature of the fire was described by varying the both growth and decay rates by estimated percentages. The appropriate percentages were estimated from Figure 77 by determining the average percentual deviation from the medium growth rate of fire growth rates in fire tests including beds or sofas in which the maximum RHR reached 1 MW. The average variation of the fire growth tests including beds was 25% and sofas 30%. Thus the range of variation of t_0 was set for the bedroom fire scenario $t_0 = 225$–375 s and for the living-room scenario $t_0 = 210$–390 s. The variation of the decay rate was estimated to be ±20%, but the value was not significant because the fire load did not burn out during the considered time period.

The maximum rate of heat release was determined using the limit value 250 kW/m^2 presented in Eurocode 1 (2002) for residential buildings. A maximum value of 3 MW was obtained by assuming the maximum size of fire in the bedroom equal to its floor area 12.5 m^2. The lower limit 1 MW was estimated from Figure 77. Although in Figure 77 in a few fire tests the minimum value remained under 1 MW, it was chosen because, in order to obtain reliable calculation results, the range between minimum and maximum values cannot be too large.

The average fire load density was obtained from Eurocode 1 and assumed to follow the Gumbel distribution (Eurocode 1 2002) with parameters α and β. With this fire load, the period of fully developed fire is much longer compared to the fire test presented in Figure 78. In Figure 79, the variation of the RHR curve used as input to the Monte Carlo simulation, where it can be seen that the fire load does not run out during the considered time period t = 20 min, is presented.

The limits and distributions of the variable parameters used in Monte Carlo simulations are presented in Table 26.

Table 26. Values and distributions of parameters characterising the variability of the bedroom design fire.

Parameter	**Average value**	**Distribution**
Maximum RHR	2 MW	Uniform distribution, range 1–3 MW
RHR Growth time	300 s	Uniform distribution, range 300 s ± 25%
Fire Load Density	780 MJ/m^2	Gumbel distribution, α = 675, β = 182
Decay rate	100 s	Uniform distribution, range 100 s ± 20%

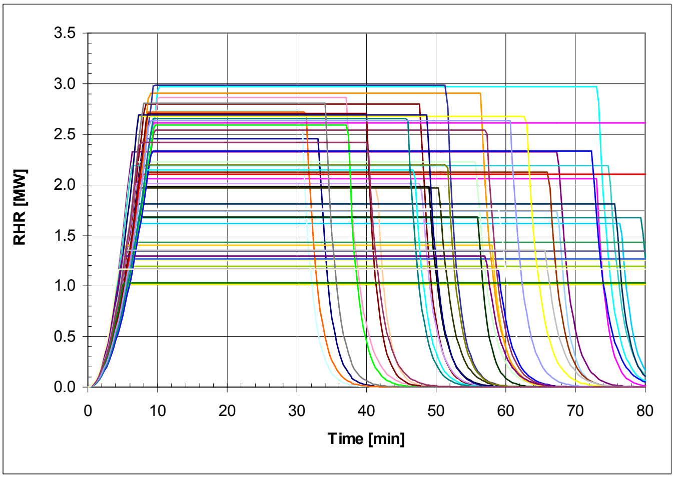

Figure 79. RHR curves of the design fire located in the bedroom.

8.3.4.2 Design fire 2: Living-room fire

The ignition source was the sofa located in the living room (see Figure 75). The fire growth and decay rates were assumed equal with the bedroom design fire. The values of the rate of heat release of the fire tests presented in Figure 77 showed somewhat higher maximum values for sofas compared to beds. The area of the living room was 23 m^2, which led to over 5 MW maximum RHR if the value 250 kW/m^2 from the Eurocode 1 (2002) was used. The peak RHR values of fire tests presented in Figure 77 varied from 0.3 MW to 3.1 MW. The maximum rate of heat release of the living-room design fire was assumed to vary uniformly between 2.5–4.5 MW.

The limits and distributions of the variable parameters used in Monte Carlo simulations are presented in Table 27 while the sample of Monte Carlo input RHR curves is presented in Figure 80.

Table 27. Values and distributions of parameters characterising the variability of the living-room design fire.

Parameter	**Average value**	**Distribution**
Maximum RHR	3.5 MW	Uniform distribution, range 2.5–4.5 MW
RHR Growth time	300 s	Uniform distribution, range 300 s ± 30%
Fire Load Density	780 MJ/m^2	Gumbel distribution, α = 675, β = 182
Decay rate	100 s	Uniform distribution, range 100 s ± 20%

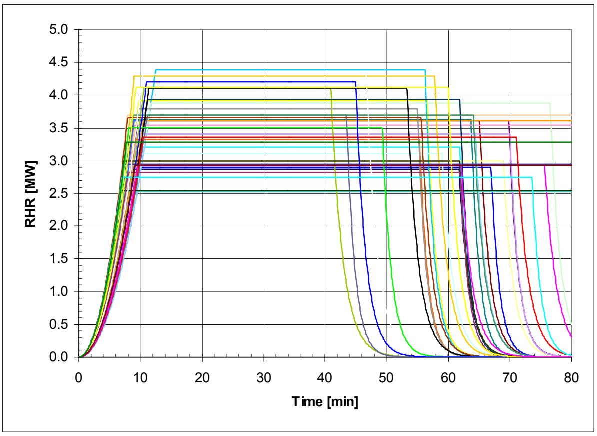

Figure 80. RHR curves of the design fire located in the living room.

8.3.5 Fire scenarios

8.3.5.1 Design fire B: Bedroom

In the example case, two separate scenarios were considered.

B1) Fire in the bedroom (Room 1) in the daytime. Bedroom door to the living room (Room 3) is open and the fire breaks the window when the upper layer temperature exceeds the critical level $t_{crit} = 350°C$. The flat is not occupied and the fire is detected by passer-bys when the window breaks. Assumed duration of this phase is 0800–2000 hours, i.e. 12 hours.

B2) Fire in the bedroom (Room 1) during nighttime. The bedroom door is closed during the whole duration of the fire. Fire breaks the window when the upper layer temperature exceeds the critical level $t_{crit} = 350°C$. The fire is detected by the occupants. Assumed duration of this phase is 2000–0800 hours i.e. 12 hours.

8.3.5.2 Design fire L: Living room

As in the bedroom fire case, two separate scenarios were considered.

L1) Fire in the living room (Room 3) in the daytime. Doors to the kitchen (Room 2) and living room (Room 3) are open and the fire breaks the window when the upper layer temperature exceeds the critical level $t_{crit} = 350°C$. The flat is not occupied and the fire is detected by neighbours. Assumed duration of this phase is 0800–2000 hours, i.e. 12 hours.

L2) Fire in the living room (Room 3) during nighttime. The door to the bedroom (Room 1) is closed and to the kitchen (Room 2) open. Fire breaks the window when the upper layer temperature exceeds the critical level $t_{crit} = 350°C$. The fire is detected by the occupants. Assumed duration of this phase is 2000–0800 hours, i.e. 12 hours.

8.3.6 Branching probabilities of event trees

8.3.6.1 General

The different branching probabilities of event trees shown in Figure 74 for the design fires presented in Section 8.3.4 were calculated using statistics, heuristic reasoning and Monte Carlo simulations. The simulations were continued until the changes in the 10% and 90% fractals and the mean values and standard deviations of the output variables were less than 1.5%.

8.3.6.2 Detection

For scenario B1, the probability distribution of the window-breaking time and for scenario L1 the flashover time, was used as the probability of detection. The time distributions were obtained as a result of the Monte Carlo simulations.

For scenarios B2 and L2, the detection probability by occupants was obtained by heuristic reasoning such that the detection probability at $t = 0$ was zero; this was assumed to grow linearly to 1 within the time the average maximum RHR, presented in Tables 26 and 27, was reached with a growth time rate of 300 s. For a t^2-fire, the detection probabilities for scenarios B2 and L2 are presented in Table 28.

Table 28. Probabilities of detection by senses in scenarios B2: fire in the bedroom during nighttime and L2: fire in the living room in the nighttime (see Section 8.3.5.2).

Duration of the fire [min]	**Detection probability**	
	B2	**L2**
5	0.63	0.50
10	1	1
15	1	1
20	1	1

8.3.6.3 Manual extinguishing

In scenarios B1 and L1, it was assumed that no manual extinguishing actions were performed, because no occupants were present. For scenarios B2 and L2, the probability of successful manual extinguishing was based on statistics from the accident database Pronto. It showed that 25% of the fires were extinguished or limited by occupants. No dependency on the duration of the fire was detected on the basis of the data.

8.3.6.4 Fire department intervention

The probability of the success of the fire department intervention was estimated using the approach presented in Section 6. Because earlier the blocking probability in Helsinki was observed negligible, in this example case the success of the fire department was assumed to depend on the response time. After the fire-department arrival, the success probability of the extinguishing actions of the example fire was considered to be 1.

The turnout time distribution of the rescue units of Helsinki presented in Figure 81 was obtained from statistics. The travel time in Figure 81 was estimated using the travel time model presented in Section 6.3. To model the stochastic nature of the travel time, the speed parameter *a* in Equation (24) was allowed to vary beyond the limits of the standard error presented in Table 9. After the arrival, it takes some time before the actual extinguishing actions start. The elapsed time was estimated using the report by the Australian Fire Authorities Council (1997). The turnout time, travel time and search time were incorporated; the resulting cumulative distribution is presented in Figure 81.

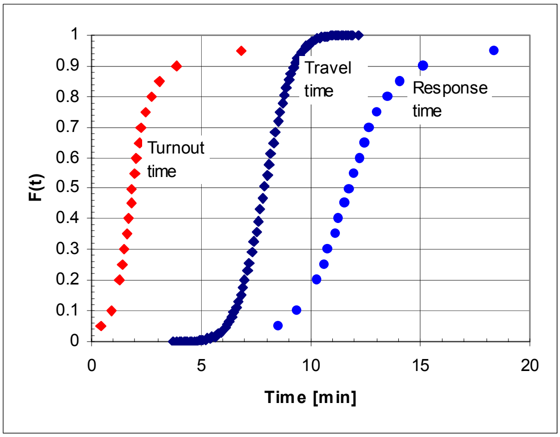

Figure 81. Cumulative distributions of the turnout, travel and response times of the fire department to the example target.

8.3.6.5 Fire load

The probability that the fire load has burned out was obtained as a result of the Monte Carlo simulation. The critical limit was the moment in the decay phase when the RHR was decreased to half of the maximum. The Monte Carlo simulation returned the ratio of the cases where the critical limit was reached to all cases at each time interval. However, Figures 79 and 80 show that during the considered time period the fire load did not run out. The value used for the fire load density (Gumbel distribution with parameters $\alpha = 675$, $\beta = 182$) was obtained from the Eurocode 1 (2002). The value for residential buildings presented in Finnish building regulations E1 (Ministry of the Environment 2002) was 600 MJ/m^2. With each of these values, the fire load would last over the whole considered time period ($t = 20$ min) and thus the results would not be affected even if the E1 value (Ministry of the Environment 2002) was used.

8.3.6.6 Probability distributions

The resulting distributions are introduced in Figure 82.

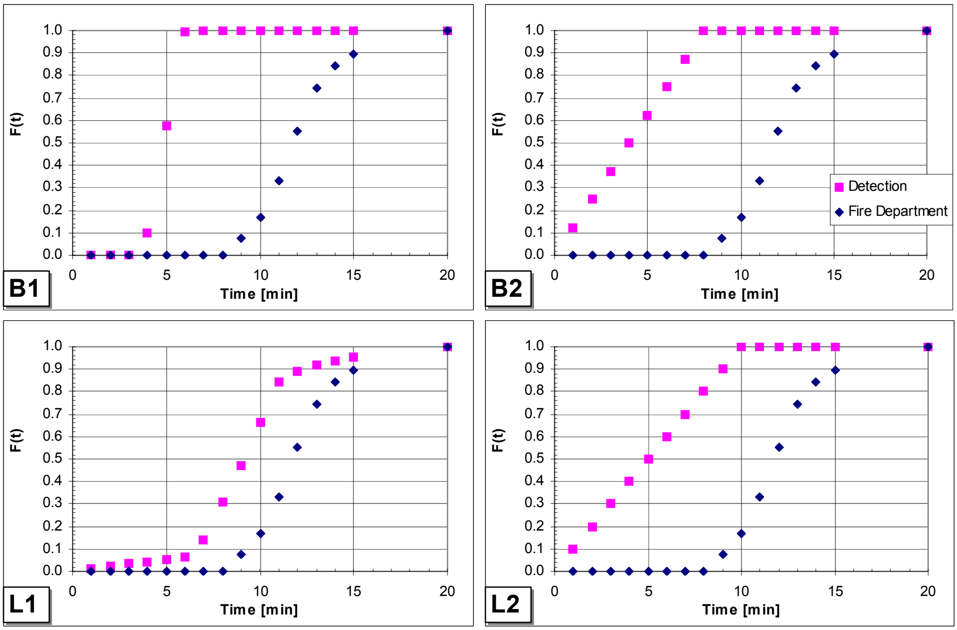

Figure 82. Probability distributions of detection and success of the fire department. B1: fire in the bedroom during daytime, B2: fire in the bedroom during nighttime, L1: fire in the living room during daytime, L2: fire in the living room during nighttime (see Sections 8.3.5.1 and 8.3.5.2).

The cumulative probability distributions, however, cannot directly be used as the branching probabilities and conditional probabilities at the branching points of the time-dependent event trees should be used. The method is described in detail in Hietaniemi et al. (2002) and Korhonen et al. (2002).

8.3.7 Results

8.3.7.1 Temperatures and smoke-layer height

In Figure 83, the probability distributions of the maximum temperature in rooms 1–3 obtained as an output of the Monte Carlo simulation are presented. The cumulative probability distribution of the time when the smoke layer reaches the middle of the room height is also presented in Figure 83. The average maximum temperatures in different rooms and the average flashover time of the ignition room are presented in Table 29.

