ESPOO 2005 VTT WORKING PAPERS 32

Fire Safety of Wooden Façades in Residential Suburb Multi-Storey Buildings

Timo Korhonen & Jukka Hietaniemi
VTT Building and Transport

ISBN 951–38–6585–1 (URL: http://www.vtt.fi/inf/pdf/)
ISSN 1459–7683 (URL: http://www.vtt.fi/inf/pdf/)

JULKAISIJA – UTGIVARE – PUBLISHER

VTT, Vuorimiehentie 5, PL 2000, 02044 VTT
puh. vaihde 020 722 111, faksi 020 722 4374

VTT, Bergsmansvägen 5, PB 2000, 02044 VTT
tel. växel 020 722 111, fax 020 722 4374

VTT Technical Research Centre of Finland, Vuorimiehentie 5, P.O.Box 2000, FI–02044 VTT, Finland
phone internat. +358 20 722 111, fax +358 20 722 4374

VTT Rakennus- ja yhdyskuntatekniikka, Kivimiehentie 4, PL 1803, 02044 VTT
puh. vaihde 020 722 111, faksi 020 722 4815

VTT Bygg och transport, Stenkarlsvägen 4, PB 1803, 02044 VTT
tel. växel 020 722 111, fax 020 722 4815

VTT Building and Transport, Kivimiehentie 4, P.O.Box 1803, FI–02044 VTT, Finland
phone internat. +358 20 722 111, fax +358 20 722 4815

Technical editing Maini Manninen

Published by

Series title, number and report code of publication

VTT Working Papers 32
VTT–WORK–32

Author(s)
Korhonen, Timo & Hietaniemi, Jukka

Title

Fire Safety of Wooden Façades in Residential Suburb Multi-Storey Buildings

Abstract

The fire classes and numerical criteria given in the regulations and guidelines of part E1 of the National Building Code of Finland (NBCF) specify limitations to the use of wood in the façades of buildings belonging to the fire class P1, but they do not, however, prevent the use of wood. The issue is the way how the essential requirement of safety in case of fire is shown to be satisfied. There are two alternative ways to show this: the other, more common way, is to design and execute the building by applying the fire classes and numerical criteria provided by the regulations and guidelines. The other way is to design and execute the building on the basis of design fire scenarios, which shall cover conditions likely to occur in the relevant building (the performance-based way). In this case, one can employ solutions that differ from the fire classes and numerical criteria given in part E1 of the National NBCF provided that they are proven to be safe. A prerequisite for the use of the alternative fire safety design approach is that there is solid, validated material to base the design on. The objective of this study is to produce such material concerning use of wooden façades in residential multi-storey buildings built according to the requirements of the P1 fire class with non-combustible load-bearing structures.

The work that has been carried out as a fire risk analysis concerning the impact on fire safety of an installation of a wooden façade. The risk analysis and associated calculations are made using state-of-the-art techniques in the fire safety sciences and technology. The results obtained show that with respect to the overall fire safety of a P1-class residential multi-storey building, the role of the combustible façade material is insignificant: the minute increment in the probabilities of fire spread from the room-of-fire-origin to the apartments above is small as compared to the influence of several other factors which are not regulated by the Fire Regulations. For example, the small amount of wood on the façade that is likely to contribute the external flaming would cause a much higher risk if it was installed - as allowed by the Fire Regulations - as a lining inside the apartments. It is shown that the results obtained for the selected example building can be generalised to other buildings with reasonably similar characteristics.

Keywords
fire safety, fire prevention, wooden façades, risk analysis, fire spread, external flaming, residential buildings

Activity unit
VTT Building and Transport, Kivimiehentie 4, P.O.Box 1803, FIN–02044 VTT, Finland

ISBN		Project number
951–38–6585–1 (URL: http://www.vtt.fi/inf/pdf/)		R4SU00235
Date	**Language**	**Pages**
July 2005	English	66 p. + app. 40 p.
Name of project	**Commissioned by**	
New simulation methods for fire safety analysis	Tekes & VTT	
Series title and ISSN	**Publisher**	
VTT Working Papers 1459–7683 (URL: http://www.vtt.fi/inf/pdf/)	VTT Information Service P.O. Box 2000, FIN–02044 VTT, Finland Phone internat. +358 9 456 4404 Fax +358 9 456 4374	

Preface

Part E1, Fire safety of buildings, of the National Building Code of Finland (NBCF) recognises two alternative approaches to show that a building satisfies the fire safety requirements. The fire safety requirement is deemed to be satisfied if the building is designed and executed by applying the fire classes and numerical criteria provided by the regulations and guidelines of the part E1 of the NBCF (the prescriptive approach), or, alternatively, by designing and executing the building based on design fire scenarios covering the conditions likely to occur in the building (the performance-based approach). In the latter approach one can employ solutions, which differ from the fire classes and numerical criteria provided by the regulations and guidelines of the part E1 of the NBCF.

In Finland, especially the residential suburb multi-storey buildings built in the 1960's and 70's require renovation, in particular their façades. The basic fire class requirement of the façade material stipulated by part E1 of the NBCF restricts strongly the possibility to use wood in a façade of the building in the P1 fire class. The objectives of this study are to establish the level of fire safety which results from retrofitting a wooden façade to a P1-fire-class building with concrete frame, to produce material showing that the essential requirement of fire safety is satisfied and to dispel the incorrect preconceptions regarding wooden façades. The approach of the study is to proceed from a specific case to generalised conclusions, *i.e.*, we first analyse the fire risks involved in installing a wooden façade to selected typical concrete framed building of the fire class P1 and secondly, we show that the conclusions drawn from this particular building are applicable to similar concrete-framed residential suburb multi-storey buildings built in the 1960's and 70's.

This study is a part of a research project funded by the Wood Focus Ltd and the Finnish Technology Agency (Tekes). The authors thank the members of the steering board, Pekka Nurro (the chairman, Wood Focus Ltd), Tero Lahtela (ProAgria, presently Tero Lahtela Consulting Engineering), Jarmo Mylläri (the House Building Commission of the City of Helsinki), Marja Kallio (Skanska) and Esko Mikkola (VTT), for their interest and expert guidance during the work.

Contents

1. Introduction

Renovation is a growing branch of building business in Finland as well as all over Europe. For example, in the Central Europe, the markets of renovation have been estimated to be tens of billions of euros (Erkki Virtanen, Permanent Secretary, Ministry of Trade and Industry). Along with the growth of the economies of the countries in the Eastern Europe (the new EU member states and the western parts of Russia), they constitute a significant growing market area for building renovation business.

In Finland, in particular the residential suburb multi-storey buildings built in the 1960's and 70's need renovation. One of the most important targets of reconstruction are façades. The reconstruction needs rise from reasons related to building technology and energy conservation, but also the aesthetic appearance of the buildings and the habitability of the environment strongly the related to the aesthetic appearance require improvements in order to meet the present-day requirements.

Wood is an excellent material for renovation. Use of wood is in accordance with the principles of sustainable development: it has low energy content as compared to other building materials and in buildings wood acts as a sink of the atmospheric CO_2 content. Use of wood in building does not threaten the European forest resources because the annual net growth of *ca*. 460 million m^3 of the economic forests exceeds the annual outturn and slash of *ca*. 300 million m^3. Wood is the only renewable resource of the building materials used in the large scale. Regarding building technology, building use of wood is lightweight and flexible making wooden constructions suitable for confined places often encountered in reconstruction work. Also the economic competitiveness of wood as compared to other building materials is good. Wood is easy to combine with other materials which offers many opportunities in renovation. Perceptible use of wood in building increases the aesthetic values of the environment, which in turn enhances the habitability of the environment and contributes to the positive development of the social structures and security.

Forests are the most important natural resource in Finland and their efficient utilisation also in the building sector is essential for the employment and the national economy.

In Finland the most important target buildings of renovation belong to the fire class P1[1], which restricts use of wood in their reconstruction due to the fire regulatory reasons. For

[1] The fire-regulatory system in Finland is strongly rooted in the three building fire classes, P1, P2 and P3. The fire class P1 is characterised by high fire-resistance requirements related to the load-bearing capacity of structures, which are assumed, as a rule, to withstand fire without collapsing. The high fire resistance of buildings in the fire class P1 allows alleviations in other requirements so that, *e.g.*, the size of the building and the number of occupants are not restricted.

example, the basic requirement of the façade material of a building belonging to the P1 fire class is B-s1, d0, which strongly restraints use of not fire-retardant treated wood material in the façades. In low P1-fire-class buildings with at most 4 storeys, use of wood as the cladding material is in principle possible provided that the apartments of the building are equipped with an automatic sprinkler system. In renovation, however, the fire safety strategy based on sprinklers is not a practical option, *e.g.*, due to the costs of the sprinkler system.

Although the fire classes and numerical criteria of the regulations and guidelines of part E1 of the National Building Code of Finland (NBCF) [Ministry of the Environment 2002] specify limitations to the use of wood in the façades and other constructions, such as balconies and additional storeys, of buildings belonging to the fire class P1, the fire regulations do not prevent use of wood even in these cases. The issue is the way how the essential requirement of safety in case of fire is shown to be satisfied. There are two alternative ways to show that the fire safety requirement is satisfied: the other, more common way, is to design and execute the building by applying the fire classes and numerical criteria provided by the regulations and guidelines. The other way is to design and execute the building on the basis of design fire scenarios, which shall cover conditions likely to occur in the relevant building (an approach often referred to as the performance-based fire design). In the latter case, one can employ solutions that differ from the fire classes and numerical criteria given in the regulations and guidelines of part E1 of the NBCF provided that they are proven to be safe. When using the performance-based design approach, the satisfaction of the essential requirement of fire safety must be substantiated through documentation of the basis for the design, the methods applied and the results obtained according to the procedure stipulated in the Part E1 including the assumptions made on the characteristics and the use of the building.

The situation regarding the attestation of the essential requirement of safety in case of fire is similar is several European countries: in addition to the prescriptive approach following the fire classes and numerical criteria of the fire regulations, a performance-based approach related to the functionality of building is allowed [Anon 2002]. The performance-based approach to fire safety design and the associated use of Fire Safety Engineering (FSE) is allowed as an alternative to the prescriptive approach in the important target countries of the export of the Finnish wood processing industry including Germany, United Kingdom, the Benelux countries, Denmark and Italy. In France performance-based fire design is possible for public buildings. However, there the development work on applications of FSE is going on strong and the range of applicability of the performance-based fire design will most probably increase in the near future. Also outside of Europe, *e.g.*, in USA, Japan and Australia the performance-based fire safety design option is a well-known and acknowledged option. Fire safety engineering introduces to fire safety design a novel high-technology approach exploiting the vast possibilities of the modern information technology thus facilitating obtaining considerable advantages with respect to cost efficiency and rationality. Thus the range of applications of the FSE increases continuously and procedures to adapt the FSE-based fire design are developed also in those EU member states in which the performance-based fire safety design option is not yet incorporated to the building legislation. In this respect it is likely that the new EU member states will adapt the performance-based fire safety design approaches.

Use of alternative construction solutions not acknowledged by the prescriptive fire regulations calls for a solid, well-founded material proving the safety of the particular construction solution. An obstacle for the use of wood in renovation of the concrete-framed residential multi-storey buildings in Finland is not the fire regulations, but the fact that at present there is no material which shows that the essential requirement of safety in case of fire is satisfied. The objective of this work is to produce such material.

The key target groups of the material are the local fire and building authorities in Finland as well as architects, structural engineers and consultancies. The regulations and guidelines presently available in Finland for performance-based fire design are still on a rather general level and especially material concerning the use of fire safety engineering design in the case of renovation is virtually non-existent. This research work produces material for the attestation of fire safety of concrete-framed residential multi-storey buildings retrofitted with wooden façades. The validity of the information and methods presented are justified in a reliable way so that the material of this report constitutes a working basis for the construction licence procedures between the constructor and the local fire and building authorities. The important fire safety aspects covered in this report include the significance of combustible claddings with respect to fire safety taking into account the building as a whole and the influence of fire services intervention and rescue operations.

The material of this report can be also used to dispel the incorrect preconceptions regarding fire safety issues of wooden façades, *e.g.*, among the general public.

Since the performance-based fire safety approach is based on the characteristics of the fire and the actions carried out to prevent and suppress the fire, the results obtained in Finland can readily be transferred to other countries by replacing the parts of the fire safety analysis pertaining to data specific to Finland by the data valid for the particular country of interest. This general validity of the performance-based approach is one of its strengths, which enables to generate additional value to the companies involved. The companies acting in Finland can use Finland as a 'research and development laboratory' and apply the results to other countries in Europe and elsewhere. Carrier out in co-operation with authorities, the activities described above promote pan-European use and extension of the applications of fire safety engineering, which will in turn lead to new opportunities to exploit the fire safety engineering applications.