Table 29. Average maximum temperatures in rooms 1–3 and average flashover time of the ignition room obtained as output of the Monte Carlo simulations.

Room	**Average maximum temperature [°C]**			**Average time to flashover [min] Ignition room**		
	B1	**B2**	**L1,L2**	**B1**	**B2**	**L1,L2**
1	660	735	360	8	8	
2	145	80	360			
3	235	125	750			10

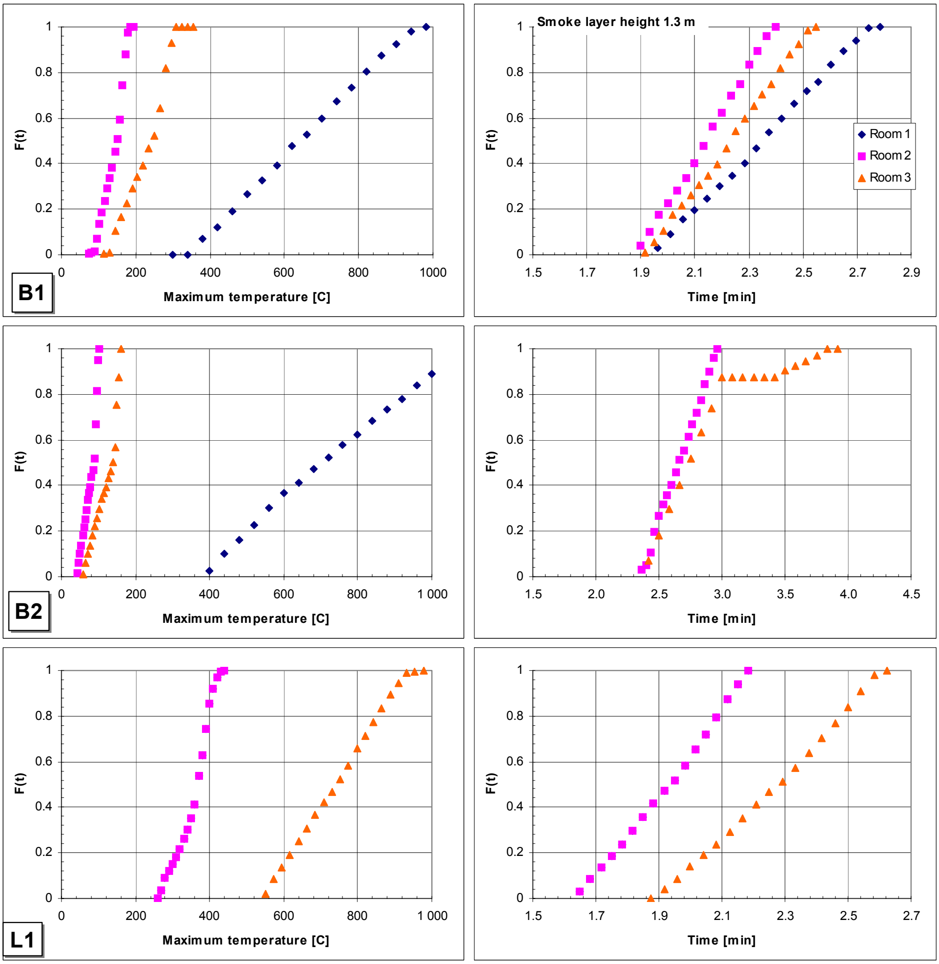

Figure 83. Probability distributions of maximum temperature and smoke layer height h=1.3 m. B1: fire in the bedroom during daytime, B2: fire in the bedroom during nighttime, L1: fire in the living room during daytime, L2: fire in the living room during nighttime (see Sections 8.3.5.1 and 8.3.5.2).

8.3.7.2 Probabilities of consequences

Using this approach, the loss in monetary terms could not be determined directly. However, the development of the fire indicates the extent of losses. As a criterion for severe economic losses, the flashover of the ignition room was considered. A flashover was assumed in this study to occur when the maximum temperature in the ignition room reached the critical value of 600°C. The probability distributions of flashover in fire scenarios 1 and 2, obtained as a result of the Monte Carlo simulations, are presented in Figure 84.

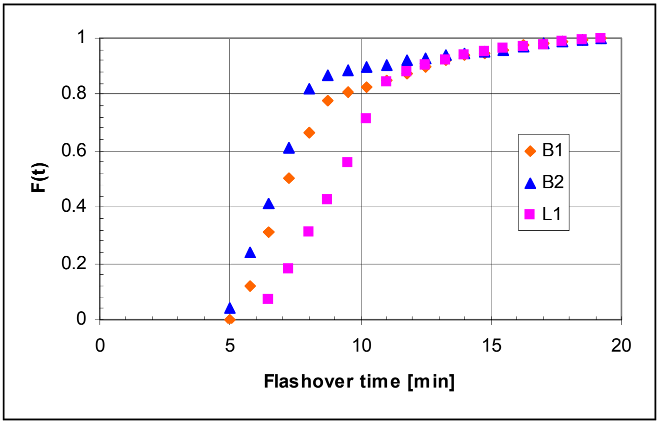

Figure 84. Probability distributions of flashover in scenarios B1, B2 and L1. B1: fire in the bedroom during daytime, B2: fire in the bedroom during nighttime, L1: fire in the living room during daytime (see Sections 8.3.5.1 and 8.3.5.2).

The damages were converted to monetary value by using the information in the accident database on the extent of damage expressed, as shown in Figure 61. It was assumed that the flashover had occurred if the extent of damage covered the whole ignition room, ignition compartment or several compartments. Respectively, the flashover had not occurred if the extent of damage was reported to cover only part of the ignition room or if the fire had extinguished. Furthermore, with this division, the average monetary loss was determined and shown in Figure 85. The average damage degree in apartment houses was 0.2% when flashover did not occur and 1.4% when it did. In detached houses, the values were 4% and 41%, respectively. The great difference between values of detached and apartment houses was caused by the fact that in the accident database the value-at-risk comprises the value of the whole building. In detached houses, the whole building generally includes one fire compartment and, in apartment houses, several. However, if the value-at-risk is known, the damage degree also can be used to estimate the monetary loss.

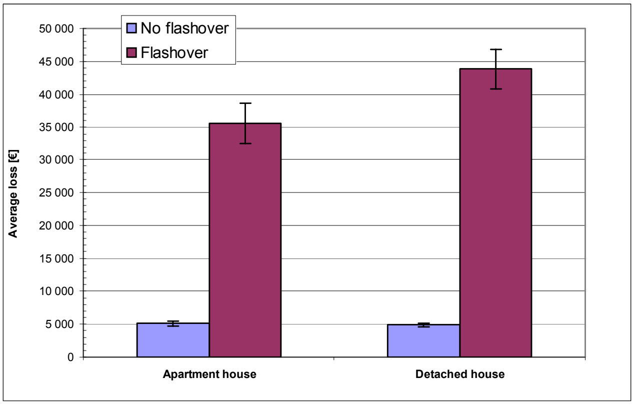

Figure 85. Average loss when the flashover had or had not occurred ($N_{apartment}$ = 2 223, $N_{detached}$ = 3 621). The error bars represent the standard error of mean (see Section 2.7).

The values of detached and apartment houses were the same order of magnitude. However, the average losses were multiple when the flashover did occur compared to situations where it did not.

8.3.7.3 State probabilities: Bedroom fire, Scenarios B1 and B2

The time evolution of the fire incident in scenario B1 is summarised in Table 30 and in scenario B2 in Table 31. Probabilities of each state $P[A_i]$ are presented and 'Fire' is the sum of states $P[A_4]$ and $P[A_6]$ and 'No fire' sum of states $P[A_1]$, $P[A_2]$, $P[A_3]$ and $P[A_5]$. The probabilities are presented as a function of time in Figure 86.

Table 30. Time evolution of the states of the system in scenario B1: fire in the bedroom during daytime (see Section 8.3.5.1).

Scenario B1					
State	**Explanation**	**Time [min]**			
		5	**10**	**15**	**20**
P[A_1]	Detected, Extinguished manually	0	0	0	0
P[A_2]	Detected, Extinguished by the fire dep.	0	0	0.19	0.90
P[A_3]	Detected, Fire load burned out	0	0	0	0
P[A_4]	Detected	0.57	1	0.81	0.10
P[A_5]	Not detected, Fire load burned out	0	0	0	0
P[A_6]	Not detected	0.43	0	0	0
Fire	States A_4 and A_6	1	1	0.81	0.10
No Fire	States A_1–A_3, A_5	0	0	0.19	0.90

Table 31. Time evolution of the states of the system in scenario B2: fire in the bedroom during nighttime (see Section 8.3.5.1).

Scenario B2					
State	**Explanation**	**Time [min]**			
		5	**10**	**15**	**20**
P[A_1]	Detected, Extinguished manually	0.16	0.25	0.25	0.25
P[A_2]	Detected, Extinguished by the fire dept.	0	0	0.25	0.70
P[A_3]	Detected, Fire load burned out	0	0	0	0
P[A_4]	Detected	0.47	0.75	0.50	0.05
P[A_5]	Not detected, Fire load burned out	0	0	0	0
P[A_6]	Not detected	0.38	0	0	0
Fire	States A_4 and A_6	0.84	0.75	0.50	0.05
No Fire	States A_1–A_3, A_5	0.16	0.25	0.50	0.95

In scenarios B1 and B2, the state probabilities A_3 and A_5 are zero because, as Figure 79 shows, the fire load does not burn out during the considered time period. State probability A_1 in scenario B1 is also zero, because the flat was assumed unoccupied and thus no manual extinguishing actions were to be performed. Thus, in scenario B1, the extinguishing is dependent on the fire department's arrival. In scenario B2, the probable manual extinguishing actions influence on the probability of fire from the moment of detection.

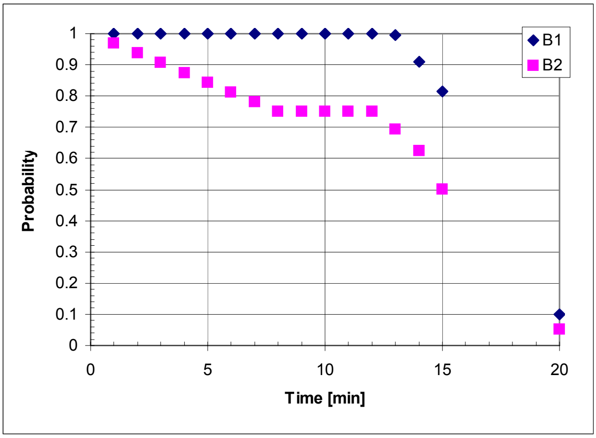

Figure 86. Probability that the fire continues at moment t. B1: fire in the bedroom during daytime, B2: fire in the bedroom during nighttime (see Section 8.3.5.1)

8.3.7.4 State probabilities: Living-room fire, Scenarios L1 and L2

The time evolution of the fire incident in scenario L1 is summarised in Table 32 and in scenario L2 in Table 33. The probabilities of 'Fire' and 'No fire' are presented as a function of time in Figure 87.

Table 32. Time evolution of the states of the system in scenario L1: fire in the living room during daytime (see Section 8.3.5.2).

Scenario L1					
State	**Explanation**	**Time [min]**			
		5	**10**	**15**	**20**
P[A_1]	Detected, Extinguished manually	0	0	0	0
P[A_2]	Detected, Extinguished by the fire dept.	0	0	0	0.28
P[A_3]	Detected, Fire load burned out	0	0	0	0
P[A_4]	Detected	0.05	0.66	0.96	0.72
P[A_5]	Not detected, Fire load burned out	0	0	0	0
P[A_6]	Not detected	0.95	0.34	0.05	0
Fire	States A_4 and A_6	1	1	1	0.72
No Fire	States A_1–A_3, A_5	0	0	0	0.28

Table 33. Time evolution of the states of the system in scenario L2: fire in the living room during nighttime (see Section 8.3.5.2).

Scenario L2					
State	**Explanation**	**Time [min]**			
		5	**10**	**15**	**20**
P[A_1]	Detected, Extinguished manually	0.13	0.25	0.25	0.25
P[A_2]	Detected, Extinguished by the fire dept.	0	0	0.13	0.67
P[A_3]	Detected, Fire load burned out	0	0	0	0
P[A_4]	Detected	0.38	0.75	0.62	0.08
P[A_5]	Not detected, Fire load burned out	0	0	0	0
P[A_6]	Not detected	0.50	0	0	0
Fire	States A_4 and A_6	0.88	0.75	0.62	0.08
No Fire	States A_1–A_3, A_5	0.13	0.25	0.38	0.92

Similar to the bedroom fire scenarios above, the state probabilities A_1 for scenario L1, and A_3 and A_5 for scenarios L1 and L2, were zero.

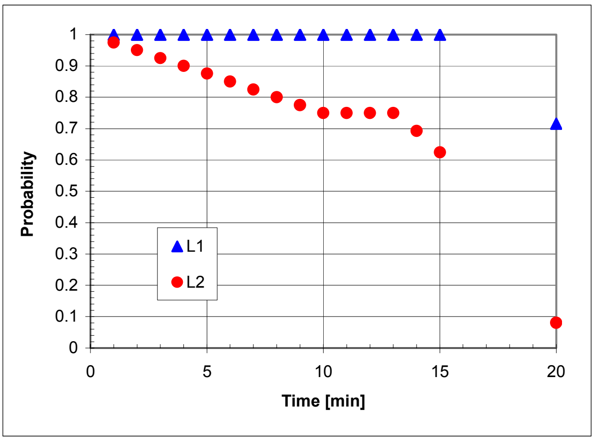

Figure 87. Probability that the fire continues at moment t. L1: fire in the living room during daytime, L2: fire in the living room during nighttime (see Section 8.3.5.2).

8.3.7.5 Probability of damages

The result after the probability of damages (flashover of the ignition room) has been incorporated into the probability of fire presented in Figure 86 and Figure 87 is presented in Figure 88.

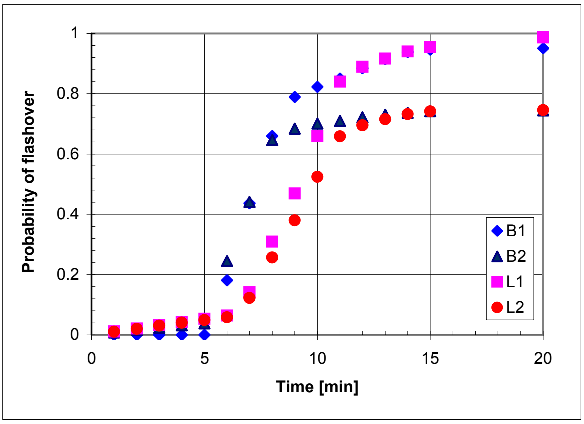

Figure 88. Probability distribution of flashover when the effects of extinguishing actions etc. are incorporated. B1: fire in the bedroom during daytime, B2: fire in the bedroom during nighttime, L1: fire in the living room during daytime, L2: fire in the living room during nighttime (see Sections 8.3.5.1 and 8.3.5.2).

The ignition frequency of the example building is placed around the 'peak' in the figures presented in Sections 5 (Figure 15) and 8.2.2 (Figure 70). Thus, if the Barrois model is used, it would be appropriate to use the partial co-efficient $\gamma_f = 3$ proposed for residential buildings in Section 5.3.3.4. That way, the ignition frequency was for all residential buildings 0.13 1/a and for concrete-framed residential buildings 0.22 1/a. The values obtained straight from the statistical observations were 0.15 1/a and 0.26 1/a, respectively. The value 0.22 1/a was used as the ignition frequency of the example building.

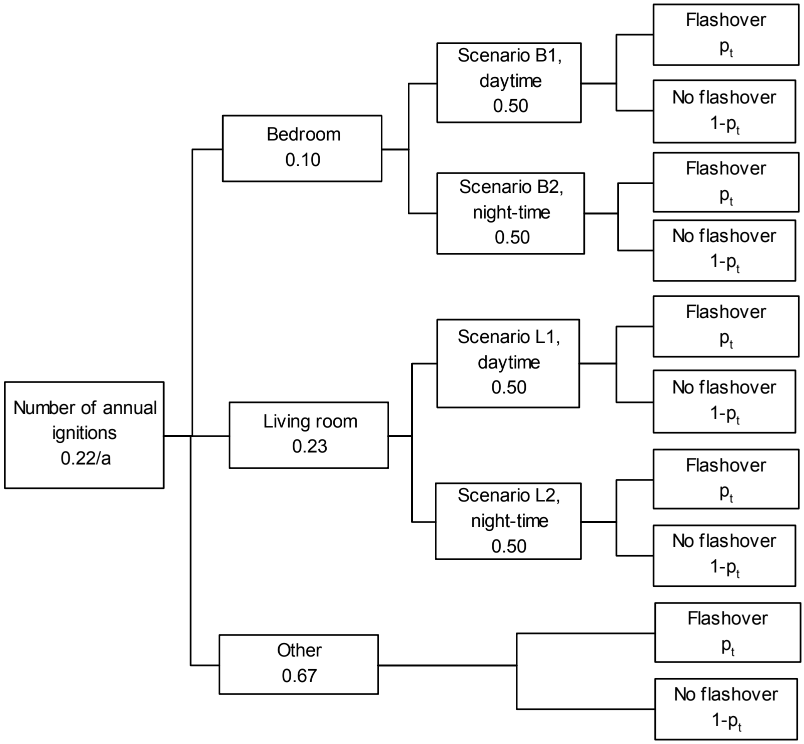

Figure 89. Flow chart of the determination of the annual probability of consequences caused by an ignition in the target flat.

Following the chart presented in Figure 89, the annual probability of a fire leading to a flashover can be determined. The probabilities related to different scenarios are presented in Table 34. Statistics showed that 67% of fires ignited premises other than living rooms or bedrooms (lowest branch in Figure 89). Those fires were excluded from the analysis, because the main purpose here was the illustration of the method. Also, it has been found that typically those fires are not very hazardous (FCRC 1996b).

Table 34. Probabilities related to different scenarios. B1: fire in the bedroom during daytime, B2: fire in the bedroom during nighttime L1: fire in the living room during daytime, L2: fire in the living room during nighttime (see Sections 8.3.5.1 and 8.3.5.2).

Number of ignitions [1/a]	**Room**	**Probability (Room)**	**Scenario**	**Probability (Scenario)**	**Flash-over**	**Probability of damages (Flashover)**			
						5 [min]	**10 [min]**	**15 [min]**	**20 [min]**
0.22	Bedroom	0.10	B1	0.5	Yes	0	0.822	0.946	0.951
0.22	Bedroom	0.10	B1	0.5	No	1	0.178	0.054	0.049
0.22	Bedroom	0.10	B2	0.5	Yes	0.038	0.701	0.742	0.744
0.22	Bedroom	0.10	B2	0.5	No	0.962	0.299	0.258	0.256
0.22	Living room	0.23	L1	0.5	Yes	0.053	0.660	0.955	0.987
0.22	Living room	0.23	L1	0.5	No	0.947	0.340	0.045	0.013
0.22	Living room	0.23	L2	0.5	Yes	0.049	0.524	0.742	0.745
0.22	Living room	0.23	L2	0.5	No	0.951	0.476	0.258	0.255

In Table 34 the probabilities related to each scenario are presented. The probability of damages represent the probability of flashover in each scenario (B1, B2, L1, L2) after the extinguishing actions have been incorporated (Figure 88). For each scenario, the total probability of flashover as a function of the fire duration is obtained by multiplying the probabilities of each column. Thus by multiplying the probabilities presented in the third row $P(t = 5 \text{ min}) = 0.22 \cdot 0.10 \cdot 0.5 \cdot 0.038 = 0.0004$, the probability of a fire igniting in the bedroom during nighttime leading to flashover is obtained. By adding together the probabilities of scenarios where flashover did and did not occur, the probability of flashover presented in Table 35 as a function of fire duration was obtained. By multiplying the result with the related financial loss presented in Figure 85 and in Table 35, the expected annual loss was obtained and is presented in Table 36 and in Figure 90.

To obtain the total fire risk level of the building, the fires igniting in other premises should be added to the results. In this example case, only the most hazardous cases were examined and the contribution of fires igniting in other premises was assumed negligible and was therefore excluded from the analysis.

Table 35. Probability of flashover.

	Time [min]				Damages [€]
	5	**10**	**15**	**20**	
Flashover	0.003	0.047	0.061	0.062	35 548
No flashover	0.070	0.026	0.011	0.010	5 114

Table 36. Expected annual loss in example building.

Probable loss [€/a]				
	Time [min]			
	5	**10**	**15**	**20**
Flashover	105	1 660	2 185	2 220
No flashover	360	130	60	50
Total	465	1 790	2 245	2 270

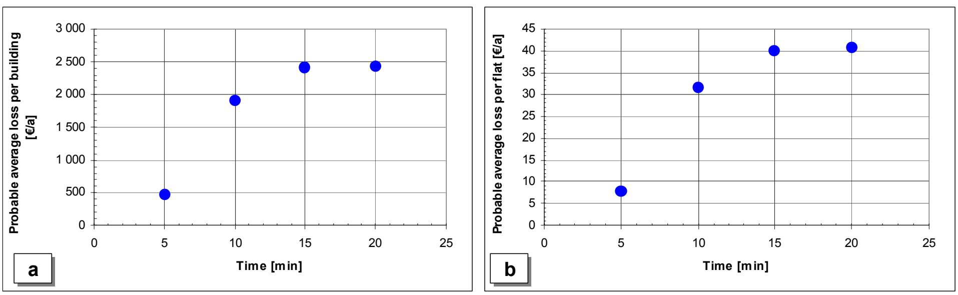

Figure 90. Probable average annual loss a) per building and b) per flat as a function of the duration of the fire.

The result was determined as annual monetary loss as a function of the duration of the fire. The loss at t =20 min was about 2 300 €, which corresponds about 40 € per one flat.

The average fire risk for apartment houses obtained in Section 8.2.1.3 was 10 €/flat and for concrete-framed houses (Section 8.2.2.3) with floor area of 13 200 m^2 the value was 6 000 €/building, which results in 100 €/flat for a building with 60 flats. The difference between the average values is caused by the determination of the ignition frequencies. The 10 €/flat is obtained using the ignition frequency value presented in Figure 67c). However, the example building is larger than an average apartment house and so to obtain comparable values the ignition frequency should be determined starting from the floor area (Figure 67a)) as in Section 8.2.2. Thus, the ignition frequency for the example building results in a value of

$$f_c = \gamma_f \cdot f_m^{"} \cdot A = 3 \cdot 6.1 \cdot 10^{-6} \cdot 13\ 200 = 0.24\ \ /\mathrm{a} \tag{35}$$

Furthermore, the fire risk is 5 500 €/building, i.e. 90 €/flat for a building with 60 flats, which is the same magnitude with the value determined for the concrete-framed houses in Section 8.2.2.3. Still the value is over twice the amount obtained using the time-dependent event-tree method. However, only the fires ignited in bedrooms or living rooms were included; the value would be somewhat larger if the fires ignited in other premises were incorporated.

8.3.8 FDS3 simulation results

8.3.8.1 General

To validate the results obtained in this section, the fire in the example flat was simulated using FDS3 (McGrattan et al. 2002). The flat layout is presented in Figure 91. The design fires (B1, B2, L1) were located in the bedroom and living room as presented in Section 8.3.5. The ignition source in the bedroom fires (B1, B2) was the bed and, in the living-room fire (L1), the sofa. The breaking of the window of the ignition room was simulated by opening a vent to the outside when the upper layer temperature reached the critical value 350°C (Shields et al. 2001, 2002). The materials of the bed, sofa and the chair in the living room were assumed polyurethane, other furniture wood and the walls plasterboard.

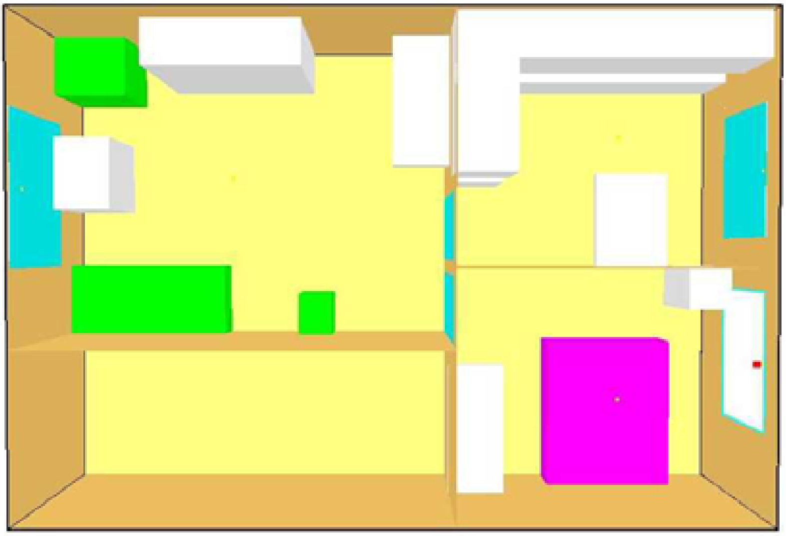

Figure 91. Floor layout of the simulated flat.

8.3.8.2 Bedroom fire

The temperature in rooms 1–3 and the total rate of heat release as a function of time is presented in Figure 93. The bedroom and the fire source are presented in Figure 92. The temperatures in Figure 93 are the same magnitude as the average temperatures obtained from the Monte Carlo simulation in Section 8.3.7.1. The assumed rate of heat release distribution between 1–3 MW seems reasonable on the grounds of the FDS3 results. The upper layer temperature in the ignition room exceeded 350°C, used as a criterion for window breaking, in around 2.5 min. The temperature rise was faster compared to Monte Carlo results in which the criteria was reached, on average, after about 5 min. The flashover criterion 600°C was reached faster, i.e. after about 4.5 min, when the average value obtained from the Monte Carlo simulation was around 8 min. This may be a result of the material properties of the ignition source, which were determined in more detailed in FDS3 simulation. The parameters used in the Monte Carlo simulations were taken from the Eurocode (2002), which is based on historical evidence. The simulations with the real material data, like the polyurethane bed as the ignition source, may lead to faster development of the fire. However, the maximum temperatures and the rate of heat release were consonant with the Monte Carlo results and thus the initial parameters used can be assumed suitable.

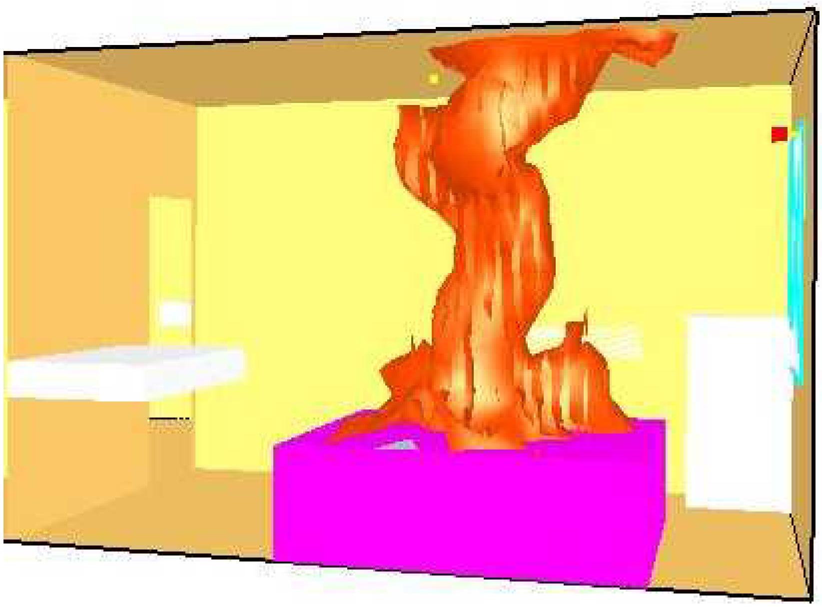

Figure 92. Ignition source (bed) in the bedroom fire scenarios B1 and B2. B1: fire in the bedroom during daytime, B2: fire in the bedroom during nighttime (see Section 8.3.5.1).