This report produces material for fire safety assessment and design concerning retrofitting of a wooden façade to a concrete-framed residential suburb multi-storey buildings belonging to the fire class P1. The study starts from an analysis of a selected typical building of this type and proceeds then to generalisation of the results for residential suburb multi-storey buildings from the 1960's and 70's with similar characteristics. The selected example building is described in Chapter 2. Chapter 3 presents the fire scenarios, the computational models and the main results of the survey carried out to establish the statistical basis of the study. The results obtained for the example building are presented in Chapter 4 and in Chapter 5 we show how these results can be generalised to apply to buildings with similar characteristics as the example building. The last Chapter presents a summary of the main results of the study and their implications concerning use of wood in renovation of façades.

2. Buildings considered in the study

2.1 General

There is great need of renovation in the suburbs built in the 1960's and 1970's. A typical building of this era is a concrete-framed house constructed using concrete element units, with the façades made of materials with very limited contribution to the fire, *e.g.*, exposed-aggregate concrete. With time, these façades have deteriorated and need renovation. The reconstruction work of the façades can be executed either by removing the uppermost concrete layer or by leaving the uppermost layer intact and assembling the new façade on the old one. There are several techniques available for the façade reconstruction work, *e.g.*, replacement of the outermost layer of the façade using brick construction. This would, however, be a rather expensive and slow alternative. Use of wood enables to carry out the renovation of the façade in an inexpensive way and at the same time to adapt the architectural image of the building better to its surroundings typically characterised by plants and trees. Wooden façades seem more appropriate to relatively low buildings with height less than the average height of trees in the surroundings because in a building higher than the tree stand in the area, the wooden façade no longer maintains its inherent closeness to the nature.

In this study we have adapted an approach proceeding from a specific case to generalised conclusions: we first analyse the fire safety of the selected example building before and after the installation of a wooden façade, thus obtaining information of the relative changes – if any – in the fire safety arising from the wooden façade retrofitting. After the case study of the specific building we carry out a parametric study of the impact on fire risks of the different influential variable factors so that as an outcome we obtain generalised results which are applicable to concrete-framed residential suburb multi-storey buildings built in the 1960's and 70's with similar characteristics as the example building.

In the assessment of the magnitude of the risks we take into account fire development as well as the influence of the intervention of the fire services. The basic risk-analytical tool we use in the event tree, but as the events related to a fire incident are very strongly dependent on the time of their occurrence (*e.g.*, detection of the fire, window fracture and fallout, the probability of success of the extinguishing efforts of the fire brigade, *etc.*), we use the specific methodology of Time-Dependent Event Trees (TDET) developed by VTT [Hietaniemi *et al.* 2002, Korhonen *et al.* 2003]. The superiority of this approach as compared to the ordinary use of event trees lies in the fact that the TDET method is able to take into account the dynamic character of a fire incident. As the temporal evolution of the incident is explicitly included in the TDET method, the selection of the moment of time for which the event tree is constructed to analyse the system is of no concern and – very importantly – also the difficulties and uncertainties pertaining to this selection vanish and thus the outcome of the analysis is free of any ambiguities of this kind.

According to a survey of the Finnish fire statistics (Section 3.1 and Appendix A), the most dangerous fire scenario in the buildings within the scope of this study is an apartment fire that has developed through flashover to engulf the whole room-of-fire-origin. Exterior ignitions (balcony fires excluded) are rare and hence, the most likely route that the flames can come into contact with the façade is either via windows broken in an apartment fire or from balconies. This study does not address the balcony fires because they have been dealt with in another investigation [RTE 2003]. The highest interest regarding the fire safety of the retrofitted wooden façades is their influence on the fire spread in the case of a flashed over apartment fire. This fire scenario is studied using empirical models describing the external flaming outside a room with fully developed fire and the heat exposure to the façade generated by these flames.

2.2 The example building

The example building is a concrete-framed residential multi-storey building belonging to the P1 fire class, the façade of which will be renovated so that a wooden façade will be placed on the old concrete façade. The building is located in Laajasalo in the Eastern Helsinki. It constitutes a typical example of the concrete-framed houses built in Finland in the 1960's and 1970's. The building was selected as the subject of the study because there are plans to renovate its façades and potentially to add the number of apartments, *e.g.*, through constructing an additional storey on top of the building. The building has 3–4 storeys and its basement is partially above ground. There are no windows in the gables of the building and there are no combustible items such as waste containers in the vicinity of the gable walls. There will be a ventilation slot with battens between the wooden cladding and the old façade. This study is comparative one, *i.e.*, we analyse the influence of the retrofitting of the wooden façade by using the situation before the renovation as the reference case. Thus, the cases analysed are the following:

a) A 3–4-storey concrete-framed residential multi-storey building belonging to the P1 fire class with the façades made of materials with very limited contribution to the fire (the reference case). There is neither an automatic fire detection/alarm nor a sprinkler system in the building.

b) A 3–4-storey concrete-framed residential multi-storey building designed and built according to the requirements of the P1 fire class with the exception that the façades are made by adding a wooden cladding on the old façade (or on the old façade with the concrete layer removed).

The apartments in the example building are in practise similar, *i.e.*, they have a floor plan as shown in Figure 1 or its mirror image. Each apartment has two bedrooms with floor areas of 2,7 × 4,1 m^2 (11 m^2) and 3,4 × 5,3 m^2 (18 m^2), a 15,6-m^2 living room (3,4 × 4,6 m^2), a kitchen with floor area of 2,4×4,5 m^2 (11 m^2), a 9-m^2 hall and a bathroom with floor area of 6,5 m^2. In each apartment the living room opens to a balcony extending the whole width of the living room (3,4 m). Floor height equals 2,8 m. Figures 2–4 show the façades and gables of the building as well as cut-away drawings.

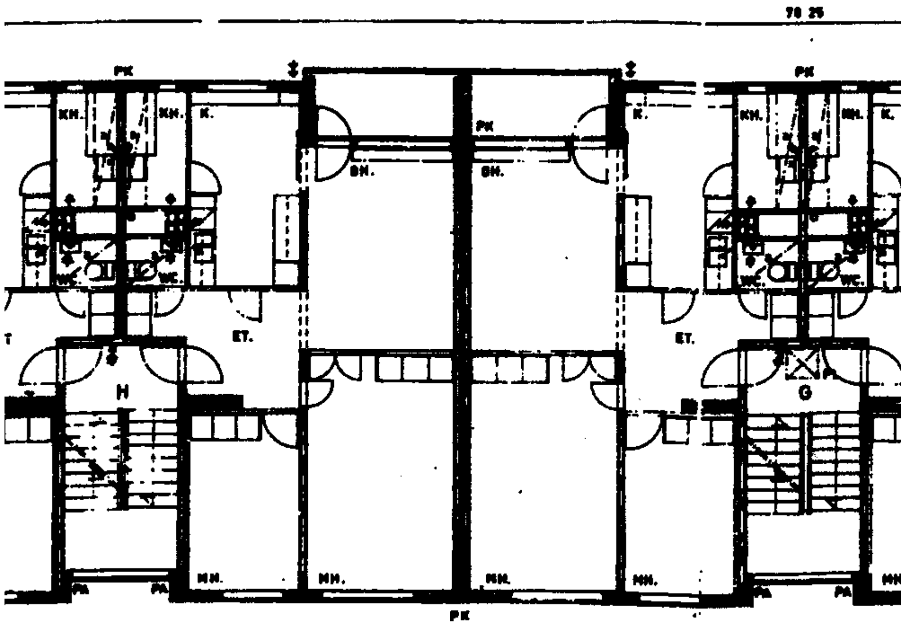


Figure 1. The floor plan of the example building. There are two kinds of plans of the apartments in the building, ones that are similar to the above plan and others that are its mirror images[2].

[2] The abbreviations of the room labels are related to their names in the Finnish language, in English they translate as follows: OH = living room, MH = bed room, K = kitchen, ET = hall, KH = bath room and PK = balcony.

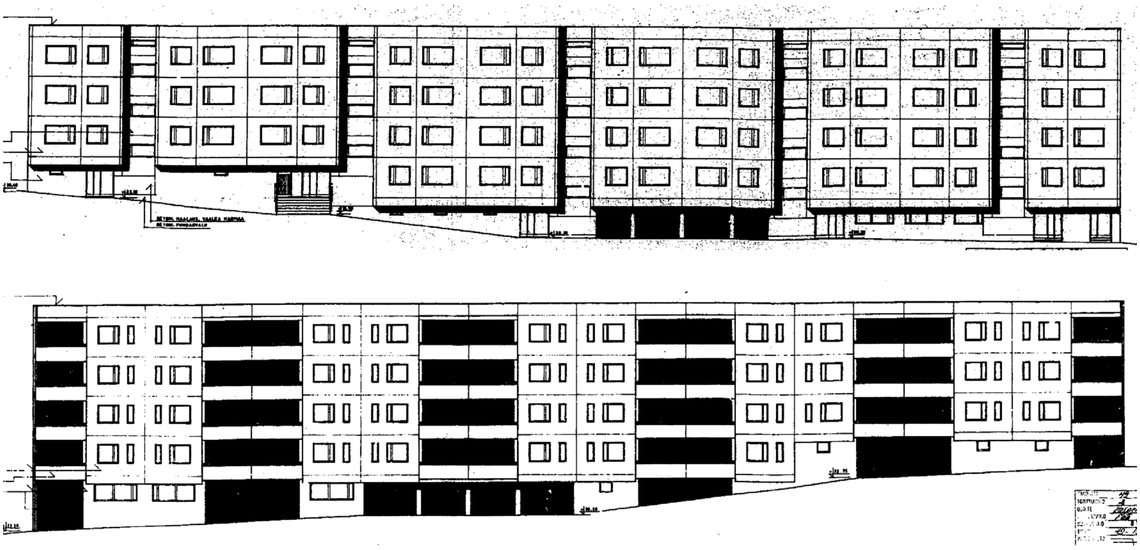


Figure 2. Façades to the east (the upper figure) and to the west (the lower figure).

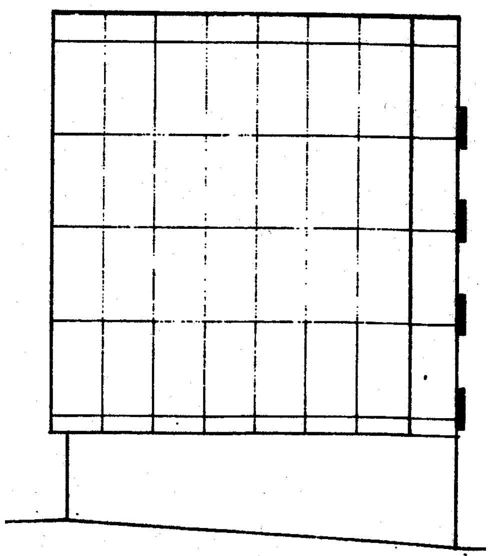
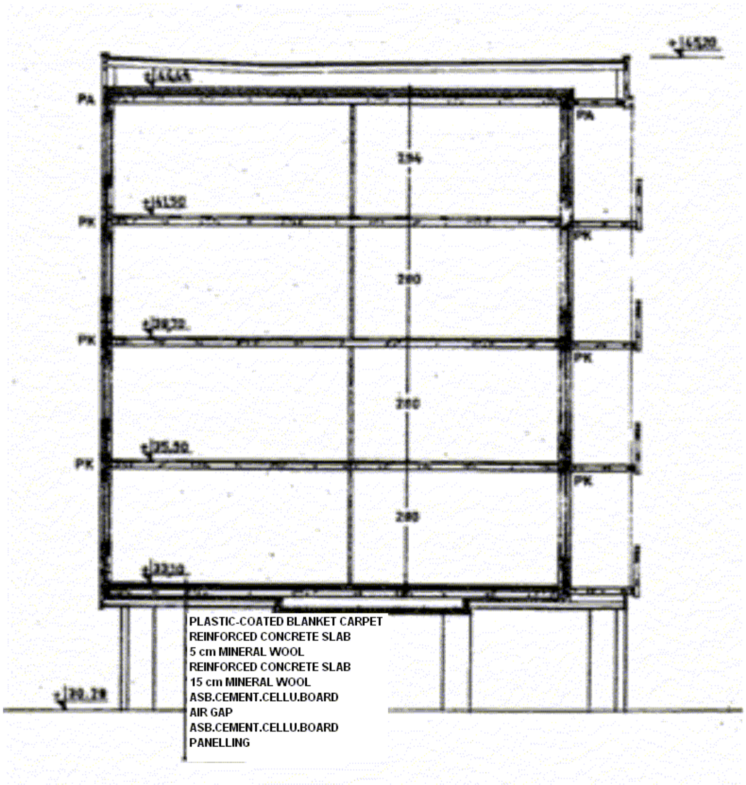


Figure 3. Gable of the building facing the north. The façade facing the south is similar with the exception that the building is one storey lower.

a)



b)