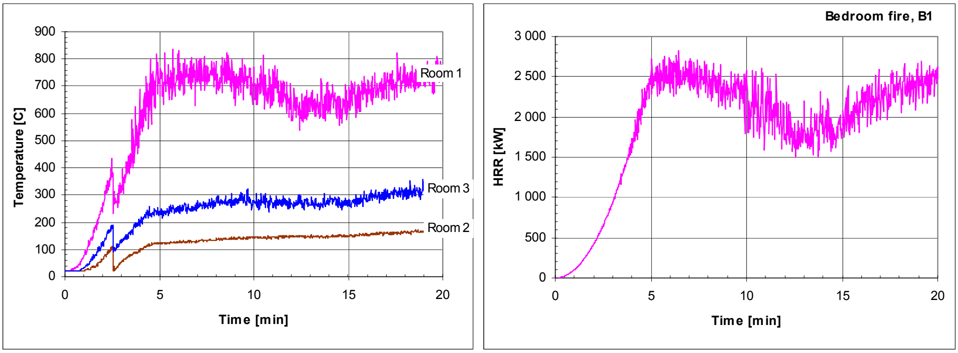

Figure 93. Upper layer temperatures in rooms 1–3 and the total heat release rate as a result of FDS3 simulation of scenario B1: fire in the bedroom during daytime (see Section 8.3.5.1).

Scenario B2, where the door to the living room was closed, was also simulated. The upper layer temperatures and the total heat release rate are presented in Figure 94. The temperature in the ignition room rose to around 850°C as a result of the FDS3 simulation. The average maximum temperature obtained from Monte Carlo simulations was 750°C. The temperatures in rooms 2 and 3 were around 100°C and 200°C, respectively.

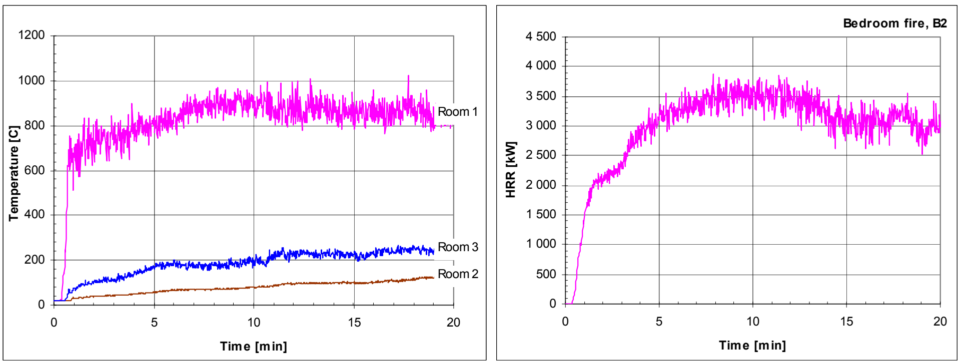

Figure 94. Upper layer temperatures in rooms 1–3 and the total heat release rate as a result of FDS3 simulation of scenario B2: fire in the bedroom during nighttime (see Section 8.3.5.1).

To figure out the possibility of the closed wooden door burning through during the fire, its surface temperature was evaluated. The data from literature (Spearpoint & Quintiere 2001, Hadjisophocleous & Benichou 1999, Tran &

White 1992, Mikkola 1989) demonstrate that there is a fair degree of variability in the ignition temperatures of wood. However, typical average ignition temperature under radiative exposure can be assumed to lie somewhere around 360 ºC (Mikkola 1989), which was used here as the criterion temperature.

The door surface temperature is presented in Figure 95, which shows that, during the simulation, the temperature was close to the critical range and that the effect of the flames touching the surface might have caused ignition. However, because the temperature was that low, the charring of wood would be very slow, even in case of ignition. Thus, the probability of the scenario in which the door is closed but will burn through during the fire was assumed low and excluded from the analysis.

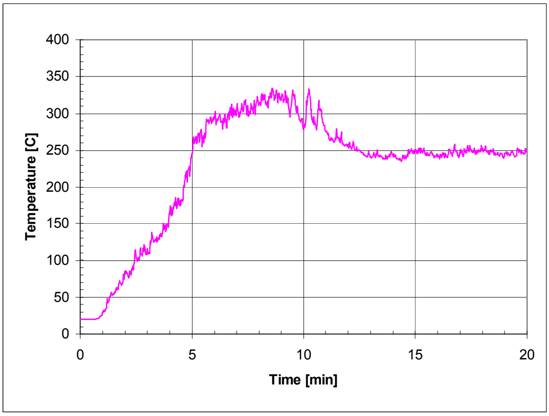

Figure 95. Door temperature of the ignition room in scenario B2: fire in the bedroom during nighttime (see Section 8.3.5.1).

8.3.8.3 Living-room fire

The upper layer temperatures and the total heat release rate in the living-room fire are presented in Figure 96. As can be seen from Figure 96, the rate of heat release was somewhat lower in the FDS3 than in the used range in the Monte Carlo simulation. However, this does not have an effect on the final result, presented in Section 8.3.7.5, because the correlation between the flashover time and the maximum RHR was not significant. In the FDS3 simulation, the flashover criteria 600°C was reached after 6–7 min, while in the Monte Carlo simulation, on average, after 10 min. Changes of the maximum rate of heat release most effect the time of the decay start and the maximum temperatures. The maximum temperature of the ignition room as a result of the FDS3 simulation was around 700°C and the Monte Carlo simulation 750°C. The temperatures in room 1 and 2 were around 200°C in FDS3. As a result of the Monte Carlo simulation with higher maximum RHR, the average maximum temperatures were higher, i.e. 360°C.

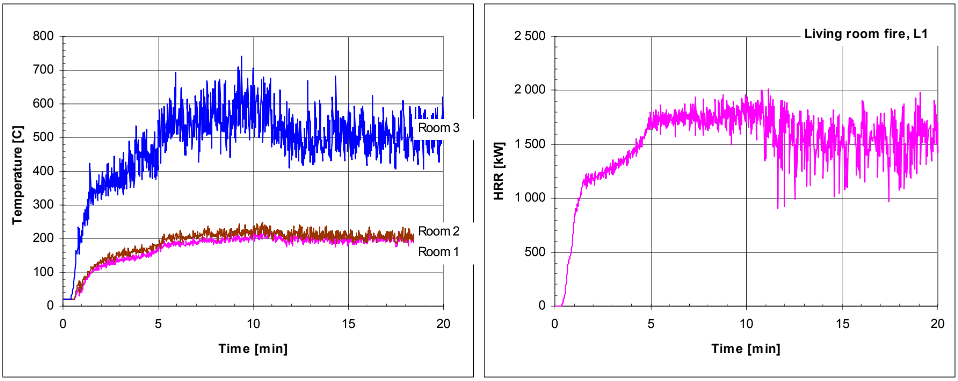

Figure 96. Upper layer temperatures in rooms 1–3 and the total heat release rate as a result of FDS3 simulation of scenario L1: fire in the living room during daytime (see Section 8.3.5.2).

8.4 Summary

The statistical information gathered and analysed was used to assess the fire risks in residential buildings. Average values were determined for wood- and concrete-framed residential buildings, in addition to the different residential building types. The gathered information was also utilised when a simple example of fire-risk determination in an average apartment house was carried out using the time-dependent event-tree approach. The development of the chosen fire scenarios were calculated by using Monte Carlo simulations incorporated with CFAST. As a result, the branching probabilities for the time-dependent event tree were obtained. The results of the Monte Carlo simulations were also compared to the fire development simulated using FDS3. The results corresponded reasonably.

The average fire risks obtained in Section 8.2 represent the average annual costs caused by fires in considered building groups, which in Section 8.2.1 were detached, row and chain and apartment houses and in Section 8.2.2 concrete-and wood-framed houses. The results were then calculated in relation to the whole building stock, i.e. per building or apartment etc. In this approach, it is assumed that the features of the normalising factor, i.e. buildings, flats and individuals, are equal in relation to fire risk. The more advanced approach presented in Section 8.3 acknowledges the individual features of the considered building and performed fire prevention measures. As a result, the probable average annual loss as a function of the duration of fire was obtained. The use of the time-dependent event-tree method requires a substantially greater amount of more detailed information on the target. The result is more accurate as well, and describes the fire risk of the exact building under consideration. Naturally, the result is sensitive to the uncertainties of the input parameters, which should be acknowledged in every phase of the analysis. In the presented example case, the uncertainty was handled by using the Monte Carlo simulation to describe the inherent variation of the input parameters. The lack of statistical data on the economic losses in relation to the state of the fire considered as a consequence (see Section 8.3.7.3) complicated the analysis. The defined spread of fire in the statistics available was not precise enough to achieve an accurate loss estimate. Due to the large uncertainty of the determined loss values, the actual monetary value of the fire risk is not, as such, accurate. However, the focus was not on the numerical values but on the illustration of the incorporation of gathered information to assess the fire risk of an individual building. The approach is valuable when loss data that completely corresponds to the chosen consequence event is available. The approach can then be used directly for predicting the insurance premiums, for example.

9. Discussion

9.1 Accident database Pronto

The accident database Pronto replaced its predecessor Ontika in the year 2000. At that time, many problems detected during Ontika's lifetime were overcome. Some remained, however, and were observed during this study. The data primarily used in this study covered the years 1996–99. Because of the continuous updating of the database, the samples picked out from the same period of time in some cases varied a little. It is estimated that in Finland approximately 3 000–3 500 building fires occur yearly. The latest sample selected from the accident database included 13 170 fires during 1996–99, which is approximately 3 300 fires per year. The variation of the number of fires had the greatest effect on the results of the ignition frequency in Section 5. The matter is considered more closely in Section 9.3. Overall, the accident database is a valuable data source as it is now, but with a more exhaustive compilation of all the data fields, some of which, although already included in the system, are often left empty, it would provide the requisites for an even more extended analysis.

9.2 Building stock

The information on the building stock was delivered by Statistics Finland. The description of the quality and reliability presented here is based on the presentation by Harala & Nieminen (1998).

In general, the coverage of the building stock is good. However, the problem is that it does not cover buildings that are built without a construction licence or are not populated year-round. Agricultural buildings, for example, or free-time residential buildings are not registered in the building stock. This problem concerns mainly the category of other buildings (N) and small warehouses. The coverage concerning agricultural buildings is especially poor. All agricultural buildings built before 1982 are not registered. The situation is the same for most of the buildings constructed after that, because, in some communities, buildings related to agricultural production can be built in some cases without a construction license. Also, small outbuildings in the context of residential buildings were systematically excluded from the stock. Fires in these buildings are, however, included in the accident database. During 1996–2001, according to the information in Pronto, an average of 125 fires ignited yearly in free-time residential buildings, 185 in agriculture buildings and 560 in other buildings.

The information on the demolition of a building is only registered in the building stock if a new building is constructed on the site and new construction license is applied. However, the information in the register is checked regularly.

The reliability of the information on the building stock has been assessed in the study carried out in connection with the calculation of population in 1990 (Statistics Finland 1994b). According to the study, the information on the building stock included 20 000 extra buildings, approximately 1.7% of the whole stock. These were demolished, destroyed or changed to free-time residential buildings. The classification of buildings was the same as the comparison data in 98.5% of the cases, and the floor area in 83%. The difference exceeded 50 m^2 in 5% of the buildings. However, the information on the floor area in the comparison data was collected by a question blank, which may have caused some inaccuracy in the estimated variations.

The reference year used here was 1999. During the years 1997–2000, the number of buildings increased 3.9% and the floor area 4.2%. Thus, the increase of buildings did not have a statistically significant influence on the results.

9.3 Ignition frequency

The ignition frequency was studied using at first the data from the years 1996–99 and later updated data from the years 1996–2001. The updating did not significantly change the results.

The analysis showed that the ignition frequency does not approach a constant level with large values of the floor area and local peaks, depending on the initial floor area distributions of buildings hit by fire and at risk, are possible. However, the theoretical floor area distribution used was still too simple to describe the actual distributions in great detail. Nevertheless, the point of the curve fitting was simply to clarify the reasons behind the floor-area-dependent variation of the ignition frequency and so alternatives that were more complicated were not tried. Before the matter is studied in more detail and the initial floor area distributions can be described more accurately, the method starting from the initial floor area distributions, will remain too uncertain for design purposes, because it is essential that the peaks are not mislocated.

Hence, for engineering design purposes, the generalised Barrois model is, for the present, more suitable. On the basis of the chi-test, the generalised Barrois model was found to fit very well to the observations of the groups including 1) industrial buildings and warehouses and 2) commercial, office, transport, fire fighting and rescue service, institutional care, assembly and educational buildings. Because of the clear peak in observations of residential buildings in a floor area region where the majority of the buildings changed from detached to apartment houses, for residential buildings the fit based on the chi-test was poor.

However, the residential buildings, which constitute the great majority (86%) of buildings, form, generally speaking, two groups: small detached houses in addition to row houses and large apartment houses. This leads roughly to the sum of two power laws. The peak was acknowledged with the appropriate partial safety co-efficient determined in Section 5.3.3.4, where the values were estimated for the four building category groups to be used for design purposes. The use of partial safety co-efficients also acknowledged the uncertainty due to the known defects of the data in the accident and the building stock databases. However, because of the serious defects of data in the latter, the results associated with the group 'other buildings' cannot be considered reliable.

As a result of the analysis, no more than pointers were obtained to settle the question of why the ignition frequency in small buildings is higher than that in larger buildings. It should be noted that the definition of ignition was a fire incident to which the public fire department had been called. So every fire extinguished by occupants, or self-terminated, and not reported to the fire department was not included in the analysis. It is clear that in larger buildings planned fire-safety measures, as well as precautions against fire, are much more stringent than those for small buildings, where generally no special requirements apply. This influences fire ignition frequency and probably has an even greater effect in terms of the ultimate consequences of the fire. Also, ignition needs ignition sources: human activity, equipment faults or natural phenomena. A daily living routine includes a number of deliberate ignitions. A small fraction of these may become uncontrolled. Similarly, certain kinds of equipment have the potential to ignite when energized. The number of these per capita may be fairly constant. In smaller buildings, these are 'packed' closer than in bigger buildings. In an uncontrolled environment, the failure probability leading to ignition grows as well. These observations suggest possible explanations but are, at this stage, only ideas that need to be tested in future studies. For these reasons, one also has to combine several statistical databases other than those used here. Some of these might be readily available, while some others may need specific data collection. These types of modelling efforts are worthwhile because they could lead directly to a better understanding of the reasons behind fire ignition.

9.4 Fire department intervention in a building fire

9.4.1 Time distributions

The operative time distributions from the year 2000 shown in Figures 20 and 21 included 5 387 observations of rescue vehicles. Of turnout time observations 4%, response time observations 19% and operating time observations 1% were marked zero or left empty. These observations were excluded from the analysis. The number of useless turnout and operating time observations was negligible but the number of useless response time observations was rather large. Since the amount of useful observations still exceeded 4 000, the useless observations were disregarded and the analysis carried out. Because there was no reason to assume otherwise, the useless observations were assumed to be equally distributed over the data set. It is reasonable to assume that the procedure did not significantly distort the shape of the distribution. The sum of two gamma distributions was fitted to the observations. The fit to the response and operating time observations was quite good. The goodness-of-fit was measured using the chi-test, which resulted in the sum of chi-squares 38 and 36, respectively (p-value = 0.01, both). The fit can be assumed to be very good as it would be very rare for any theoretical distribution to give an absolutely perfect fit to observed phenomena such as the time distributions considered here. The fit to the turnout time distribution was clearly weaker; a more complicated function would be needed to achieve a reasonable fit. Therefore, the turnout time when needed should be estimated straight from the observed values. For an estimation of the response or operating time, the sum of two gamma distributions can be used.

9.4.2 Travel time model

In this study, the travel time model was primarily used to assess the probable response time of the fire department. When the results obtained from the model were added up with the turnout time from the statistics and compared to response-time observations, the results corresponded to each other quite well. Thus, the results obtained from the travel time model were accurate enough for the purposes of this study.

When the travel time model (Equation (24)) was adapted, the digital road network was not available. Thus, the travel distances used in the parameter estimation could not be measured accurately. In addition, the distance data was not available from the whole country but only from three example areas. They however represented well the different types of area structures existing in Finland. The first of them was the capital city of Finland, where distances are short but traffic jams ordinary. The second area was a smaller town 170 km north of Helsinki. There, the traffic obstacles do not have an effect comparable to Helsinki and the travel distances are more often longer. The third example was a rural area on the west coast of Finland approximately 400 km from Helsinki. In that area, the travel distances are often extremely long compared to other example areas. There are no traffic jams but the quality of the roads varies. However, the differences of travel time between the test areas are small (Tillander & Keski-Rahkonen 2000a).

The most serious deficiency of the analysis was the lack of the digital road network. To be able to get more accurate results, the number of observations should be larger and the actual distances measured with a higher accuracy using the digital road network. The model should also be improved in the future in such a way that it would acknowledge the features of the road network and the influence of the variation of the traffic flow.

9.4.3 Fault-tree approach

The used fault trees were simple and primarily constructed for demonstrating the technique. The lack of statistical data prevented their more detailed extension. In spite of their simple structure, for the purpose they were used for, i.e. to compare alternative design solutions, the method in the presented form was suitable. To obtain as good results as possible, the primary event should be divided into as many sub-events as the available data allows.

9.5 Fire losses

9.5.1 Economic loss data

The analysis was carried out using fire loss data for the years 1996–99. The parameters of the loss distribution did not change significantly when the data was extended to cover the years 2000–01 also. The analysis of the effect on the load-bearing structure material covered the fire loss data from the years 1996–2001. The extent of the analysis was narrowed by the deficient registration of the information on the material, which was entered appropriately in only 50% of the fires ignited in buildings. However, the analysis showed that it was not the material of the load-bearing member itself, but the use of the building, that was the primary factor affecting the fire loss, although the materials seemed to be divided characteristic to the type of use. Only in 0.6% of the observations the type of use of the building was unknown. Despite of the defects mentioned above, the shapes of the distributions, tendencies and behaviour of the loss became evident.

The changes in the value of money during the reference period were assumed insignificant, taking into account the estimation methods of the economic losses and values-at-risk. No trend of loss transpired during the period, as can be seen from Figure 97, in which the medians of the total loss for each year are plotted.

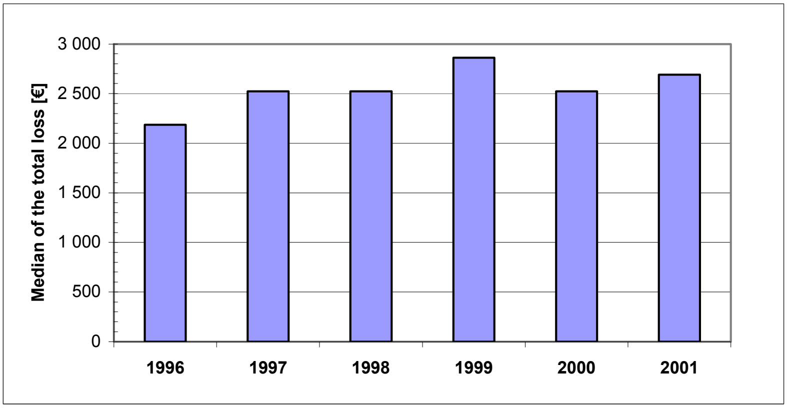

Figure 97. Medians of the total loss during 1996–2001.

9.5.2 Theoretical models

In Section 7.1, Ramachandran's theory was applied to Finnish fire losses. Ramachandran (1979/80, 1982) has stated that the tails of the loss distribution differ from lognormal distribution, but that it is highly unlikely that any mathematical distribution could fit the loss data absolutely perfectly, and thus the assumption of the lognormality is reasonable.

In his theory, the value-at-risk equals to the sum insured and thus individual loss (indemnity) cannot exceed the sum insured. Therefore, the theory is suitable for estimating the expected indemnity in the similar group of buildings for which the insured value is V. Statistical treatment of fire insurance claims, however, includes some complications. Claims of properties underinsured distort the loss data, because the indemnity paid by the insurance company to the property owner is only a portion of the real loss. Also, some losses are not reported to the insurance companies, generally because of some agreement on the deductibles, i.e. the amount the insured will bear in case of the fire is made on the insurance contract. For instance, by some fire prevention measures or other actions reducing the loss in case of a fire, some policyholders are willing to accept rather large deductibles to obtain a reduction to premiums. Thus, the insurance claim data does not include the losses under the given deductible, which distorts the loss distribution.

Finnish fire loss data was based on the estimate made by the fire officials and included all fires to which the fire department was called. Thus, the data also included the losses under deductible amounts and also possibly some misjudged amounts. However, the estimates of the large properties were found to correspond well to estimates made by the insurance companies (Lindblom 2001) and so the loss data in the accident database was considered reliable.

However, particularly the small losses in the first part of the distribution influence the shape of the distribution and the parameters of the lognormal fit. In Finnish fire loss data, 30% of losses in residential buildings, and 20% of other buildings, were under 1 000 €. Furthermore, 40% of losses in residential buildings, and 30% in others, were under 2 000 €. A better fit of observations with the Ramachandran's theory was achieved when the small losses were ignored.

9.5.3 Results

Because of the different definition of the value-at-risk and other uncertainties, the actual numerical values obtained using Ramachandran's theory to estimate the expected loss and loss probability (Sections 7.1.5 and 7.1.6) should be considered with caution. However, by releasing the parameters of the theoretical curve for predicting the expected loss, a good fit to the observations was achieved. To decrease the uncertainty of the loss estimates, the assessment of the monetary value of the loss and value-at-risk should be reliably unified nationally. However, based on the analysis by Lindblom (2001), the data in the accident database relating to large losses corresponded well to the data in the possession of the insurance companies. The loss data can therefore be assumed reliable. However, the possibility of comparing the data including also smaller losses with the data in the possession of the insurance companies would be beneficial. Unfortunately, that information is often very difficult to obtain. Nevertheless, for comparison of the groups of buildings or different design solutions etc., the quality of the statistical information in Section 7 is adequate. The error bars plotted in each figure indicated the deviation of the loss data from which the level uncertainty of every result can be seen. However, especially in relation to results in which a large uncertainty was observed, the actual numerical values should be validated by comparing the loss data with some other database before the results can be used for purposes where the exact numerical values play a significant role. In general, for fire-risk assessment, the loss data should be limited to the specific building category considered in order to decrease the effect of the differences in building types or manner of compartmentation on the loss estimates.

9.5.4 Fire deaths

The fire-death data in the accident database turned out to be incomplete, which was a serious defect of the system. The problem seems to be organisational, because the information on the fire deaths that occur after the victim has been transported from the fire scene is not returned to the fire officials and so is not registered in the accident database. The studies must therefore be carried out using other databases (Rahikainen 1998b, Rahikainen & Keski-Rahkonen 1998 c, 1999a, b, 2001) or by combining other databases with Pronto (Tillander et. al. 2002b). In this work, two statistical sources were combined and a 67% coverage of all fire deaths was achieved. Because only deaths in building fires were considered here, the real coverage was actually somewhat higher. Overall, the annual number of fire deaths is, from the statistical point of view, very small, which complicates the analysis. From the results of the analysis presented in this work, the tendencies and general features could be noted. For actual numerical estimates, the data was too sparse.

9.6 Summary

This study was the first relatively broad statistical survey that utilised the statistical data collected in the national accident database and it aimed to produce knowledge and new information related to fire risks in buildings. However, many of the methods used are well known in other application areas and the available statistical data now offer the possibility of applying them to fire technology also. In risk-analysis-based design, the presented approach is very useful and, in general, the methods are capable of being used for the fire-risk assessment of buildings. Some of the results of this work have already been utilised in the design of real building constructions, but still some of the preliminary models must be checked and improved, and the statistical analysis carried out in more detail to obtain more accurate and reliable risk estimates.

The use of statistics as a background to the models brings an objective viewpoint to the analysis as the statistics are based on real fire incidents, which is the real strength of the approach. Furthermore, this approach is totally frequentistic and thus useful in the fire-risk assessment of buildings about which an adequate amount of statistical information is available. Although, there is always a debate on the quality and accuracy of the statistical data, this study strengthened the standpoint that the use of statistical information is a good objective way to characterise fire.

9.7 Future work

Following this part of the work, an overview of the ignition frequency, consequences of fires and fire department operation is established on the basis of the statistical data on building-fires in the accident database Pronto. Furthermore, first proposals for utilising the available statistical material in fire-risk assessment were drawn up. A challenge for future research is to improve the preliminary models by, for example, combining information on databases other than those used here with Pronto, and by using more sophisticated statistical analysis methods. The preliminary exploration has now been carried out and a good base for further research established. A few observations that were particularly noticed during this work and that will be useful in future studies are listed below.

The statistical data is collected for the accident database by several people, which automatically leads to at least slight differences in estimates sensitive to individual opinions. Most of such weak points of the system are well known and the greatest problem is not as much the misentered but the non-entered information. Most of all the carefulness, judgement and motivation of the fire officials entering the information into the accident database define the quality of the data. Therefore, the importance and significance of the thorough compilation of all available information should be emphasised to the people responsible, so the uncertainty due to human actions might be decreased further.

The study revealed a serious defect in data gathering. In addition to the whole floor area of the building registered in the database, the information on the floor area of the compartment(s) that the fire in reality has threatened would be relevant. With the available information on the fire compartment sizes, it would be possible to get closer to the real mechanisms producing the area dependence of the ignition frequency and fire loss. This is essential for fire prevention work.

In relation to the fire losses, the definition of the value-at-risk causes complications. In the accident database, the value-at-risk is the value of the whole building and property regardless of its use or size. For example, in large apartment houses the fire generally remains in the ignition flat and seldom threatens all apartments of the building and its whole value-at-risk. Thus, as is the case with floor area, a more specified level of information on the value-at-risk should also be available.

For future research, the statistical information on the fire department operation after they have arrived at the fire scene would be valuable. Knowledge of this would make it possible to examine the influence of the elements following the arrival on the success of the fire fighting. The available information would further allow a more detailed structure of the fault tree (see Section 6.6) and thus lead to more accurate probability estimates.

By using the digital road network, a more advanced travel time model could be formulated for the fire units. In addition to accurate distance estimates, it would allow the consideration of the features of the road network in the model. Most of all it would decrease the confidence levels of the model considerably. Although the superficial analysis of response times of fire units did not bring forward a significant effect of season or the time of day on the response time, their effect should also be considered in the formulation of the advanced model.

10. Conclusions

This work was the first relatively broad study utilising the information collected in the national accident database Pronto and the first attempt to utilise it extensively to obtain valuable new information related to fire risks. Although there are numerous factors affecting the fire risk of a building, they can generally be reduced to a product of the two components: probability of ignition and damages caused by the occurring fire. In addition to these risk components, the contribution of the fire department operation to the fire risk was estimated. In this work, a general view of these subjects was established and new valuable information relating to fire risks was gained, together with the quantitative tools and methods suitable for use in the fire-risk assessment of buildings as well as in engineering design.