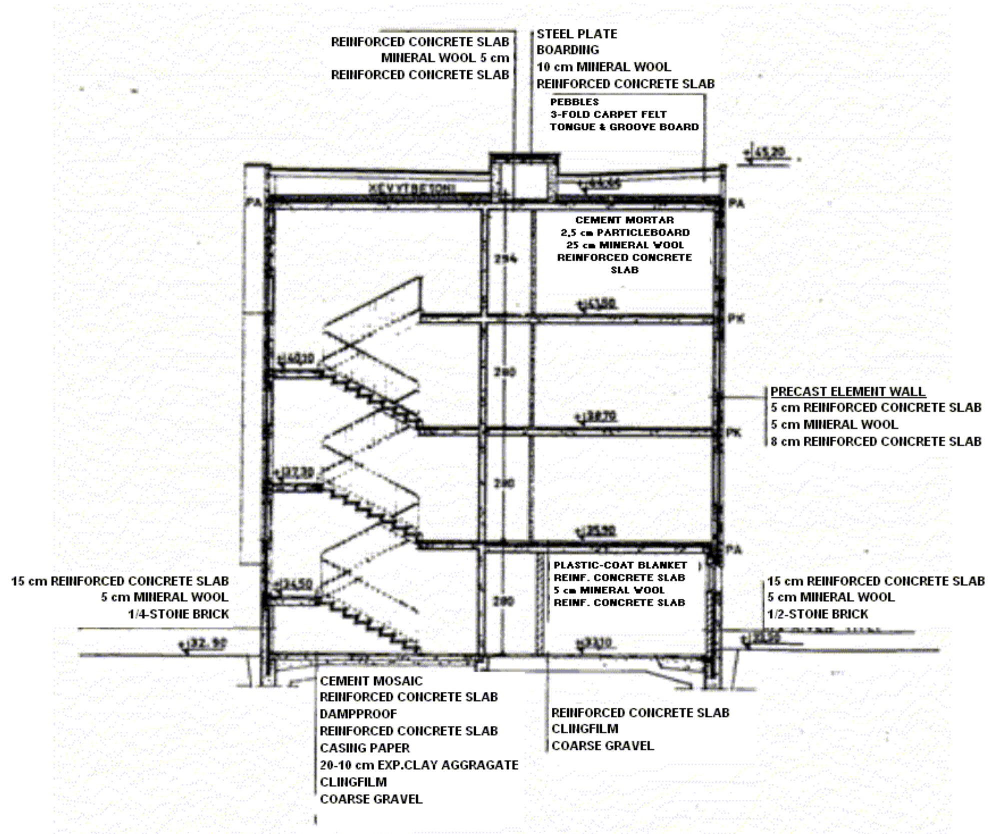


Figure 4. Cut-away drawings: a) at a balcony and b) at the stairway.

3. Methods

3.1 Statistical survey

To establish the statistical basis to the work in this report, a survey was carried out on the material recorded in the Finnish National Accident Database (PRONTO) maintained by the Ministry of the Interior concerning residential fires and the role of the façade material in these fires. The years covered in the survey are 1996–2001. The material and results of the statistical survey are presented in details in Appendix A. In following we present the results which are essential for the risk assessment carried out in this report.

3.1.1 Statistics on the role of the façade material in fires in residential multi-storey buildings

Search of fires recorded to the PRONTO database in years 1996–2001 enabled us to establish the division of ignitions of fires in residential multi-storey buildings to exterior and interior ignitions (see Appendix A). Regarding the influence of the façade material, the most important piece of information extracted from the statistics is the proportion of exterior ignitions with respect to the fire classification of the façade. In buildings with façade classified as a 1/I or B-s1,d0 material[3] (*e.g.* coated non-combustible board products), the portion of external ignitions of all fires is smaller than in buildings with façade classified as a 2/- or D-s2,d2 material[4] or -/- material[5]. The portions are the following: class 1/I: *ca.*10 % and classes 2/- and -/-: 15–20 %. A similar difference emerges when one uses the building fire class (P1, P2 or P3) as the determinant factor: in buildings belonging to the fire class P1, the percentage of exterior fires of all fires is *ca.* 10 % and in buildings belonging to the fire classes P2 and P3 about 15 %. The coincidence between the percentages evaluated either on the basis of the façade material fire classification or the fire class of the building stems from the fact that in practise, these two factors describe the same thing, *i.e.*, the façades in the class P1 buildings belong mainly to the reaction-to-fire class 1/I while in the buildings belonging to the fire classes P2 and P3 it is quite rare that the façades are constructed of a 1/I material.

---

[3] 1/I: a non-igniting and non-fire spreading surface in the old Finnish reaction-to-fire classification system. B-s1,d0: products which contribute to fire in a very limited extent in the harmonised European reaction-to-fire classification system.

[4] 2/-: a slowly igniting surface with rapid fire-spreading in the old Finnish reaction-to-fire classification system. D-s2,d2: products which contribute to fire to an acceptable extent in the harmonised European reaction-to-fire classification system.

[5] -/-: an easily ignitable surface with rapid fire-spreading in the old Finnish reaction-to-fire classification system.

3.1.2 The number of fires and fire spread

Of the fires in residential multi-storey buildings recorded to the PRONTO database in years 1996–2001 there were on the average 425 fires per year with interior ignition (the 95 % confidence interval is equal to 385–466). Only 3 % of these fires were registered to have spread to several fire compartments at the time when the fire brigade arrived at the scene. 74 % of the fires with interior ignition remained confined to the room-of-fire origin or a part of it. First-aid extinguishing was able to put out the fire in 14 % of the fires and in 8 % of the fires first-aid extinguishing limited to the fire spread. Only in 2 % of the fires it was a mentioned that the fire had broken the fire-room window hence letting the flames to flare outside the room-of-fire origin, and only in three such incidents the external flaming was accompanied by spread of the fire to the apartment located above the room-of-fire origin via breaking the windows of the above apartment (these incidents constitute *ca.* one out of thousand fires with interior ignition).

During the time covered by the statistics survey (1996–2001) the annual average number of fires with exterior ignition was *ca.* 50 or *ca.* 10 % of all ignitions. The majority, *i.e.*, four out of five external ignitions, took place in the balcony and 'genuine' external ignitions constitute a portion of 2 %. Such 'genuine' ignitions include, *e.g.*, ignition of waste containers or shelters in the vicinity of the building or ignition of façades due to reasons of electrical origin, *etc*. It can be estimated that about 15 % of the fires that initiate in the balcony and are not extinguished by the first-aid extinguishing attempts spread into the apartment. Consequently, *ca.* 10 % of all fires starting in the balcony spread inside the apartment.

3.2 Fire scenarios

The worst fire scenario concerning safety of life in the buildings considered in this study, *i.e.*, the typical concrete-framed residential multi-storey buildings built in the 1960's and 70's, are the fires that ignite inside the apartments because they expose to danger the people in the apartment-of-fire origin as well as other people who have apartments in the same staircase since their safety may be threatened by the smoke spreading to the stairway. The material of the façade has no influence on the safety in this fire scenario because unless the people inside the apartment-of-fire origin can exit the apartment they will perish either due to smoke inhalation or heat exposure well before the fire becomes into contact with the façade. The material of the façade is irrelevant also to the safety of the people inside the stairway: should there be smoke in the stairway, its origin would be the fire in the apartment, especially if those who escape leave the door open as they exit the apartment.

As the material of the façade is not relevant in the worst fire scenario, we consider here only fire scenarios which in the light of the statistical survey are much less important than the worst-case scenario described above. These secondary fire scenarios are ones that involve ignition of the façade, which may take place in several ways: the façade may be ignited 1) by the flames of a room fire that has flashed over and broken the fire room windows hence generating external flaming (or, considerably more rarely, external flaming may occur through a window readily open as the fire ignites), 2) by the flames of fires in the balconies as well as 3) through external ignition (*e.g.*, burning of a waste container or car fire close to the façade).

3.2.1 Fires starting inside the building

The development of a fire initiated inside an apartment does not depend on the characteristics of the façade before the flames reach the façade, which usually takes places when a window or windows of the apartment-of-fire origin break and fallout due to the fire-induced thermal stresses. It may also be assumed that the material of the façade has no influence on the perception of the fire before the breakage and fallout of the windows of the apartment-of-fire origin. When the windows of the apartment-of-fire origin have been broken to form a ventilation opening, the flames and smoke burst out of this opening and expose the façade to heat; it is after this moment that the fire may be observed by passers-by or occupants of the building-of-fire origin. Technically at this point, in the case of a combustible façade there will be somewhat more flaming and smoke generation than in the case of a non-combustible façade, which in turn may potentially speed up the fire detection in the case of a combustible façade. However, we take a conservative approach and assume that the time of fire detection after the flames have burst out of the broken window of the apartment-of-fire origin is the same for combustible and non-combustible façades.

The fire scenario considered is modelled in three phases. First, the events that have bearing on the timing on the fire detection, *i.e.*, the fire growth within the apartment-of-fire origin and the time of window breakage and fallout are modelled using a two-zone fire model augmented by a quantified expert-assessment of the window performance under enclosure fire heat exposure. Secondly, the size and temperature the external flames as well as the heat exposure from the flames to the façade of are evaluated using well-known empirical models. The contribution to the fire of the combustible façade material is incorporated into the modelling in this second phase. The third and final phase of the fire scenario description is the potential spread of the fire in the apartment-of-fire origin to other apartments via external flaming. These three phases constitute the design fire referred to in the clause 1.3.2 of Part E1 of the National Building Code of Finland.

3.2.2 External ignitions

According to the statistical survey covering the years 1996–2001 (see Appendix A), the proportion of external ignitions make up 10 % of ignitions in buildings belonging to the fire class P1. Most of these ignitions, 80 %, take place in the balcony. Balcony fires are not considered in this report because they are dealt with in another report [RTE 2003] made within the framework of the research project on the use of wooden façades in building and renovation. In the case of a fire starting in a balcony, the façade material may have influence on the fire spread upwards and to other apartments. The statistics survey reveals that a few fires started in a balcony have spread upwards (or horizontally). The most important hazard related to fires initiated in a balcony is the fire spread directly into the apartment either via a window that breaks due to the fire exposure or via a readily open balcony door or window. Judging by the statistics it may assumed that every tenth fire that starts in the balcony spreads inside the apartment. The prescriptions of the Part E1 of the National Building Code of Finland allow use of wood or other combustible materials (reaction-to-fire class D products) as a part of the external surface of the external walls in up to 8-levels high buildings in the fire class P1 provided that the constructions surrounding such parts protect the wall surface from the spread of fire, which is the case if the part of the external wall of a living room or some other room that opens to the balcony is made out of wood. The potential contribution of this wooden surface is higher than that of wooden material that is attached to the outer surface of the balcony.

There are about ten incidents per year in which external ignition occurs elsewhere than in balcony. These ignitions include, *e.g.*, arson fires of waste containers or shelters in the vicinity of a building. In the example building we are considering, there are no waste containers or shelters or other potentially igniting items in the vicinity of the building, and, *e.g.*, parking next to the façade is prohibited. It is only when a sizable pile of combustible material is wilfully burner just next to the façade below the windows of the first storey that an external ignition other than one occurring in a balcony can spread inside the apartments in the first storey and, consequently, give rise to a hazard to life of the occupants. In a technical sense the role of the combustible façade in fire spread in such an incident is analogous to the case when there is external flaming emanating from a room with a flashed-over fire and thus, the computational treatment of this fire scenario is similar to the phases two and three described above regarding the fire spread in the case of a flashed-over room fire. External ignition other than one occurring in a balcony may cause upward fire spread along the façade, but hazards to life in such a fire scenario are low, because the fire spread along the wooden façade is after all relatively slow and it does not compromise the safety of the evacuation of the building, not even in the extreme case when the evacuation is executed by the help of the fire services via windows as the flaming on the façade is feeble and thus, easily quenched by the firemen. For these reasons we do not elaborate this fire scenario using modelling. Some technical solutions intended to diminish the potential damage to property are presented below.

There are no windows in the gables of building and hence, before the façade renovation, besides some nuisance caused by smoke smudging, the potential external ignitions at the building gables do not cause any danger to the building. After the façade renovation with the façades in the gables of the building replaced by wooden façades, a fire set in the vicinity of the gable of the building may ignite the façade material despite of the fact that the concrete footing is quite high (see Figure 3). Once ignited the fire may spread upwards towards the eaves and, if there is an attic or a roof void space, the fire may spread via the eaves into this space provided that it has not been extinguished by the fire brigade before the flames reach the eaves. In the example building there only a shallow roof void space and hence the worst case damage in this fire scenario for the wooden-façade case is replaceable damage to the skin of the building. Even if there was a sizable roof void space or attic, the fire spread to this space would not endanger the occupants because these is a reinforced concrete slab with considerable fire resistance separating the roof void or attic from the apartments.

The east and west faces of the building have windows and hence, there is a potential that an externally ignited fire may be able to penetrate inside the apartments through ventilation windows that happen to be open or via balconies. The danger is highest for the apartments on the first storey, because the upper storey windows and balconies are protected against the fire spread by the 'fire barriers' formed by the windows in the lower storeys. Due to these obstacles to fire spread, the flames can propagate only in the wall area between the windows. If there are continuous windows, these constitute a very effective obstacle to the fire spread along the façade preventing the flames from reaching the upper storeys or the eaves. The heat flux to windows from the flames of the burning wooden façade is relative low [Hakkarainen *et al*. 1997, Hakkarainen & Oksanen 2002, Lattimer 2002], most likely too low to induce breakage of the outer and the inner window pane [Mowrer 1998].

3.2.3 The role of the construction of the façade and eaves and attic/roof void space in the fire scenarios

The speed of propagation of a fire on a wooden façade is affected by the construction of the wall, especially the openness of the air gar behind the façade boarding. The spread of fire on a wooden façade has been investigated at VTT in several studies [Hakkarainen *et al*. 1996, Kokkala *et al*. 1997, Hakkarainen *et al*. 1997, Hakkarainen & Oksanen 2002]. Hietaniemi *et al*. [2003] have summarised the results of these studies into the graph shown in Figure 5. If there are functional fire stops in the air gap, the fire propagation speed becomes halved to about 20 cm/min from the speed of 40 cm/min corresponding to an open air gap. The fire stops in the air gap hinder also the stack-effect driven flow of the hot fire gases to the eaves.

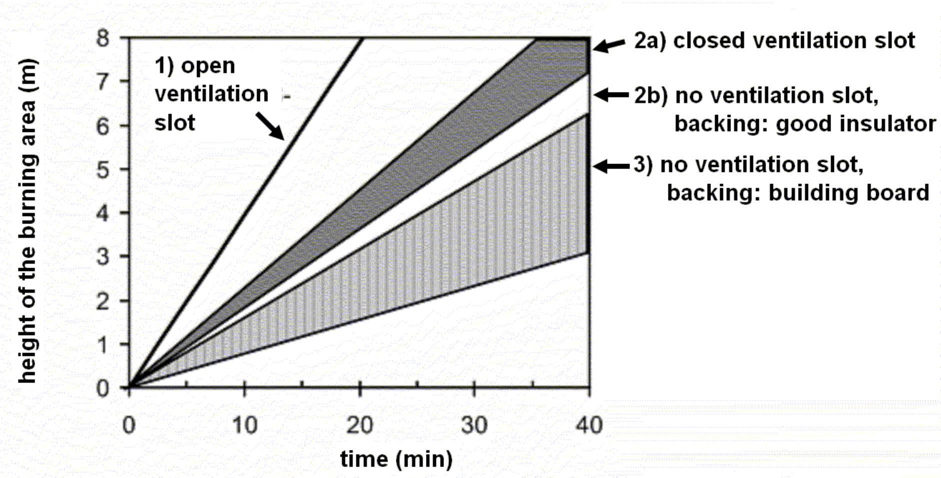


Figure 5. Fire spread on wooden façade with different constructions: when the air gar behind the boarding is open (vertical battens), the upward fire propagation speed is ca. 40 cm/min and ca. 20 cm/min for a façade with a closed air gap (horizontal battens or fire stops).

Renovation of the façade may be accompanied by additional changes in the building construction, one potential option being altering the roof construction from the flat roof construction typical to the original architecture of the multi-storey buildings built in the 1960's and 70's to a pitched roof. In such roof renovation, a void space is formed between the uppermost reinforced concrete slab and the roof with the roof constructions in most cases being made of wood. In this case, one must take into account the potential fire spread via the eaves to the roof void and further within the roof void. This fire hazard is related to loss of property, not to safety of life. Fire spread to the roof void also hampers the operations of the firemen. The likelihood of the fire scenario involving fire spread from the combustible façade to the roof void can be greatly reduced by constructing the eaves in such a way that it retards or prevents the fire spread. Figure 6 shows an example of a fire-spread-retarding eaves construction [Hietaniemi *et al.* 2003]. A further reduction in the potential property losses and facilitation of the fire fighting tasks is obtained by compartmentation of the roof void by structures with sufficient fire resistance.

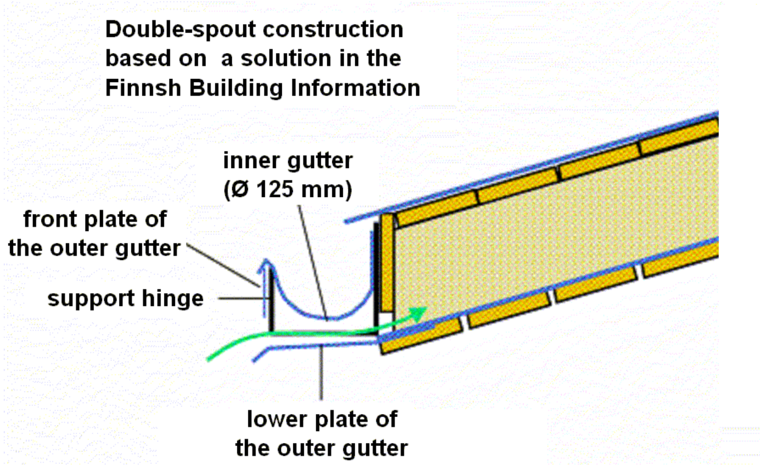


Figure 6. A prototype of a fire-spread-retarding eaves construction [Hietaniemi et al. 2003].

The cost efficiency of the structural measures, *i.e.*, installing fire stops to the air gap, improving the fire performance of the eaves and providing appropriate fire compartmentation in the roof void, taken to reduce the possibility of fire spread along the wooden façade and via the eaves into the roof void as well as to prevent fire spread within the roof void by can be assessed on the basis of the frequency of fires in residential multi-storey buildings. If we assume that the life cycle of the renovation is 30 years, then the probability of a fire occurrence per the life time is *ca.* 1,5 %. The statistics show that only a small fraction of all ignitions lead to fire exposure of the façade because in a majority of the incidents the windows of the apartment-of-fire origin remain unbroken. According to our statistical survey the fires that lead to heat exposure of the façade and, thus may lead to fire spread along the façade, constitute about 10 % of the recorded incidents. This 10 % fraction includes external sources of ignition such as intentionally or unintentionally ignited waste container fires, those balcony fires that are not extinguished by the first-aid extinguishing efforts as well as the external flaming associated with flashed-over apartment fires. This means that, *e.g.*, in a unit of buildings with 100 apartments, there is a 15 % probability of occurrence of a fire that will expose the façade. For example, if the expected roof damage and its repairing would cost of the order of 50 000–100 000 euros and that the additional water damage to the apartments in uppermost storey of the 4-storey building (25 apartments) would be ca. 5 000–10 000 euros per apartment, then the expected property losses related to the fire spread on the combustible façade are of the order of magnitude of 30 000–50 000 euros, which is high enough a sum to justify investments to proper structural fire spread prevention measures.

3.3 Modelling of the spreading of a flash-over room fire

Modelling of the spread of the flash-over fire in some apartment includes three phases:

1. Modelling of the development of fire in the room-of-fire-origin.
2. Modelling of the external flaming.
3. Assessing the probability of the spread of the fire to apartments above the room-of-fire-origin on the basis of the magnitude of the heat exposure caused by the external flaming.

All these phases are subject of considerable uncertainties, which are included in the modelling in such a way that the calculations are carrier out using the Monte Carlo technique. In practise this is realised so that the calculations are done using the Probabilistic Fire Simulator (PFS) program developed at VTT [Hostikka *et al*. 2003, Hostikka & Keski-Rahkonen 2003, Hietaniemi *et al*. 2004]: in the apartment fire simulations we use the PFS-CFAST tool and in the external flaming and fire spread calculations we use the models described below run in a Monte Carlo mode.

It is pointed out that when the fire simulations and other calculations are performed using the Monte Carlo technique, the results include automatically the information concerning the sensitivity of the results on the input factors and the assumptions made regarding them.

The mode of fire spread considered is the propagation of fire from one apartment to another via external flaming. The models presented below can equally well be applied also to assess the potential of fire spread from an apartment fire to the attic or roof void space via the eaves. However, in the example building such fire spread mode in irrelevant as the building has a flat roof with only a shallow roof void space. Thus we do not delve into this matter with the same thoroughness as we consider the apartment-to-apartment fire spread. It should noted also that while the apartment-to-apartment fire spread is a question of safety of life, the fire spread from an apartment to the attic is a matter of property losses, which can – as detailed above in Section 3.2.3 – be reduced by appropriate structural solutions.

One detail of our description and modelling of the fire scenario is that we assume that the ventilation windows of the apartments above the room-of-fire-origin are closed, which naturally may not be the case, e.g., on a warm summer day. There are two aspects that justify this assumption. First, when the ventilation window is open, it is very likely[6]

[6] In Finland a warm summer day can rapidly turn into a rainy summer day and thus, it is rather light-headed to leave the ventilation window open when leaving the apartment. Such can naturally happen, but quite rarely mainly as a careless mistake, not intentionally.

that there are also people inside the apartment who will be alarmed by the smoke and noise of the fire and. consequently, close the window and make an alarm. Secondly, if the ventilation window is open, the external flames of the fire in an apartment beneath are so big that they will enter the window opening regardless of the façade material.

3.3.1 The model for the fire in an apartment

The development of the fire in the apartment-of-fire-origin is modelled using the CFAST two-zone model program [Peacock et al. 1993]. The subscenarios corresponding to the different locations of the fire initiation include ignitions in the bedrooms (with two different sizes), in the living room and in the kitchen (total of 4 subscenarios). The door of the fire room is assumed to be open because if it is closed, the fire will rapidly become underventilated hence leaving the hot gas layer temperature too low to be able to break the window and thus, the fire will most probably self-extinguish due to lack of oxygen. The proportion of the fires that grow hot enough to be able to break the window can be estimated on the basis of the statistical survey. Thus we do not model the self-extinguishing fires or fires that are suppressed by first-aid extinguishing; our design fires include only those fires that become hot enough to be able to break the fire room window and hence expose the façade to heat. The CFAST simulations are used to obtain information on the hot gas layer thickness and temperature and these pieces of information are used to assess the magnitude of the heat exposure to the fire room window which then is used to assess the timing of the breakage and fallout of the window. As all the rooms in the example building are roughly of the same size, there are no big differences in the times of the window breakage and fallout in the different subscenarios. Factors that have a pronounced influence on the window breakage and fallout include the installation of the window pane to the frame, potential pre-stress fields in the window panes, fissures in the window edges and the growth rate of the fire. All these factors are subject of considerable uncertainties, which are included in the calculations in such a way that they are carrier out with the Monte Carlo technique using the PFS-CFAST program developed at VTT [Hostikka *et al.* 2003, Hostikka & Keski-Rahkonen 2003, Hietaniemi *et al.* 2004].

The occurrence of breakage and fallout of the windows of the room-of-fire-origin is estimated on the basis of the hot gas layer temperature T_g obtained from the fire simulations as follows: the inner window pane is assumed to fallout when T_g reaches 500 °C and the outer pane on the average t_{outer} minutes later. Due to the uncertainties involved were treat the time lag t_{outer} as a random quantity characterised by a lognormal distribution with the most probable value equal to 3 minutes and 80 % fractile equal to 5 minutes, see Figure 7.

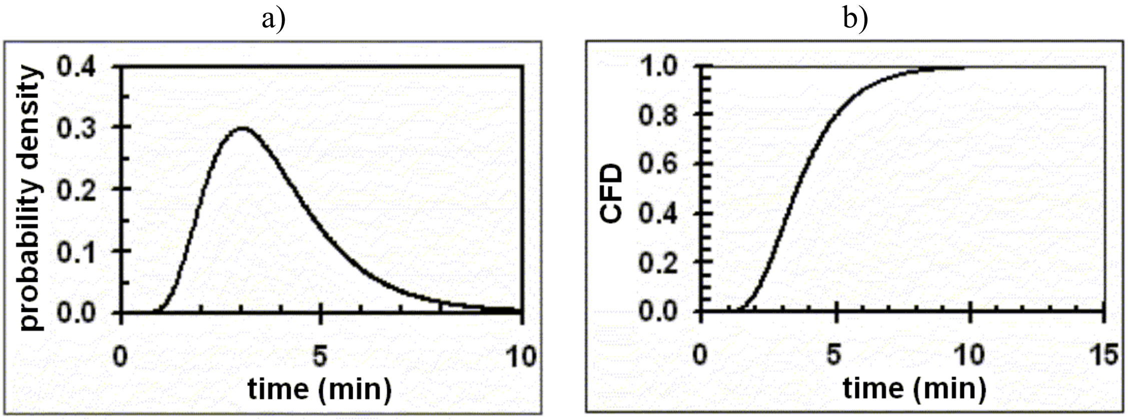


Figure 7. The lognormal distribution used to characterise the time lag of the breakage of the outer window pane with the most probable value equal to 3 minutes and 80 % fractile equal to 5 minutes: a) probability density function and, b) cumulative frequency distribution (CFD).