Considering that this was the first time these statistics were utilised to this extent, the methods of analysis used were kept simple. This work will provide a good base for more detailed studies in the future; however, the tentative results and methods are already useful as they are, provided that the uncertainty of the results is recognised. In order to reduce the possibility of misinterpretation of the results, the uncertainty is represented visually with error bars in all figures.

In examining the first component of the fire risk, the ignition frequency of building fires was derived from statistics for different building categories in Finland. The analysis showed that the variation of the ignition frequency derived as a function of the total floor area of the building is dependent on the initial floor area distributions of the buildings involved in fires and total stock at risk. Good agreement with the observations was obtained using this approach. It showed that small local peaks of ignition frequency are possible and that in large values of the floor area ignition frequency does not approach a constant level. However, due to uncertainty of the theoretical fit on the floor area distributions, for engineering design purposes, the sum of two power laws proposed earlier (Rahikainen & Keski-Rahkonen 1998a,b) is still a suitable simple calculation form, provided partial safety coefficients are calculated properly. The sum of two power laws, called the generalised Barrois model, is a generalization of the theory starting from the initial floor area distributions and is applicable to determining the ignition frequency of buildings with a total floor area of between 100 and 20 000 m^2. With a large amount of data, the model parameters and partial safety co-efficients for engineering purposes were estimated for three building groups.

As the consequences of the fires, the economic losses were considered. The loss data confirmed a dependency between the floor area and the value-at-risk, which thereby can be used as equal descriptors of the size of the building. The skewed nature of the loss distribution was observed and a reasonable fit, especially at the middle part, was achieved with the lognormal distribution. Consideration of loss data of all buildings as one group showed a clear growth of average loss as a function of the floor area, which settled to a constant level with large floor areas or values at risk.

The detailed analysis of the individual building groups proved that the use of the building substantially influences the fire risk. The material of the load-bearing member itself did not seem to be that relevant, nevertheless the materials seemed to be divided according to the type of use. The analysis of separate building groups revealed local peaks in the area dependency of both the ignition frequency and fire loss. The use of the total floor area as a correlation descriptor brought out the effect of the compartmentation on the risk components. The analysis showed that in one-fire-compartment buildings the ignition frequency decreased and fire loss increased steeply with the floor area. In buildings with several fire compartments, the ignition frequency started to increase and the growth of fire loss slowed down. The peaks appeared around the floor area region where the dominant building type of the total building stock, and therefore the compartmentation manner, changed. A natural explanation for the behaviour is that in buildings with several fire compartments the number of ignition sources is also multiple and thus the ignition probability higher. However, an average fire generally remains in the ignition compartment and only this is damaged. Therefore, the average loss does not vary as a function of the total floor area but the size of the fire compartment. Apartment houses versus detached houses are an example of this. Naturally, ignition sources are multiple in apartment houses with several flats. The individual analysis of losses in both groups showed that the loss grew rapidly as a function of the total floor area in detached houses, while the growth was substantially slower in apartment houses. A natural explanation for this is compartmentation.

The analysis of the available data on fire deaths in building fires showed in general somewhat larger losses and wider spread at fire department arrival in fatal fires. The results supported the conclusion drawn in earlier studies (Rahikainen 1998b, Rahikainen & Keski-Rahkonen 1998c, 1999a, b, 2001) that the main cause of fire deaths is the victims own behaviour and thus any technical fire safety measures might not have an extensive influence in reducing human fire losses in Finland.

In addition to the assessment of the probabilities of ignition and fire loss, an essential part of the risk-analysis based fire safety design is the consideration of the fire department operation in case of a fire. For design purposes, two alternative approaches were presented to distinguish the buildings in which the fire safety depends completely on automatic extinguishing systems from those in which the fire department is able to arrive at the fire scene early enough to have a good chance to save the building.

In the first approach, the fault-tree technique was used. The branches of the fault tree are strongly dependent on the available statistical information but, where the data is not too sparse, quantitative estimates of the success probability of the fire department operation can be made for a particular building anywhere in the area. The time distributions describing the operation of the fire department (turnout, response, service time) turned out to be skewed, which should be acknowledged when the performance of the rescue force is estimated. The detailed analysis showed that in regions similar to Finland, characteristic of which are large sparsely inhabited areas and long travel distances, the most essential factor affecting the performance of the rescue force is the travel time to the fire scene. For estimating the travel times of the fire units with reasonable accuracy, the simple travel time model was adapted for rescue and command vehicles. In areas with high alarm rates, another factor limiting the successful operation of the fire department is the blocking probability, i.e. the probability that no free units are available to serve the incoming call. In Finland, the simultaneous alarms did not turn out to be too frequent and thus they do not contribute much to the success probability of the rescue team. However, it became evident that the number of ignitions was strongly dependent on the time of day, which is important knowledge when the required resources of the fire department are optimised. The diurnal variation could be described reasonably well with a cosine function.

For regions where the travel time is clearly the dominant factor, a more convenient approach in which the response time of the rescue team was compared to the time-dependent fire growth was presented. Overall, the analysis showed that, in order to make the task easier for the fire department, special attention must be paid to rapid fire detection and locating of the fire seat. Delays in these actions lengthen the total response time and reduce significantly the chances of the fire department to successfully intervene in the progress of the fire.

The presented techniques can be used in risk assessment in performance-based design and a number of buildings have been designed, approved by local authorities, and constructed along these lines in Finland. In future, these models could build a theoretical basis on which some part of the operative performance of the fire departments could be monitored and possibly assessed.

The information related to the examined fire risk components and fire department operation was utilised in the example building, the fire risk of which was assessed using the time-dependent event-tree approach. As a result, probable annual monetary loss was obtained as a function of the fire duration. Also, the average fire risks of the different types of residential buildings were determined on the basis of the presented statistical information.

The study revealed a significant deficiency in the compilation of the statistics. During the analysis, it became evident that the fire compartment size would be a more proper descriptor than the whole floor area of the building. In the future, to examine the dependencies of the fire risk in detail, the statistical information concerning the ignition compartment in addition to the whole building is essential. At the moment, the information is not collected in the Finnish accident database and so, with the data available, the matter could not be examined further. To achieve the most reliable risk estimates, the importance of the careful and exhaustive compilation of the statistics should be emphasized to the officials responsible for the data input. Also, the presentation of the information and its utilisation for practical purposes motivates fire officials to compile the information as thoroughly as possible, as it allows them to see the real importance of their effort.

As a result of this study, valuable new information on the fire-risks of buildings is now available. In addition to that, an overview of the contents of the database Pronto has been given and, most importantly, proposals for its utilisation in fire-risk assessment have been drawn up. As this was the first relatively broad statistical survey in connection with the fire statistics in the accident database, the methods used in this phase were quite simple. However, many of the methods used are well known in other application areas; the available statistical data now offers the possibility of applying them to areas related to the fire-risk problem. The methods are, in general, suitable for such areas; some of the presented methods have already been used in risk-analysis-based fire safety design. Nevertheless, this study may be considered as a first part of a long research effort and further studies are needed to improve the models and to obtain more detailed and reliable risk estimates. In this work, the preliminary exploration has been carried out and a good base for further research established.

The use of statistics as a background to the models brings an objective viewpoint to the analysis as the statistics are based on real fire incidents, which is the real strength of the approach. Furthermore, this approach is totally frequentistic and thus useful in the fire-risk assessment of buildings about which an adequate amount of statistical information is available. Although, there is always a debate on the quality and accuracy of the statistical data, this study strengthened the standpoint that the use of statistical information is a good objective way to characterise fire.

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Appendix A: Building classification 1994

According to classification of buildings 1994 by Statistics Finland (1994a) the buildings are divided to following groups:

A Residential buildings

01 Detached houses
011 One-dwelling houses
012 Two-dwelling houses
013 Other detached and semi-detached houses
02 Attached houses
021 Row houses
022 Terraced houses
03 Blocks of flats
032 Balcony-access blocks
039 Other blocks of flats

B Free-time residential buildings

04 Free-time residential buildings
041 Free-time residential buildings

C Commercial buildings

11 Wholesale and retail trade buildings
111 Shopping halls
112 Shops, department stores and shopping centres
119 Other wholesale and retail trade buildings
12 Hotel buildings
121 Hotels, etc.
123 Holiday, rest and recreation homes
124 Rental holiday cottages and flats
129 Other hotel buildings
13 Residential buildings for communities
131 Residences for communities, etc.
139 Other residential buildings for communities
14 Restaurants and other similar buildings
141 Restaurants and other similar buildings

D Office buildings

15 Office buildings
151 Office buildings

E Transport and communications buildings

16 Transport and communications buildings
161 Rail and bus stations, air and harbour terminals
162 Vehicle depots and service buildings
163 Car parks
164 Communications buildings
169 Other transport and communications buildings

F Buildings for institutional care

21 Health care buildings
211 General hospitals
213 Other hospitals
214 Health centres
215 Specialised health care buildings
219 Other health care buildings
22 Social welfare buildings
221 Old-age homes
222 Children's homes, reform schools
223 Nursing homes for the mentally retarded
229 Other social welfare buildings
23 Other social service buildings
231 Children's day care centres
239 Social service buildings n.e.c.
24 Prisons
241 Prisons

G Assembly buildings

31 Theatres and concert halls
311 Theatres, opera houses, concert halls and congress centres
312 Cinema halls
32 Libraries, museums and exhibition halls
322 Libraries and archives
323 Museums and art galleries
324 Exhibition halls
33 Association and club buildings, etc.
331 Association and club buildings, etc.

34 Buildings for religious communities
341 Churches, chapels, monasteries, convents and prayer houses
342 Parish halls
349 Other buildings for religious communities
35 Buildings for sports and physical exercise
351 Indoor ice rinks
352 Indoor swimming pools
353 Indoor tennis, squash and badminton courts
354 Gymnasia and other sports halls
359 Other buildings for sports and physical exercise
36 Other assembly buildings
369 Other assembly buildings

H Educational buildings

51 General education buildings
511 General education buildings
52 Vocational education buildings
521 Vocational education buildings
53 University and research institute buildings
531 University buildings
532 Research institute buildings
54 Other educational buildings
541 Educational buildings of organisations, unions, employers, etc.
549 Educational buildings n.e.c.

J Industrial buildings

61 Buildings for energy supply, etc.
611 Power stations
613 Public utility buildings
69 Industrial production buildings
691 Manufacturing plants
692 Workshops for industry and small-scale industry
699 Other industrial production buildings

K Warehouses

71 Warehouses
711 Industrial warehouses
712 Commercial warehouses
719 Other warehouses

L Fire fighting and rescue service buildings

72 Fire fighting and rescue service buildings
721 Fire stations
722 Civil defence shelters
729 Other fire fighting and rescue service buildings

M Agricultural buildings

81 Livestock buildings
811 Cowsheds, pighouses, hen-houses, etc.
819 Animal shelters, harness horse stables, maneges, etc.
89 Other agricultural buildings
891 Grain drying and storage buildings
892 Greenhouses
893 Fur farms
899 Other buildings in agriculture, forestry and fishing

N Other buildings

93 Other buildings
931 Sauna buildings
941 Outbuildings
999 Buildings n.e.c.

References

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Appendix B: Fire department intervention in a building fire

Confidence intervals of the travel time

Confidence interval on the mean value of travel time was obtained from (Milton & Arnold 1990)

$$t_i = \mu_t + t_{\frac{\alpha}{2}} \sqrt{\frac{\sigma^2}{n} + (s - \mu_s)^2 Var(b)} \tag{36}$$

where μ_t is the average travel time, σ^2 standard deviation of the travel time, n the number of observations, s the travel distance, μ_s the average travel distance and α the confidence interval. $t_{\alpha/2}$ is the appropriate point based on the T_{n-2} distribution.

Prediction interval on the value t_0 (Milton & Arnold 1990)

$$t_i = t_0 + t_{\frac{\alpha}{2}} \sqrt{\sigma^2 + \frac{\sigma^2}{n} + (s - \mu_s)^2 Var(b)} \tag{37}$$

Abridgement of the theory of blocking probability of fire units by Brušlinskij (1988)

General

Simplified presentation of the system is shown in Figure 98. In this system, there are an infinite number of queuing places and a certain number of service places (operative units). Independent alarms (alarm rate λ_l) arrive at the alarm control centre; these differ from each other by the number of units l (l = 1,2,…,L)

needed to complete the task. *L* is is equal to the largest number of units that can be sent simultaneously to serve the alarm. The duration of the alarm is the time from the moment the alarm arrives at the alarm control centre to the moment the units notify the centre that they have returned from the scene of the accident. The alarms are arbitrarily related to the time of day, the place, and the number of units needed, in addition to the service time.

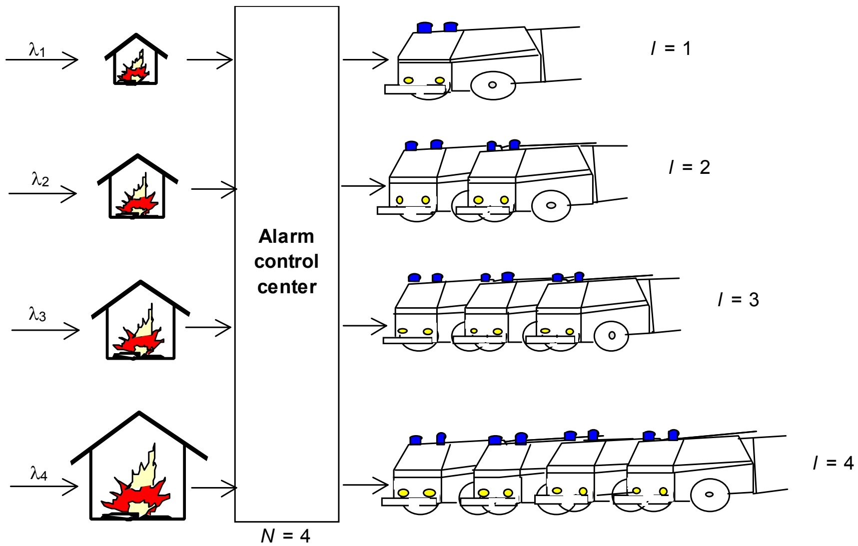

Figure 98. Various alarm rates requiring l units arrive at arbitrary moments to the system, which has in all S units to serve the alarms.