In our simulations we assume that the ventilation window is closed. Should the ventilation window be open, the likelihood that the fire extinguishes due to lack of oxygen in the case when the door is closed would diminish and consequently, the probability that fire grows hot enough to break the window would increase. Yet, we do not have to consider the case with open ventilation window as a separate fire scenario as it leads to the same fire spread scenario as the cases that we consider, *i.e.*, external flaming due to breakage and fallout of the (big) window of the room. The probability aspects are handled through the statistical information on the frequency of the apartment fires that lead to external flaming.

3.3.2 Heat exposure generated by the external flaming

When the window has broken to form an opening the flames expose the façade to heat. The size of the external flames is calculated using the Law model for external flaming [Law & O'Brien 1981, CEN 2002]. In a ventilation limited fire[7], the heat release rate $\dot{Q}$ (kW) of the room fire in this model depends on the dimensions of the opening and the room as follows:

$$\dot{Q} = 3150\left(1 - e^{-0{,}036/O}\right) A_v \sqrt{h_{eq}\left(W/D\right)}\,, \qquad (1)$$

[7] In a fuel-limited case, we calculate the maximum heat release rate on basis of the heat release per floor area, for which we use the value of 250 kW/m^2 recommended in the Eurocode 1 [CEN 2002].

where h_{eq} is the opening height (m), A_v the area of the opening (m^2), W is the room width (m), D is the room depth (m) and O is the opening factor given by $O = A_v \sqrt{h_{eq}} / A_t$, where A_t is the total area (m^2) of inner surfaces of the room (*i.e.*, the combined area of the floor, walls and ceiling). The height of the flame measured from the top of the opening, L_L (m), depends on the heat release rate and the opening dimensions according to the following formula:

$$L_L = h_{eq}\left(0{,}0237\left(\frac{\dot{Q}}{A_v \rho_g \sqrt{h_{eq} g}}\right)^{2/3} - 1\right), \tag{2}$$

where ρ_g is the density of the hot gases (kg/m^3) and g is the acceleration of gravity (m/s^2). The flame height given by the above expression equals to the height at which the flame temperature is equal to 540 °C (or, more generally, the ambient temperature +520 °C).

We take into account the variability of the various factors such as amount, properties and positioning of fuel in the fire room as well as the model uncertainty pertaining to the Law model by allowing the heat release rate to vary within limits of –20 % – +50 % (uniform distribution) in the Monte Carlo runs. This range of variability reflects the results presented by Harmathy [1980/81], who compiled data from fully-developed room fires and studied their variability.

In case of a combustible façade, the contribution of the façade material to the fire increases the heat release rate. The increase of the heat release rate is calculated on the basis of the burning area of the façade and the heat release rate per unit area $\dot{q}''_{wood}$ of the façade material. We take into account the uncertainties involved in the burning of the façade by allowing the value of $\dot{q}''_{wood}$ to vary randomly according to a triangular distribution with lower and upper bounds equal to 60 kW/m^2 and 120 kW/m^2, respectively, and the most probable value equal to 90 kW/m^2.

The region of applicability of the Law model ranges only up to the height at which the flame temperature equals 540 °C. We, however, need information of the heat fluxes above this height and the model that we use for this region is the model for heat flux from a flame adjacent to a vertical wall to the wall developed by Back *et al*. [1994, Lattimer 2002]. The model of Back *et al*. [1994] uses the Heskestad plume model for the flame height L_f (m),

$$L_f = 0.23 \cdot \dot{Q}^{2/5} - 1.02D, \tag{3}$$

where D is the diameter of the fire (m) and $\dot{Q}$ is the heat release rate (kW). In the empirical relations of Back *et al.* [1994], the maximum heat flux to the wall q''_{peak} (kW/m^2) depends on the heat release rate as follows:

$$q''_{\mathrm{peak}} = 200\left[1 - \exp\left(-0{,}09 \cdot \dot{Q}^{1/3}\right)\right] . \qquad (4)$$

The maximum heat fluxes are found on the centreline of the flame below the height $z = 0{,}4L_f$, where z (m) is the height measured from the base of the flame. Above this height the heat flux values decrease according to Eqs. (6) and (7). The dependence of the heat flux on the height z may hence be expressed as follows[8]:

$$q''_{cl} = q''_{\mathrm{peak}} \qquad z \le 0{,}4L_f \qquad (5)$$

$$q''_{cl} = q''_{\mathrm{peak}} - \frac{5}{3}\left(z/L_f - 2/5\right)\left(q''_{\mathrm{peak}} - q''_{L_f}\right) \qquad 0{,}4L_f < z \le 1{,}0L_f \qquad (6)$$

$$q''_{cl} = q''_{L_f}\left(z/L_f\right)^{-5/3} \qquad z > 1{,}0L_f \qquad (7)$$

where q''_{L_f} (kW/m^2) is the heat flux at the tip of the flame. The models of Law and Back *et al*. were matched together so that heat flux value at the tip of the flame given by the Law model equals the value given by the model of Back *et al.*

3.3.3 Breakage of the windows above the room-of-fire-origin

The likelihood of fire spread to the apartments above the apartment-of-fire-origin is evaluated by comparing the calculated heat flux values (Eqs. (5)–(7)) to the experimental data on external heat flux required to cause window breakage [Mowrer 1998]. The procedure followed is the following: a heat flux equal to 35 kW/m^2 is assumed to break the window relatively rapidly, *i.e.*, in 3 minutes and a heat flux below 10 kW/m^2 is taken too weak to break the window. The piece of information that heat exposure at 35 kW/m^2 that lasts for 3 minutes will break the window gives us the heat energy Q_b required to cause the window breakage (6,3 MJ/m^2). This energy limit can be used to calculate the time lag of a window breakage at lower heat exposures than the value of 35 kW/m^2. The uncertainties involved in the window breakage induced by the external flaming are characterised in the Monte Carlo simulations by drawing the

[8] Back et al. [1994] give also relations for the dependence of the heat flux on the distance from the centerline of the flame. Howevere, we do not use those relations but employ a conservative approach and use the centerline heat flux value also for regions away from the centreline.

values for Q_b from a symmetrical triangular distribution with minimum and maximum value ranging ±20 % around the mean value of 6,3 MJ/m^2.

3.3.4 Assessment of the model validity

The validity of the models described above is shown in Appendix C by comparing the results calculated by the models to experimental data and observations. The data of the comparisons are obtained in full-scale fire experiments in Canada [Oleszkiewicz 1990], Germany [Schild *et al*. 2004] and at VTT [Hakkarainen *et al.* 1996, Kokkala *et al*. 1997, Hakkarainen *et al*. 1997, Hakkarainen & Oksanen 2002]. The agreement between results of the models and the data and observations is good. It should be noted the model results are true predictions and no adjustment of parameters was done to improve the agreement with the data and observations.

3.4 Time-Dependent Event-Tree method

3.4.1 Description of the model and its use in the present context

The models and simulations described above give the time development of the potential fire spread *in the absence of any attempts to detect and extinguish the fire*. In reality, such development is extremely rare because generally, the fire is noticed and the fire services are alarmed to execute rescue and extinguishing tasks. Thus, to get a realistic picture of the fire development we must assess the fire development taking into account the fire detection and active attempts to extinguish the fire (either by the personnel – or in this context the occupants – or the fire brigade) as well as potential self-termination of the fire when the fire load is exhausted.

This can be done by using the Time-Dependent Event-Tree (TDET) method developed by VTT [Hietaniemi *et al*. 2002, Korhonen *et al*. 2003]. The model differs from the conventional event-tree modelling in the important point that the TDET method takes explicitly into account the time dependence of the incident analysed, while conventional event-trees only reflect the temporal development via the inherent causality of their structure. The explicit incorporation of the time in the TDET model is realised so that time period under study (*e.g.*, the time from ignition to the end of the fire) is divided in to short time intervals each of which is analysed by a conventional event tree. It should be noted that branching probabilities of the event trees change with time: for example, before the time when the fire brigade arrives at the scene, the probability that the fire brigade extinguishes the fire is zero, while after the fire brigade has arrived and is ready to fight the fire, the probability that the fire brigade extinguishes the fire is some number between

0 and 1 depending on the ability of the fire brigade to suppress the fire, which in turn depends strongly on the size of the fire at the moment when the extinguishing attempts are started. The evolution of the incident from its start to the end is obtained by combining the sequential event trees. The combination of the large number of sequential event trees is a non-trivial problem of probability calculus. We have solved it by treating the fire as a Markovian process which enables as to reduce the problem to handling of transition matrices of a Markov chain, which can be automated to a TDET software.

Some of the branching probabilities can be obtained from calculations; in this work this means specifically the arrival and success of the fire brigade extinguishing attempts, which can be calculated on the basis of the data on the fire services response times [Tillander & Keski-Rahkonen 2000a, Tillander & Keski-Rahkonen 2000b] and the calculated development of the fire as well as the ending of the fire load, which can be calculated on the basis of the known fire load density data [CEN 2002]. Some branching probabilities are estimated on a basis of expert judgement/common sense; in this work such branches correspond to the perception/detection of the fire.

The primary output of the TDET method is the probability that the fire has ended, the reason being either active attempts to extinguish the fire or fire self-termination to exhaustion of the fuel. The models described in the previous sections provide the other component of the risk, *i.e.*, the potential magnitude of the damages at given times during the fire. Combination of the probabilities and the magnitudes of the consequences gives the risks.

In the present application of the TDET method, we only take in to account the fire detection and the influence of the fire services operations. The results we obtain tell how much – if at all- the fire risks differ in the example building with the original concrete façade and when there is a wooden façade installed to the example building. It should be noted that the TDET analysis could readily be extended to cover the influence of different fire detection and alarming systems as well as automatic extinguishing systems.

3.4.2 The structure of the event tree

The structure of the event tree presently implemented in the TDET method is shown in Figure 8. The event tree is more general than what is needed in the present analysis, but this constitutes no problem as the irrelevant branches, such as those that take into account automatic extinguishing or alarming systems, can be cut off by setting the associated branching probability to zero. The event tree that is left takes into account fire perception by senses (*e.g.*, a visual cue or smell of smoke), potential first-aid fire fighting by the occupants, the influence of the fire brigade extinguishing actions and self-termination when the fire load ends.

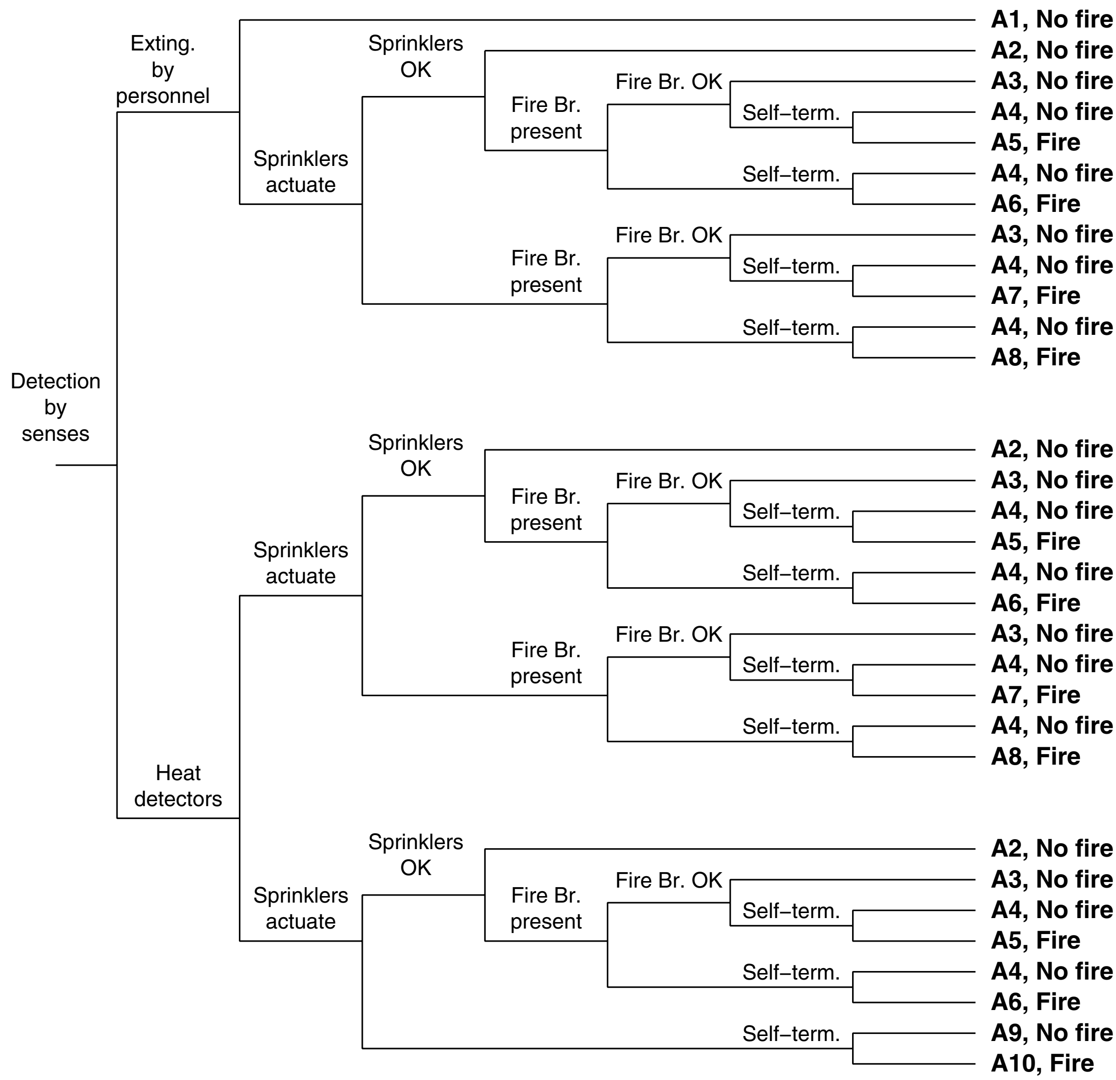


Figure 8. The structure of the event tree used to model the fire detection and active attempts to extinguish the fire (either by the personnel – or in this context the occupants – or the fire brigade) as well as potential self-termination of the fire when the fire load is exhausted. It should be noted that the event tree above is a logical structure and the explicit time dependence of the fire incident is taken into account by dividing the time into short intervals each of which is analysed by an event tree shown above. The sequential event trees are combined together to form the time line of the incident by treating the fire as a Markovian process which in turn allows to model the system using Markov chain transition matrices [Hietaniemi et al. 2002, Korhonen et al. 2003]. Note that the very first event, the ignition, is not included in the graph as the probability assigned to the ignition acts just as a common scaling factor to all the other probabilities.

3.4.2.1 The initiating event: ignition

The initial event of fire is the occurrence of sustained ignition. This event is not shown explicitly in our event tree as it acts just as a common scaling factor to all the other probabilities. The frequency of the ignitions are obtained from statistics, see Section 3.1. We assume that the specific ignition frequency estimated from the statistics to some building type applies to all spaces and rooms of the building.

3.4.2.2 Fire perception or detection and first-aid extinguishing

The initial branch in our event tree is perception of the fire via cues such as seeing or smelling smoke or through detector activation. In Finland there should be a functioning smoke detector in each apartment[9] which gives a voice signal in case of fire. We include the fire detection by these devices in to the category of "fire perception by senses", as it is through hearing that the information of these devices are perceived and the alarming takes place similarly to the cases where the occupant becomes aware of the fire through an actual sensation. If there would be a detector that besides giving the voice alarm would also transmit a signal to the fire station, then it would be included in our event tree system as follows: the automatic detection and alarming is taken into account only if it takes place before sensual perception (*i.e.*, we assume that if a person has already noticed that there is a fire, the operation of the automatic detection and alarming system will not change the course of events). The logic goes further so that after automatic detection and alarming there is no first-aid extinguishing branch, but the automatic detection and alarming is followed directly by branches related to automatic extinguishing and fire brigade operations.

The timing of fire perception and the role of the first-aid extinguishing in the fire development were assessed using statistical data collected in the statistics survey of this work (see Section 3.1 and Appendix A). On the basis of the statistical findings, we divide the perception via senses to two categories:

1. Rapid perception, which means that the occupant is awake and in good physical and mental state (typically a sober adult) and is thus able to alarm the fire brigade as well as make an attempt of first-aid extinguishing. Here we assume that the time delay of perception is of the order of magnitude of one or two minutes and that the handling of the emergency call takes about one minute. In the incidents in this category, some of the fires are put out by the first-aid

[9] Yet in practise, the statistics seem to indicate that although there may be smoke detectors in most apartment, not all of them will function in case of fire.

extinguishing and the fire brigade may be able to intervene the fire development inside the apartment and thus prevent external flaming. The percentage of this category is assumed to be 70 %.

2. Slow perception, when the apartment is either empty or the occupant is not able to act in the way as described in the category 1, in which case the fire will be noticed only after it breaks the windows. In this case, the fire brigade will not be able to influence to the fire development in the apartment and hence we assume that all these cases lead to our design fire, *i.e.*, external flaming via the broken windows of the room-of-fire-origin. The percentage of this category is assumed to be 30 %.

The reasoning behind the percentages associated with the two fire perception categories may be find in the statistics, which show that 74 % of all fires ignited inside residential multi-storey buildings were confined to the room-of-fire-origin or a part of it. Thus, approximately 70 % of fires ignited inside residential multi-storey buildings never reach the façade, which corresponds to the category 1 above[10].

The statistical survey reveals that concerning fires with internal origin, first-aid extinguishing extinguished 14 % of the fires and limited the fire development in 8 % of the fires. On the basis of these numbers we assume that first-aid extinguishing puts out about 25 % of the fires that have been perceived rapidly. This assumption corresponds to a first-aid extinguishing efficiency of 17,5 % which is in line with the statistical findings.

In our approach some fires that have been perceived rapidly break the fire room windows and expose the façade before the fire brigade arrives at the scene. This means that our design fires are considerably more severe than real fires which include also small fires. This circumstance is in fact the design-fire-normalisation problem that is well-known among fire-safety engineers using probabilistic approaches in their work. As we have the relevant statistical data available, we can use these data and normalise the frequency of the ignitions so that the results of our model agree with the statistical findings.

---

[10] The fire perception could be speeded up by adding more detecting devices into building. The influence of such devices could readily be taken into account in our analysis by increasing the percentage of rapidly perceived fires. However, in the analysis of the example building we assume that there are only the normal battery-operated smoke detectors and thus also the percentages of the rapidly and slowly perceived fires correspond to the portions revealed by the statistics.

3.4.2.3 Operation of fire services

The fire brigade response time, *i.e.*, the time delay from the reception of the alarm to the time when the fire brigade arrives at the fire scene consists of two separate time factors, the turnout time (time from the alarm to the moment when the fire brigade leaves the fire station) and the travel time [Tillander 2004]. Both these time factors, the turnout time and the travel time are modelled on basis of their statistical distributions[11] established by VTT [Tillander & Keski-Rahkonen 2000a, Tillander & Keski-Rahkonen 2000b]. Before the rescue and extinguishing operations can commence, there is a time taken by the access and set up. The data on this time factor is scarce, the only data available in literature seeming to be that of Särdqvist [1998] which, however, is related to fires in other-than-residential premises in the London region and hence is not very usable in the present work addressing a residential buildings in Finland. Yet, in absence of better data, we estimate the time needed for access and set up on the basis of the data of Särdqvist [1998]. The example building is located about 8 km from the nearest fire station, Mellunmäki in Eastern Helsinki. We assume that the first unit will arrive from this fire station. The distance to the main fire station in Helsinki, the Kallio Fire Station, is roughly the same, 10 km, as the distance to the Mellunmäki Fire Station.

The fire brigade is assumed to be able to control the fire so that the fire does not spread any further from the extent of spread reached at the time when the fire brigade starts its extinguishing operations, *i.e.*, only those fire compartments that are involved in the fire at the fire brigade intervention are assumed to the affected by the fire. This assumption is based on the fact that we are considering concrete-framed buildings belonging to the fire class P1 which have fire resistant concrete fire barriers surrounding each fire compartment. There is also the fact that a typical fire brigade unit is able to control and actually to extinguish quite rapidly a fire of the size of typical apartment fire, *i.e.*, less than 10 MW. The fire brigade may encounter problems in controlling the fire spread mainly in the cases when the fire has spread to the attic or a roof void and the particular attic or roof void is not divided to appropriately to fire compartments. Such cases do not, however, create significant danger to the occupants, because the buildings that we considering have a reinforced concrete slab between the potential attic or roof void and the apartments.

---

[11] The statistical distribution that describes well the statistical data is the gamma distribution with the density function given by

$$f(x) = \frac{1}{\Gamma(\alpha)\beta^{\alpha}} x^{\alpha-1} e^{-\frac{x}{\beta}}$$

where $\Gamma(\alpha)$ is a gamma function

Figure 9 shows the statistical distributions of the time of the fire brigade intervention with the time zero corresponding to the moment of alarming. Besides the average response time of rescue units in Helsinki, Figure 9 shows response times for selected distances between the fire station and the building in fire. The obtain the times from the fire ignition, one has to add to the times shown in Figure 9 the times taken by the perception of the fire as well as the alarming time (emergency call).

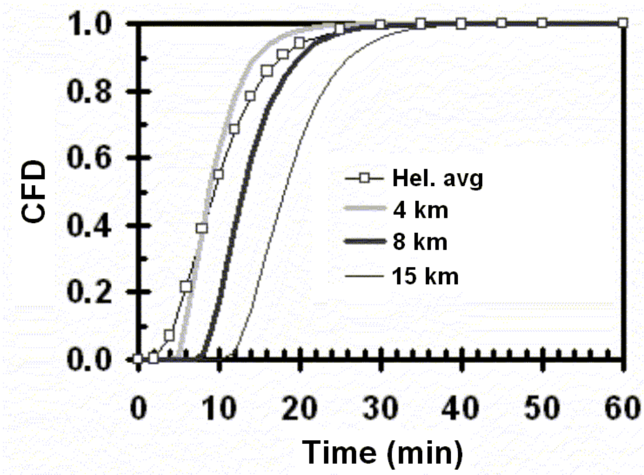


Figure 9. Cumulative frequency distributions of the operation times of rescue units in Helsinki. The squares denote the average response time in Helsinki and the lines without markers depict the turnout plus the travel time for the different distances shown plus the time required for access and set up. The thick black curve corresponds to the example building with 8 km distance to the nearest fire station.

3.4.2.4 Exhaustion of the fire load

The amount of fire load is calculated on the basis of the room floor area and the statistical distribution of the fire load in dwellings given by the Eurocode 1 [CEN 2002]: the Gumbel distribution with the mean value equal to 780 MJ/m^2 and the 80-% fractile value equal to 948 MJ/m^2. The decay of the fire is assumed to start when 70 % of the fire load has been consumed. It is further assumed that the flames do not project out of the window during the decay phase.

3.5 Normalisation of the calculated risks

The modelling and risk analysis tools described in the previous sections give the *risks per one design fire*. As not all fires are as severe as our design fire, we have to normalise the calculated risk so that their magnitude coincides with the data derived from the statistics. The calculated risks that are used in evaluating the normalisation factor are those which correspond to the average performance of a fire brigade in Helsinki. As we are addressing buildings that are located typically in suburbs of cities, this normalisation works reasonably well also for other locations in Finland than the Helsinki region provided that building considered is not located very far from a fire station.

Our design fires are very severe, *i.e.*, if not interrupted, each design fire would grow so hot that it would break the fire room window. The statistics, however, show that the percentage of fires that break the fire room window is not 100 % but much lower: 2 % of fires were recorded to actually have broken the window and 3 % of fires were recorded to have spread to several fire compartments, which in the case of fires in residential multi-storey buildings can be interpreted to mean spread to other apartments, mostly located above the fire room. Thus, we can assume that about 5 % of internally ignited fires become into contact with the façade. This piece of information was incorporated into the TDET model by adjusting the ignition frequency so that the TDET results on the probability of the fire spread became equal to 5 %. This adjustment was applied to fires in the category of "rapid perception". The fires that belong to the category "slow perception" are assumed by definition to break the fire room window.

3.5.1 Normalisation of the probability of fire spread from an apartment to apartments above

Figure 10 shows the calculated unnormalised probabilities per one fire for the fire spread from an apartment to the apartment in the next storey. As described above, the calculation model takes into account that only *ca*. 5 % of fires break the fire room window. As the fire brigade intervention was modelled using the average response time in Helsinki, the results apply to residential multi-storey buildings in or near big cities. The procedure of normalisation goes as follows. We know from the statistics that there are on the average *ca*. 400 fires per year with interior ignition in residential multi-storey buildings and thus, the unnormalised probabilities would predict that every year about ten fires ($400 \times 0{,}02 = 8 \approx 10$) would spread to the above apartment. The statistics show, however, that the actual frequency of such incidents is about once in a year, *i.e.*, by a factor of ten less than the unnormalised calculated probabilities suggest. Hence our normalisation factor for the probabilities of fire spread from an apartment to apartments above is 10.