At an arbitrary moment, the system is at some "state" that is described by reference to the number of busy units. The probability of the next state is independent of the past and is a result of the present state. This behaviour is known as the Markov process. In the model used here, the following values are determined theoretically:

- state probability P_E that the system is at state E at an arbitrary moment
- duration of state E, $\overline{T}_E$
- transfer rate F_E to state E

- probability $P_{EE'}$ and frequency $f_{EE'}$ that the system transfers directly from state E to state E'

Furthermore, the L ($l = 1,2,...,L$) alarm rates are assumed independent and Poisson distributed and the service time exponentially distributed.

State probabilities

The probability $P(k)$ that k units are busy at an arbitrary moment is obtained from

$$P(k) = \frac{1}{k}\sum_{j=1}^{L} j\lambda_j \bar{\tau}_j P(k-j)\ ; \quad k = 1,...,S \tag{38}$$

which is also called the Kaufman-Roberts recursion (Kaufman 1981). For k<0, $P(k)$ = 0. The sum of the probabilities must be equal to unity

$$\sum_{i=0}^{S} P(k) = 1 \tag{39}$$

In order to determine $P(0)$, let us start from the local balance equations

$$\begin{aligned} &P(i)\lambda = P(i+1)\cdot(i+1)\cdot\frac{1}{\tau} \\ &\Rightarrow P(i+1) = \frac{\lambda}{(i+1)\frac{1}{\tau}}P(i) = \frac{\lambda\tau}{i+1}P(i) \\ &\Rightarrow P(i) = \frac{(\lambda\tau)^i}{i!}P(0),\quad i = 0,1,2... \end{aligned} \tag{40}$$

In this case, the arriving alarm flows are diverse (l = 1,2,…,L). The appropriate state description, therefore, is $E = (e_1, e_2, \ldots, e_L)$ and the state distribution is a somewhat more complicated form of the Equation (40) (Kaufman 1981)

$$P(E) = \frac{\prod_{l=1}^{L} \frac{(\lambda_l \overline{\tau_l})^{e_l}}{e_l!}}{\sum_{all\ E} \left[\prod_{l=1}^{L} \frac{(\lambda_l \overline{\tau_l})^{e_l}}{e_l!} \right]} \tag{41}$$

e_l indicates the number of type l alarms in the system. P(0) is obtained (Kaufman 1981)

$$P(0) = \frac{1}{\sum_{all\ E} \left[\prod_{l=1}^{L} \frac{(\lambda_l \overline{\tau_l})^{e_l}}{e_l!} \right]} \tag{42}$$

It is assumed that the total number of units S is large ($S > 5$). Determination of $P(0)$ requires calculation of all states to infinity.

$$P(0) = \frac{1}{\sum_{e_1=0}^{\infty} \cdots \sum_{e_L=0}^{\infty} \left[\prod_{l=1}^{L} \frac{(\lambda_l \overline{\tau_l})^{e_l}}{e_l!} \right]} = \frac{1}{\sum_{e_1=0}^{\infty} \frac{(\lambda_1 \overline{\tau_1})^{e_1}}{e_1!} \cdot \sum_{e_2=0}^{\infty} \frac{(\lambda_2 \overline{\tau_2})^{e_2}}{e_2!} \cdots \sum_{e_L=0}^{\infty} \frac{(\lambda_L \overline{\tau_L})^{e_L}}{e_L!}} = \exp\left[-\sum_{l=1}^{L} (\lambda_l \overline{\tau_l}) \right] \tag{43}$$

The probability that at an arbitrary moment the number of units needed in the considered area exceeds m is

$$P(>m) = 1 - \sum_{k=0}^{m} P(k) \tag{44}$$

According to Brušlinskij (1992), the number of units must be estimated so that $P(>m)$ is low enough. Brušlinskij (1992) proposed $P(>m) = 10^{-4}$-10^{-3} as acceptable values.

Frequencies

At a specific fire station, there are, in all, S units in the same shift. At the moment when k of these S units are unavailable, an alarm requiring l units enters the system. The specific state frequency is $\lambda_l P(k)$ and the probability is $P(k)$.

Thus at the moment the alarm arrives, there is S-k free units at the fire station. If $l < S$-k, there is no problem. However, if S-$l < k < S,$ there are not enough free units available, and only S-k ($< l$) units can be sent to serve the alarm. This is called a partial blockage, the frequency of which is obtained from

$$f_{pb} = \sum_{l=2}^{L} \lambda_l \sum_{k=S-l+1}^{S-1} P(k) \tag{45}$$

If all units are already serving other alarms, a new alarm cannot be served. The frequency of this total blockage is

$$f_{tb} = \sum_{l=1}^{L} \lambda_l \sum_{k=S}^{+\infty} P(k) = \sum_{l=1}^{L} \lambda_l \left[1 - \sum_{k=0}^{S-1} P(k) \right] \tag{46}$$

The frequency of blockage f_b is obtained by summing up the frequencies of partial and total blockages.

$$f_b = f_{pb} + f_{tb} \tag{47}$$

In Equation (47) the alarms that can be served completely are subtracted from the total alarm flow.

The time interval between blockages is obtained as an inverse number of the frequency. The probability of blockage is obtained by determining the ratio of blocked alarms to the total number as

Block $$P_b = \frac{f_b}{\sum_{l=1}^{L} \lambda_l}$$

Partial block $$P_{pb} = \frac{f_{pb}}{\sum_{l=1}^{L} \lambda_l} \qquad (48)$$

Total block $$P_{tb} = \frac{f_{tb}}{\sum_{l=1}^{L} \lambda_l}$$

References

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Appendix C: RHR of the design fire

According to Keski-Rahkonen (1993), the rate of heat release of the design fire can be characterised by three phases: fire growth, fully developed fire and decay phase.

During the growth period RHR is obtained from

$$\dot{Q}_c = Q_0 (\frac{t}{t_0})^2 ; t \leq t_1 \tag{49}$$

During the fully developed fire, RHR is assumed to be constant, i.e. the maximum value allowed by, for example, the ventilation conditions.

$$\dot{Q}_c = \dot{Q}_{\max} ; t_1 \leq t \leq t_2 \tag{50}$$

During the decay phase, RHR decreases from maximum value exponentially with time constant τ.

$$\dot{Q}_c = \dot{Q}_{\max} \exp\left[-(\frac{t - t_2}{\tau}) \right] ; t > t_2 \tag{51}$$

In Equations (49)–(51), $\dot{Q}_0$ is the reference RHR 1.0 MW and t_0 the fire growth time, i.e. the time required for the fire to reach $\dot{Q}_0$ .The fire growth times are categorised as slow, normal, fast and very fast according to Table 37.

Table 37. Values of fire growth time t_0.

	t_0 [s]
Slow	600
Normal	300
Fast	150
Very fast	75

References

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Appendix D: Consequences of fires

Expected loss

The theory (Ramachandran 1979/80, 1982, 1998) is based on the assumption that the fire loss distribution is lognormal. The expected value is thus

$$E[X] = \int_{-\infty}^{\infty} x f(x) dx \tag{52}$$

When the value-at-risk V [€] of the individual building is known, the expected value can be determined. If the actual distribution of the group of buildings for which value-at-risk V is unknown, it can be approximated with the main distribution as the so-called truncated distribution (Ramachandran 1982)

$$f_V(x) = \frac{\frac{1}{\sqrt{2\pi}\sigma x} \exp(-\frac{1}{2}(\frac{\ln(x)-\mu}{\sigma})^2)}{\int_{-\infty}^{V} \frac{1}{\sqrt{2\pi}\sigma x} \exp(-\frac{1}{2}(\frac{\ln(x)-\mu}{\sigma})^2) dx} \tag{53}$$

where μ and σ are the average and standard deviation of ln(x). Furthermore,

$$f_V(z) = \frac{\frac{1}{\sqrt{2\pi}\sigma} \exp(-\frac{1}{2}(\frac{z-\mu}{\sigma})^2)}{G(k)} \tag{54}$$

where

$$G(k) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{k} \exp(-\frac{t^2}{2}) dt \tag{55}$$

$G(t)$ is cumulative normal distribution with average 0 and standard deviation 1. Furthermore

$$k = \frac{\ln V - \mu}{\sigma} \tag{56}$$

In the truncated distribution Equation (53), it is assumed that the maximum loss cannot exceed the value-at-risk V. Thus

$$z \le \ln(V) \tag{57}$$

From Equation (53) or (54), the expected loss of the building for which value-at-risk is V is obtained from the equation

$$\bar{x}_V = \frac{\int_0^V x f(x) dx}{G(k)} = \frac{1}{G(k)} \int_0^V \frac{1}{\sqrt{2\pi}\sigma} \exp(-\frac{1}{2}(\frac{\ln(x)-\mu}{\sigma})^2) dx \tag{58}$$

$$= \frac{1}{G(k)} \int_0^k \frac{1}{\sqrt{2\pi}} \exp(-\frac{t^2}{2} + \sigma t + \mu) dt$$

$$= \frac{G(k-\sigma)}{G(k)} \exp(\mu + \frac{\sigma^2}{2})$$

where $G(k\text{-}\sigma)$ is similar to Equation (55).

Loss probability

Probability that the loss does not exceed x [€] is obtained from (Ramachandran 1979/80)

$$F_V(z) = \int_{-\infty}^{z} f_V(z) = \frac{G(u)}{G(k)} \tag{59}$$

where

$$u = \frac{\ln x - \mu}{\sigma} \tag{60}$$

References

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Ramachandran, G. 1982. Properties of Extreme Order Statistics and their Application to Fire Protection and Insurance Problems. Fire Safety Journal, 5, p. 59–76.

Ramachandran, G. 1979/80. Statistical Methods in Risk Evaluation. Fire Safety Journal, 2, p. 125–145.

Appendix E: Used class intervals

Ignition frequency

Table 38. Floor area class intervals used in Section 5.3.

	Floor area [m^2]
1	0–9
2	10–19
3	20–39
4	40–59
5	60–79
6	80–99
7	100–119
8	120–149
9	150–199
10	200–299
11	300–499
12	500–699
13	700–999
14	1 000–1 999
15	2 000–2 999
16	3 000–4 999
17	5 000–9 999
18	10 000–19 999
19	20 000–49 999
20	50 000–

Operative time distributions of fire department

Table 39. Time intervals used in Figure 20.

Years 1994–97	
	Interval
Turnout time	1 min
Response time	1 min
Service time	15 min

Table 40. Time intervals used in Figure 20.

Year 2000		
Turnout time [min]	**Response time [min]**	**Service time [min]**
0	0–2	0–9
1	3	10–19
2	4	20–29
3	5	30–39
4	6	40–49
5	7	50–59
6	8	60–69
7	9	70–79
8	10	80–89
9	11	90–99
10	12	100–109
11–15	13	110–119
16–20	14	120–149
21–30	15	150–179
31–60	16	180–209
61–180	17	210–239
	18	240–299
	19	300–359
	20–24	360–419
	25–29	420–479
	30–39	480–539
	40–59	540–
	60–119	
	120–	

Table 41. Travel distance intervals used in Figure 24.

Class interval of travel distance
0–1 km
1–2 km
2–3 km
3–4 km
4–5 km
5–6 km
6–7 km
7–8 km
8–9 km
9–10 km
10– km

Economic loss

Expected loss, Section 7.1.5

Table 42. Class intervals of value-at-risk and floor area used in Figure 42.

	Value at risk [€]	Floor area [m^2]
1	0–1 682	0–9
2	1 682–3 364	10–19
3	3 364–5 045	20–29
4	5 046–6 727	30–39
5	6 728–8 409	40–49
6	8 409–10 091	50–59
7	10 091–11 773	60–69
8	11 773–13 455	70–79
9	13 455–15 137	80–89
10	15 137–16 819	90–99
11	16 819–33 637	100–199
12	33 638–50 456	200–299
13	50 456–67 275	300–399
14	67 275–84 094	400–499
15	84 094–100 913	500–999
16	100 913–117 731	1 000–4 999
17	117 732–134 550	5 000–9 999
18	134 550–151 369	10 000–49 999
19	151 369–168 188	50 000–99 999
20	168 188–840 939	100 000–1 477 854
21	840 940–1 681 879	
22	1 681 879–8 409 396	
23	8 409 396–16 818 792	
24	16 818 793–504 563 779	

Building categories, Section 7.1.7.2

Table 43. Class intervals of the floor area [m²] used in Figure 47.

Residential	Industrial + Warehouses	Others
1–19	1–49	1–9
20–29	50–99	10–19
30–39	100–299	20–29
40–49	300–499	30–39
50–69	500–699	40–49
70–99	700–999	50–59
100–299	1 000–2 999	60–69
300–499	3 000–4 999	70–79
500–699	5 000–9 999	80–89
700–999	10 000–99 999	90–99
1 000–2 999	100 000–999 999	100–299
3 000–4 999		300–499
5 000–9 999		500–699
10 000–99 999		700–999
		1 000–2 999
		3 000–4 999
		5 000–9 999
		10 000–99 999
		100 000–999 999

Table 44. Class intervals of the value-at-risk [€] used in Figure 47.