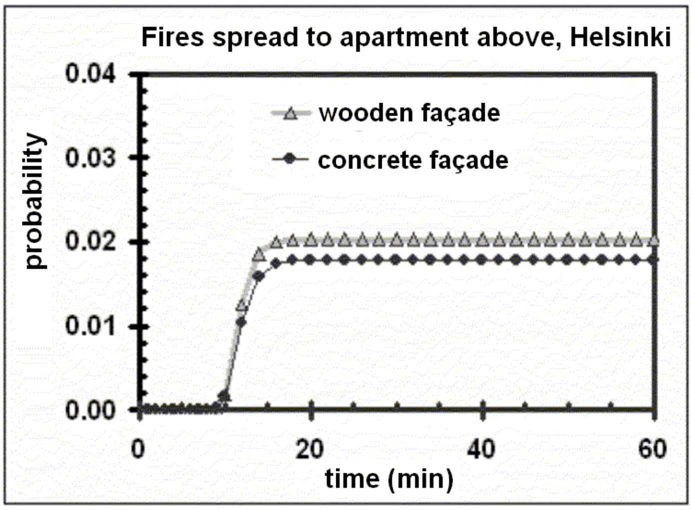


Figure 10. The unnormalised probabilities per one fire for the fire spread from an apartment to the apartment in the next storey.

3.5.2 Normalisation of the probability of fire spread from an apartment to the eaves

Figure 11 shows the calculated unnormalised probabilities per one fire for the fire spread from an apartment to the eaves of the building[12]. The results are calculated in the same way as in the previous case by quantifying the fire brigade operations using the data obtained for Helsinki. The probability that the fire spreads to the eaves is of the same order of magnitude as the probability of fire spread to the above apartments. Thus also the normalisation factor is the same, 10.

[12] Here, we do not consider the consequences that the fire spread to the eaves may have; in the example building model the consequences will be small, because there is only a shallow void bounded on its lower sideby a reinforced concrete slab.

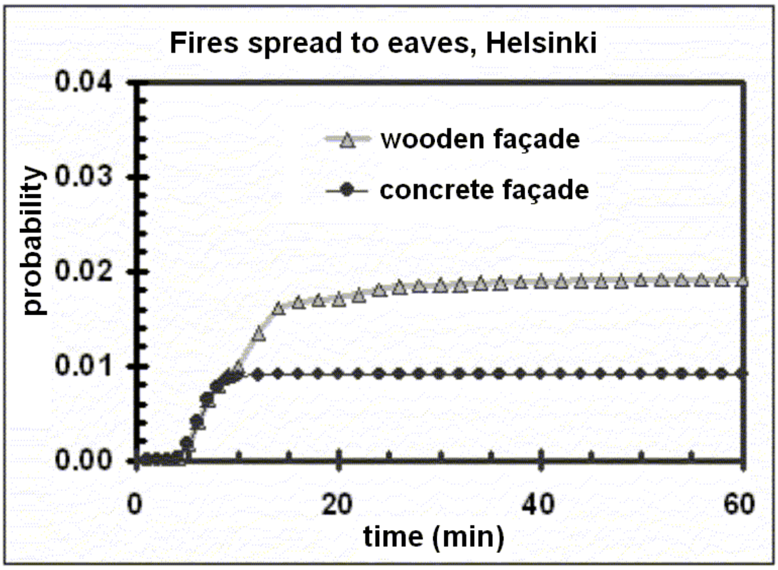


Figure 11. Unnormalised probabilities per one fire for the fire spread from an apartment to the eaves of the building.

4. Results for the example building

The example building is a concrete-framed residential multi-storey building belonging to the P1 fire class located in Laajasalo in the Eastern Helsinki at 8 kilometres distance from the nearest fire station. The building is scheduled to be renovated and its façade, presently made of concrete, may be changed to a wooden façade. There may be further modifications concerning, *e.g.*, the roof, which may be changed from the present flat roof to a pitched roof. With respect to the present study, the potential changes to the roof are not very significant as long as the reinforced concrete slab now existing above the uppermost apartments is not modified, because with the concrete slab in place, the risks of downward fire spread from the roof to the apartments is negligibly small.

4.1 Fire spread from an apartment fire

4.1.1 Fire spread to the apartments above the fire room

Figure 12 shows the probabilities per one fire for the fire spread from an apartment to the above apartments. The probabilities of fire spread one storey or two storeys upwards are shown, but not three storeys up, because for that case, the probabilities are practically zero.

The probability of fire spread one storey up is about 0,25 % per fire and it is almost the same for the concrete façade and the wooden façade, the probability for the wooden façade being only 9 % higher (0,27 % per fire for the wooden façade vs. the 0,25 % per fire for the concrete façade). Expressed as a frequency, the increment in the fire spread probability related to the wooden façade corresponds to one incident in ten years in all residential multi-storey buildings in Finland. This means that if the material of all façades of residential multi-storey buildings in Finland was changed to wood, the difference caused by this chance in the frequency of fires that have spread to other compartments could not be discerned from the fire statistics, because the change would vanish in to the inherent statistical fluctuations.

The construction of the wooden façade, *e.g.*, added fire stops in the air vent slot, does not in practise influence on the fire spread probability to the apartment right above the fire room, since their influence is hidden by the intensity of the external flaming from a flashed-over room fire.

The relative difference in the probabilities of fire spread two storeys upwards is clear: with a wooden façade this probability rises by a factor of *ca*. 3,5 as compared to the concrete façade. This change is, however, totally irrelevant, because the absolute values of the probabilities are so low. The order of magnitude of the probability is only 0,001–0,003 %, which is in practise equal to zero, *i.e.*, according to the results the spread of fire two storeys upwards is a pure matter of chance[13].

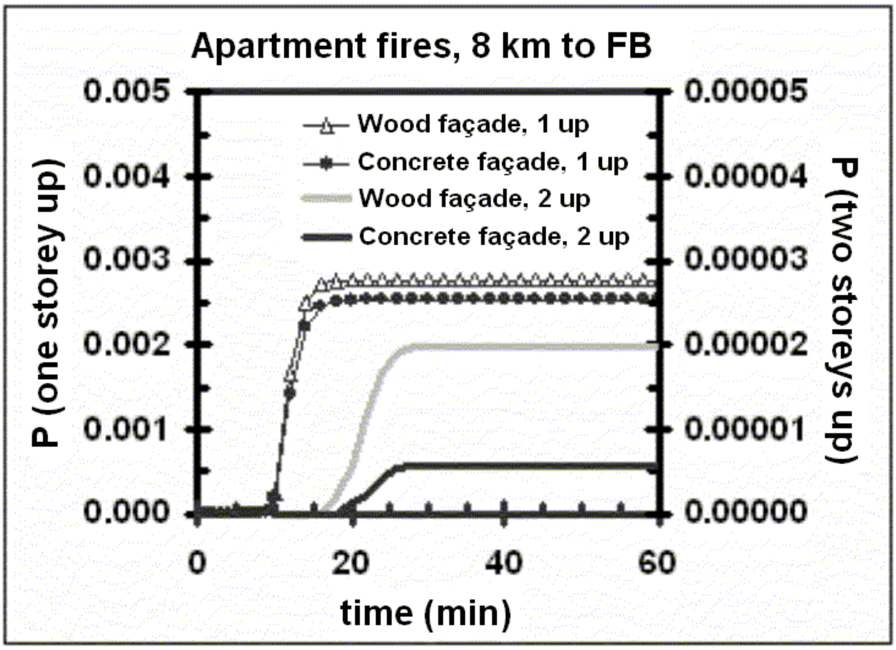


Figure 12. The example building, probabilities per one fire for the fire spread from an apartment to the apartments in the upper storeys: the left-hand side axis gives the probability of fire spread one storey upwards and the right-hand side axis the probability of fire spread two storeys upwards. The distance to the nearest fire station is 8 km.

4.1.2 Fire spread to the eaves

In the example building, or in any buildings with a similar flat roof construction typical of the architecture of the 1960's and 1970's, the fire spread up to the eaves causes no significant risks, because the reinforced concrete slab protects the apartments in the uppermost storey against a fire in the roof: a potential ignition of materials in the roof construction with shallow void above the reinforced concrete slab would only lead to minor damage. With respect to the safety of the occupants, the insignificance of the risks holds true even if the roof structure would be modified, *e.g.*, to a pitched roof. If the potential new roof construction involves a roof void with combustible structures or an attic, the fire spread to the eaves may give rise to a potential cavity fire within the

[13] The discussions presented in Chapter 5 and Appendix B deal with the magnitudes of the changes in the fire spread probabilities induced by such not-regulated matters as the room shape, the window shapes, amount and properties of the fire load inside the apartments *etc*. It is seen that the changes in probabilities presented above are very small as compared to the influence of several other factors.

roof structures. In a bigger cavity or in an attic, the fire must be fought against, but this is often a difficult task and the fire spread to roof cavities may raise the property losses considerably as besides the fire damage there may also be significant water damages. Also the fire brigade safety may be compromised by a difficult fire fighting task in a high place which may contradict the essential requirement of the need to take care of the safety of rescue teams. These problems can, however, be tackled with by appropriate design of the eaves and compartmentation of the attics or roof void spaces.

Figure 13 shows probabilities per one fire for the fire spread from an apartment to the eaves of the building. In the case of a non-combustible façade, the fire spread mechanism is straightforward: the fire will spread to the eaves if it takes place in some of the uppermost apartments. This is the major fire spread mechanism also in the case of a façade made of combustible material. However, in the case of the combustible façade, also the fires that occur in the apartment one storey below the uppermost storey can spread to the eaves via ignition and flame propagation on the façade, because the external flames of a flashed-over room fire reach so high that they can ignite the façade above the window of the uppermost apartment. Fire spread to the eaves from room fires of apartments below the uppermost or the second uppermost storey is quite unlikely event because it takes a relatively long time and the fire brigade will be able to stop the fire spread with probability. As shown in Figure 13, improvement of the fire performance of the eaves construction can be an inexpensive and yet sufficiently effective way to compensate for the increased probability of fire spread to the eaves in the case of a wooden façade.

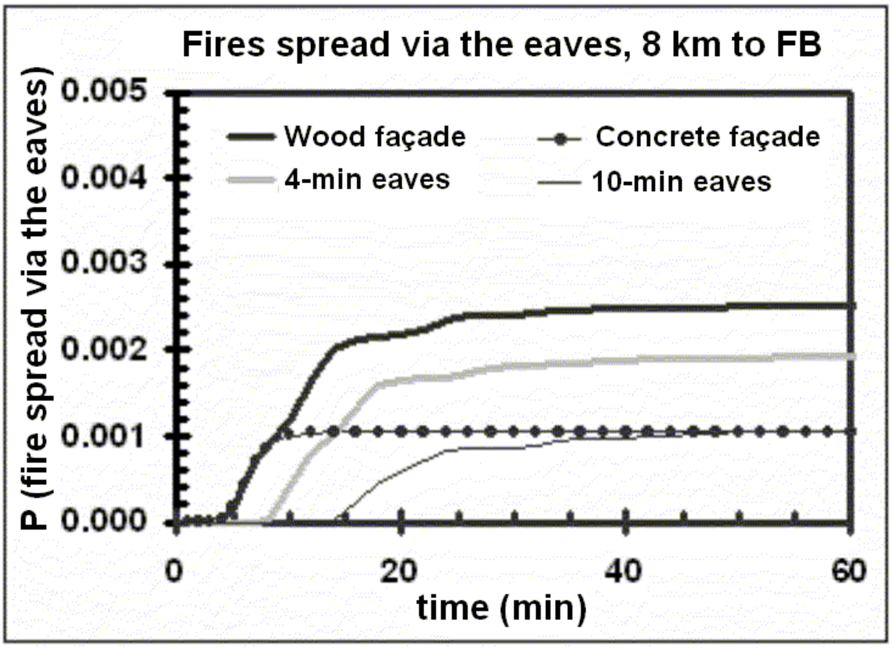


Figure 13. The example building, probabilities per one fire for the fire spread from an apartment to the eaves of the building. In the case of the wooden façade (the curves without markers) we have studied three different options with respect to the performance of the eaves in case of fire: in the case labelled 'Wood façade' we have assumed that there is an ordinary eaves construction that does not retard the fire spread at all, the case labelled '4-min eaves' corresponds to an eaves construction that can withhold the fire spread for 4 minutes and the case labelled '10-min eaves' corresponds to an eaves construction that can withhold the fire spread for 10 minutes (this corresponds roughly to the performance of the eaves shown in Figure 6). The reference case is the building before the façade renovation, i.e., with a concrete façade (the curve with markers).

4.2 External ignitions

According to the statistical survey (Section 3.1 and Appendix A), the proportion of external ignitions is *ca*. 10 % of all fires in residential multi-storey buildings and most of these external ignition take place in the balcony. Thus, balcony fires constitute a greater risk potential than other fires with external ignition source, such as fires of waste containers and shelters. The major risk in fires starting in balconies is the spread inside to the apartment.

4.2.1 Other externally igniting fires than balcony fires

When there is the original concrete façade in the example building, external ignitions near the walls cause negligible danger of fire spread to the eaves because to create flames reaching the eaves of the 3–4-storey building would require a large amount combustibles next to the wall. As there are not any waste containers or car shelters or any other such items in the vicinity of the building, it would require a wilful act to generate big enough fire which, however, is not imaginable.