	All building category groups
1	0–8 409
2	8 409–16 819
3	16 819–84 094
4	84 094–168 188
5	168 188–840 939
6	840 940–1 681 879
7	1 681 879–8 409 396
8	8 409 396–16 818 792
9	16 818 793–168 187 926
10	168 187 926–504 563 779

Effect of material of load-bearing structures on economic fire loss, Section 7.2.2

Table 45. Class intervals of the floor area [m^2] used in Figure 52.

Concrete	Wood	Other
1–199	1–39	1–49
200–499	40–59	50–99
500–999	60–79	100–499
1 000–1 999	80–99	500–999
2 000–2 999	100–149	1000–9999
3 000–4 999	150–199	10 000–
5000–9999	200–249	
10 000–49 999	250–299	
50 000–	300–399	
	400–499	
	500–999	
	1000–2999	
	3000–	

Residential buildings, Section 7.3

Table 46. Class intervals of the floor area [m^2] used in Figure 55.

Apartment	Detached houses	Row houses
1–99	1–19	1–99
100–499	20–29	100–499
500–999	30–39	500–999
1000–2999	40–49	1 000–2 999
3000–4999	50–59	
5000–9999	60–69	
10 000–99 999	70–79	
	80–89	
	90–99	
	100–149	
	150–199	
	200–249	
	250–299	
	300–399	
	400–499	
	500–999	
	5 000–9 999	

Damage degree, Section 7.3.3

Table 47. Class intervals of the floor area [m^2] used in Figure 58.

Concrete	Wood	Other
1–199	1–39	1–49
200–499	40–59	50–99
500–999	60–79	100–499
1 000–1 999	80–99	500–999
2 000–2 999	100–149	1000–9999
3 000–4 999	150–199	10 000–
5000–9999	200–249	
10 000–49 999	250–299	
50 000–	300–399	
	400–499	
	500–999	
	1000–2999	
	3000–	

All other buildings, Section 7.4

Table 48. Class intervals of the floor area [m²] used in Figure 63.

Concrete	Wood
10–99	1–9
100–299	10–19
300–499	20–29
500–699	30–39
700–999	40–49
1 000–4 999	50–59
5 000–9 999	60–69
10 000–99 999	70–79
100 000–	80–89
	90–99
	100–199
	200–299
	300–399
	400–499
	500–699
	700–999
	1 000–4 999
	10 000–99 999

Appendix F: Results of the statistical tests

Average annual ignition frequencies of different building categories

Table 49. Results of the Kruskal-Wallis test used to test the differences between the ignition frequencies of chosen building categories (Figure 9).

Kruskal-Wallis All-Pairwise Comparisons Test

Building category	Homogeneous groups
A	B
C	AB
F	AB
G	B
J	A
F = 13.5 p-value = 0.0000	
Building category	**Homogeneous groups**
D	B
E+L	AB
G	A
H	B
F = 21.1 p-value = 0.0000	
Building category	**Homogeneous groups**
J	A
K	AB
M	BC
N	C
F = 84.0 p-value = 0.0000	

The p-value under 0.05 shows that there are significant differences between the means of the building categories. The groups A, B and C are the groups in which the means are not significantly different from one another.

Time distributions of ignitions

Table 50. Results of the Kruskal-Wallis Test used to compare whether the number of ignitions differ significantly from each other. Relative numbers of ignitions are presented in Figure 17.

	Residential buildings	**Industrial buildings and warehouses**	**Other buildings**
	Homogeneous groups		
Monday	A	A	C
Tuesday	A	A	BC
Wednesday	A	A	BC
Thursday	A	A	BC
Friday	A	A	B
Saturday	B	B	A
Sunday	A	B	BC
	F = 6.75 p-value = 0.0000	F = 9.23 p-value = 0.0000	F = 14.4 p-value = 0.0000

The p-value under 0.05 indicates a significant difference. The groups A, B and C are the groups in which the means are not significantly different from one another.

Table 51. Results of the Kruskal-Wallis Test used to compare the differences between months. Relative numbers of ignitions are presented in Figure 17.

Month	**Residential buildings**	**Industrial buildings and warehouses**	**Other buildings**
	Homogeneous groups		
January	A	AB	BC
February	ABC	AB	C
March	ABC	AB	BC
April	ABC	AB	ABC
May	ABC	A	AB
June	ABC	A	A
July	ABC	AB	A
August	C	AB	ABC
September	BC	AB	ABC
October	BC	AB	BC
November	ABC	B	BC
December	AB	AB	ABC
	F = 5.12 p-value = 0.0000	F = 3.22 p-value = 0.0012	F = 12.6 p-value = 0.0000

The p-value under 0.05 indicates a significant difference. The groups A, B and C are the groups in which the means are not significantly different from one another.

Material of the load bearing structure

Fire loss (Section 7.2.2)

Table 52. Results of the Kruskal-Wallis test used to compare the differences of total loss and value–at-risk between different materials of the load-bearing structures (Figure 51).

Material	**Total loss**	**Value-at-risk**
	Homogeneous groups	
Concrete	A	A
Wood	B	B
Other	B	C
	F = 44.7 p-value = 0.0000	F = 2146 p-value = 0.0000

Fire loss and floor area (Section 7.3.1)

Table 53. Results of the Kruskal-Wallis test used to compare the differences of total loss and value-at-risk between different residential building types (Figure 54).

	Loss [€]	**Floor area [m^2]**
	Homogeneous groups	
Detached houses	A	A
Row and chain houses	A	B
Apartment houses	B	C
	F = 40.0 p-value = 0.0000	F = 1755 p-value = 0.0000

Fire loss and value-at-risk (Section 7.3.2)

Table 54. Results of the Kruskal-Wallis test used to compare the differences of total loss and value-at-risk between different materials of the load-bearing members in apartment and detached houses (Figure 57).

Apartment houses		
Material	**Total loss [€]**	**Value-at-risk [€]**
	Homogeneous groups	
Concrete	A	A
Wood	B	B
Other	AB	A
	F = 15.4 p-value = 0.0000	F = 12.3 p-value = 0.0000

Detached houses		
Material	**Total loss [€]**	**Value-at-risk [€]**
	Homogeneous groups	
Concrete	A	A
Wood	B	B
Other	A	A
	F = 50.3 p-value = 0.0000	F = 21.3 p-value = 0.0000

The p-value under 0.05 indicates a significant difference. The groups A and B are the groups in which the means are not significantly different from one another.

Damage degree (Section 7.3.3)

Table 55. Results of the Kruskal-Wallis test used to compare the extent-of-damage differences between different materials of the load-bearing structures in detached and apartment houses (Figure 59).

Damage degree Apartment houses	
Material	**Homogeneous groups**
Concrete	B
Wood	A
Other	B
F = 37.9, p-value = 0.0000	

Damage degree Detached houses	
Material	**Homogeneous groups**
Concrete	B
Wood	A
Other	B
F = 153, p-value = 0.0000	

The p-value under 0.05 shows that there are significant differences between the means of damage degrees. The groups A and B are the groups in which the means are not significantly different from one another.

Floor area distributions (Section 7.3.3)

Table 56. Results of the Kruskal-Wallis test used to compare the differences of floor area distributions (Figure 60).

Material	Apartment houses	Detached houses
	Homogeneous groups	
Concrete	A	A
Wood	B	B
Other	A	A
	F = 64.4 p-value = 0.0000	F = 11.0 p-value = 0.0000

The p-value under 0.05 indicates a significant difference. The groups A and B are the groups in which the means are not significantly different from one another.

Extent of damage (Section 7.3.3)

Table 57. Results of the Kruskal-Wallis test used to compare the extent-of-damage differences between different materials of the load-bearing structures in detached and apartment houses (Figure 61).

Extent of damage at fire department arrival			
Part of the room		**Ignition room**	
Material	**Homogeneous groups**	**Material**	**Homogeneous groups**
Concrete	A	**Concrete**	B
Wood	B	**Wood**	A
Other	AB	**Other**	B
F = 61.7, p-value = 0.0000		F = 17.4, p-value = 0.0001	
Ignition compartment		**Spread beyond ignition comp.**	
Material	**Homogeneous groups**	**Material**	**Homogeneous groups**
Concrete	B	**Concrete**	B
Wood	A	**Wood**	AB
Other	AB	**Other**	A
F = 61.7, p-value = 0.0000		F = 26.1, p-value = 0.0000	

Extent of damage at the end			
Part of the room		**Ignition room**	
Material	**Homogeneous groups**	**Material**	**Homogeneous groups**
Concrete	A	**Concrete**	B
Wood	B	**Wood**	A
Other	AB	**Other**	B
F = 40.8, p-value = 0.0000		F = 18.6, p-value = 0.0001	
Ignition compartment		**Spread beyond ignition comp.**	
Material	**Homogeneous groups**	**Material**	**Homogeneous groups**
Concrete	B	**Concrete**	A
Wood	A	**Wood**	AB
Other	AB	**Other**	A
F = 49.1, p-value = 0.0000		F = 9.49, p-value = 0.0022	

Surface layer (Section 7.3.3)

Table 58. Results of the Kruskal-Wallis test used to compare the differences of the effect on fire of the ignition flat surface layer between different materials of the load-bearing structures in detached and apartment houses (Figure 62).

Material	**Slowed down the fire**	**No effect**	**Boosted the fire**
	Homogeneous groups		
Concrete	A	A	B
Wood	B	A	A
Other	AB	A	AB
	F = 25.0 p-value = 0.0000	F = 3.78 p-value = 0.0469	F = 62.3 p-value = 0.0000

The p-value under 0.05 indicates a significant difference. The groups A, B and C are the groups in which the means are not significantly different from one another.

Average ignition frequency (Section 8.2.1.1)

Table 59. Results of the Kruskal-Wallis test used to compare the differences of the average ignition frequency between residential building types (Figure 67).

Average ignition frequency per floor area	
Residential building type	**Homogeneous groups**
Apartment houses	AB
Row and chain houses	B
Detached houses	A
F = 15.0, p-value = 0.0003	

Average ignition frequency per inhabitant	
Residential building type	**Homogeneous groups**
Apartment houses	AB
Row and chain houses	B
Detached houses	A
F = 37.0, p-value = 0.0000	

Average ignition frequency per flat	
Residential building type	**Homogeneous groups**
Apartment houses	B
Row and chain houses	B
Detached houses	A
F = 15.4, p-value = 0.0002	

The p-value under 0.05 shows that there are significant differences between the average ignition frequencies. The groups A and B are the groups in which the means are not significantly different from one another.

Economic consequences (Section 8.2.1.2)

Table 60. Results of the Kruskal-Wallis test used to compare the differences of the average loss between residential building types (Figure 68).

Average loss of building and property	
Residential building type	**Homogeneous groups**
Apartment houses	A
Row and chain houses	B
Detached houses	B
F = 40.0, p-value = 0.0003	

The p-value under 0.05 indicates a significant difference. The groups A and B are the groups in which the means are not significantly different from one another.

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Title
Utilisation of statistics to assess fire risks in buildings

Abstract
This study is the first relatively broad statistical survey utilising the statistical data collected in the national accident database, Pronto. As a result valuable new information relating to fire risks is obtained and quantitative methods for fire risk assessment of buildings are presented. This work is a step forward in the field of risk-analysis-based fire safety design and overall a step towards a better understanding of the anatomy of fires.

The use of statistical information is a good objective way of attempting to characterise fires. This study concentrates on ignition frequency, economic fire losses and fire department operation in the event of building-fires. Ignition frequency was derived as a function of total floor area for different building categories. The analysis showed that the variations of ignition frequency are dependent on initial floor area distributions of the buildings hit by fire and at risk. For engineering design purposes, the generalisation of the theory starting from the initial floor area distributions, leading to a sum of two power laws, was found suitable. The parameters and partial safety coefficients for the model were estimated for three building groups. The model is suitable for determining the ignition frequency of buildings with a total floor area of between 100 and 20 000 m^2.

The elements describing the fire department operation were analysed on the basis of statistical information. In the presented approach, the buildings in which fire safety depends completely on automatic extinguishing systems can be distinguished from those in which the fire department is able to arrive at the fire scene early enough to have a good chance of saving the building. The most important factor affecting the performance of the rescue force was found to be the travel time to the fire scene. Thus, to make the task easier for the fire department, special attention must be paid to rapid fire detection and locating of the fire seat. Delays in these actions lengthen the total response time and reduce significantly the chances of the fire department successfully intervening in the progress of the fire.

Economic losses were considered as consequences of the fires. The analysis showed the dependency of loss and value-at-risk of the building on the floor area. Clear local peaks were detected for both the ignition frequency and fire losses. A more detailed analysis of residential buildings where the phenomenon was most apparent revealed that the peaks were located around the floor-area region where the dominant building type of the building stock, and thus the compartmentation manner, changed. With small values of the total floor area of the building, the rise of the loss was very steep, but levelled off to substantially slower growth with large values. A natural explanation for the behaviour is compartmentation. Both the ignition frequency and the fire losses should therefore be examined in relation to the size of the ignition compartment, which would be a significantly more appropriate descriptor than the total floor area of the building. Hence, it is essential that the information becomes available to the Finnish accident database, in which it is not at the moment included. The analysis shows that the type of building and compartmentation, rather than the material of the load-bearing member itself, was the factor having the greatest effect on the risk of fire.

The use of the information gathered was demonstrated through a simple example case in which the fire risk was assessed using the time-dependent event-tree approach.

This study concentrates on the utilisation of statistics to collect information and gain an understanding of the elements affecting fire risks in buildings. Many of the methods used are well known in other application areas; the available statistical data now offers the possibility of applying them in connection with fire-risk problems as well. In risk-analysis-based design, the presented approach is very useful and the methods can be used for fire-risk assessment of buildings. Nevertheless, this study should be considered the first part of a major research effort and further studies will be needed to improve the tentative models to obtain more detailed and reliable risk estimates. In this work a preliminary exploration is carried out and a good base for further research is established.

Keywords
fire risk, building fires, fire safety, statistics, ignition frequency, economic losses, fire department

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