In the case of a wooden façade, the danger of spread of a fire ignited near the walls corresponds roughly to external flaming caused by a flash-over fire in some of the apartments in the first storey. We can use Figure 13 to assess the magnitude of this hazard: on one hand, it takes 15 (25) minutes of the fire to propagate upwards three (four) storeys and on the other hand, Figure 13 shows that the fire brigade can stop the fire propagation if there is a delay of 15 minutes or longer unless the building is quite far from a fire station (and such buildings are beyond the scope of this work). Note that in estimating the fire propagation speed we have tacitly assumed that there are functioning fire stops in the air ventilation gaps of the façade.

The gables of the example building have no windows and hence, external ignitions on these façade give rise to only negligible risks even with a combustible façade material. Should the renovation involve change of the flat roof to a pitched roof, the eaves at the gables should be constructed so that they resist fire spread to the attic or the roof void in order to keep the property damages low and provide safety at work for the firemen. Compartmentation of the attic or the roof void serves the same purposes and should thus be made. Actually, according to the Environmental Guide no. 39 of the Ministry of the Environment [Ympäristöministeriö 2003], the gable façades of the example building can be made of wood as it allowed to use wood in building gables with no openings provided that this part of the building does not form a part of a corner or it is not too close (less than 8 m) to another building; these provisions are met in the example building.

Spread of fires ignited externally in the vicinity of the walls of the building into the apartments is a minor hazard as compared to fires that ignite inside the apartments or in balconies. The highest hazard related to the external ignitions is a wilful act of igniting combustibles below a window of an apartment in the first storey. In this case, the contribution of the combustible façade material is of the same order of magnitude as in a flash-over room fire with external flaming, which means that the influence of the fire performance of the façade material is not the crucial factor, but the size of the flames of the initial fire is. In the example building, the basement is partially or completely over the ground and hence the wooden façade will start at a relatively high level and hence is not easily ignited by a small 'camp fire'.

4.2.2 Fires in balconies

The balcony front walls and the wall between the apartments and the balconies of the example building are made of reinforced concrete slabs. If the renovation involves only minor changes to the structure of the balconies, the fire safety aspects with respect to fire spread of a balcony fire to the balcony of the above apartment do not change. When assessing the risks related to balcony fires, it should also be borne in mind that Part E1 of the NBCF allows use of wood, *e.g.*, on the surface wall between the balcony and the apartment and in the balcony railings. There is an added threat related to the wooden façade that the fire on the balcony may ignite the façade next to the balcony which may give rise to upward flame spread. This hazard is not, however, very significant as the flame propagation in the horizontal direction is very slow and also beside the actual fire plume the upward flame propagation speed is low.

In our statistical survey covering the years 1996–2001, there were no recordings of incidents in residential multi-storey buildings in which a balcony fire would have spread upwards. In two cases there was a record of fire spread sideways. The most important hazard related to balcony fires is the possibility of fire spread to the apartment either by breaking the window between the balcony and the room or via a readily open door or window. In The statistical survey revealed that about 10 % of balcony fires spread directly inside the apartment or broke windows between the balcony and the apartment thus having the potential of spreading to the apartment. Such fire spread is a direct threat to safety of life and it is not influenced by the material of other façades than that in the wall between the balcony and the room. The report [RTE 2003] done in parallel with this report shows that role of the wood in the part of façades that belong to balconies may have only a secondary influence on the development of the balcony fire, because there may be much more higher quantities of fire load with higher combustibility than the area of wood in the wall, such as plastic tables, chairs and foot gratings.

4.3 Sensitivity study of the results of the example building

As our fire modelling and simulations are carried out using the Monte Carlo technique, variation of the influential parameters is an inherent part of our analysis process and our way of expressing the results in terms of probabilities corresponds to a sensitivity analysis with respect to those parameters that were varied in the fire modelling and simulations. There are, however, some factors that fall beyond the scope of the Monte Carlo variations and it is the sensitivity of the results with respect to changes in these factors that is analysed in this Section. Figure 14 shows that probability of an apartment fire spread to the apartment above when distance between the building and the fire station is 15 km instead of the 8 km considered in Figure 12 As it would in this case take longer of the fire brigade to start their intervention, the probabilities of fire spread one storey upwards grows by *ca*. 30 % for both the non-combustible and the wooden façade as compared to the 8 km case. For the fire spread two storeys upwards, the fire spread probabilities roughly double as compared to the 8 km case. The relative probability values for the non-combustible and the wooden façade do not change significantly: for the distance of 15 km, the fire spread probability one storey up for the wooden façade is 8 % higher that for non-combustible façade when it for the 8 distance was 9 %. The corresponding numbers for fire spread two storeys upwards are 3,3 for the 15-km case and 3,5 for the 8-km case.

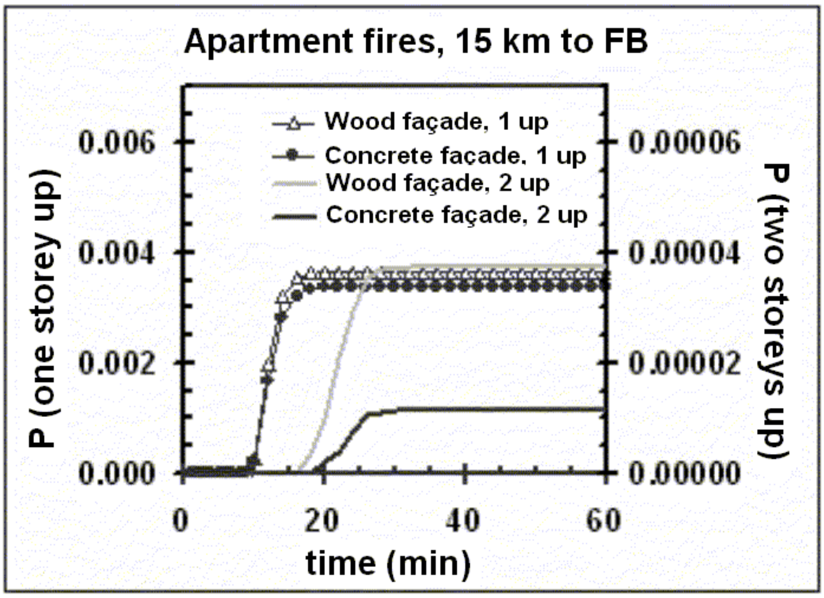


Figure 14. Sensitivity study with respect to the fire brigade intervention timing for the example building, probabilities per one fire for the fire spread from an apartment to the apartments in the upper storeys: the left-hand side axis gives the probability of fire spread one storey upwards and the right-hand side axis the probability of fire spread two storeys upwards. The distance to the nearest fire station is assumed to be 15 km instead of the actual distance of 8 km.

Figure 15 shows the influence of fire brigade travel time (here taken as the time from the alarming to the starting of the extinguishing intervention) to the probability of fire spread to the apartments above the apartment-of-fire-origin. It is seen that the travel time of the fire brigade has a more pronounced influence on the fire spread probability that the potential addition of a wooden façade. With respect the probabilities of fire spread two storeys upwards, the influence of wooden façade seems to be larger than that of the fire-brigade travel time: However, here we must again pay attention absolute values of the probabilities that are very low. The order of magnitude of the probability per one fire is only 0,001–0,004 %, which as such is virtually equal to zero. These probabilities are also one order of magnitude lower than the probability of fire spread via a mechanism in which the external flames first ignites the apartment above the room-of-fire-origin and this ignition then grows to a fully-developed room fire and the secondary external flaming associated with this fire causes fire spread to the apartment two storeys up: the probabilities associated with such fire spread mechanism in the example case are 0,033 % for wooden façade and 0,027 % for concrete façade. An inspection of the model results reveals that this fire spread mechanism is associated with the tail regions of the skewed distributions used to characterise the fire brigade response, *i.e.,* the very small probabilities predicted by the gamma distribution that there may occur very large values of the argument. However, further analysis of the situation reveals that the uncertainties in the many different factors that can influence this fire mechanism complete hide it under the larger variability arising from these other factors (see also Chapter 5 and Appendix B).

Thus it may be concluded that the *relative* probabilities of fire spread for the wooden or the concrete façade are not sensitive to the travel time or the set up and access time of the fire brigade.

The results obtained for the example building are not sensitive to the fire perception, which in our approach was modelled using two categories of fire perception, rapid and slow fire perception. In the model, the time of fire perception has a similar influence to the results as the fire brigade travel time, *i.e.*, they both adjust the time delay of the fire brigade intervention. An increase of the percentage of slowly perceived fires would effectively transfer the fire station away from the building. An increase of the percentage of rapidly perceived fires (e.g., from the percentage of 70 % to 80 %) gives a results in which the fire spread probabilities one storey upwards for both the wooden façade and the concrete façade diminish by an amount corresponding to the difference between the wooden façade and the concrete façade in Figure 12.

a) b)

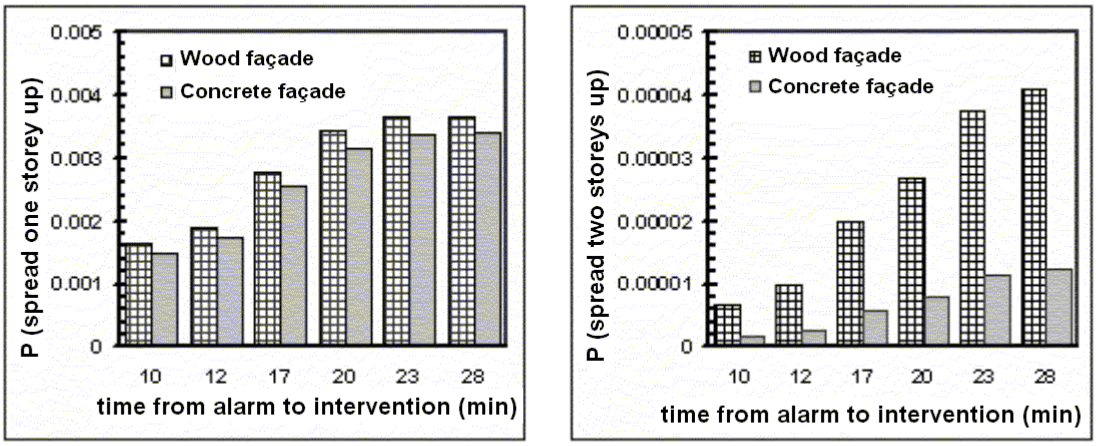


Figure 15. Influence of the fire brigade travel time to the fire spread probability to the apartments above the apartment-of-fire-origin, a) fire spread one storey above and b) fire spread two storeys above. It is seen that the travel time of the fire brigade has a more pronounced influence on the fire spread probability that the potential addition of a wooden façade. It is also seen that the influence of the fire brigade to the fire spread two storeys upwards is stronger than its influence on the fire spread one storey upwards, because the potential fire spread two storeys upwards takes places later than one storey upwards and hence there is more time for the fire brigade to affect the fire spread. It should, however, be noted that fire spread probability two storeys upwards is very small, two orders magnitude lower than that of one storey upwards. (The 17-minutes case corresponds to example building.)

4.4 Summary of the result obtained for the example building

In the previous sections we show results of the fire risk analysis for those fire scenarios in which the fire can involve the façade, *i.e.*, flash-over room fires with external flames projecting out of the fire room, balcony fires and external ignitions close to the building. Below we summarise the fire risks emphasising those aspects that are relevant regarding the fire performance of the façade material. It should be noted that as it is not relevant with respect to the façade material, this summary does not include the most important fire hazards of a residential multi-storey building, *i.e.*, the fire hazards related to smoke and heat inside the apartment-of-fire-origin and to the potential spread of smoke and heat to the stairway via an unclosed door, which are the fire scenarios behind practically all casualties in fires in residential multi-storey buildings in Finland.

4.4.1 Role in wooden façade in potential fire losses

Almost all fire deaths in Finland are due to fires in dwellings [see, *e.g.*, Valonen *et al.* 2004]. Typically the victims are found in the compartment-of-fire-origin or -in fewer cases- in the stairway. The loss of these lives is not influenced by the material of the façade. This applies also to fires that initiate, *e.g*., as an act of an arsonist in the stairway or other common spaces in the building such the storing cellars, saunas, storages for bikes, *etc*. It is only when flames of the fire come into contact with the façade that the façade material may have influence on the development of the fire.

A fire in an apartment can come into contact with the façade when the fire flashes over and hence turns in to fully developed fire with externally projecting flames. Such fire may pose a threat to occupants in the apartments above. The risk analysis carried out on the example building reveals that as compared to a concrete façade, a wooden façade gives a small increase in the probability of fire spread to the apartment one storey above, but that this increase was insignificantly small both statistically as well as when it was compared to the influence of the changes in the operational preconditions of the fire services. In addition, in Section 5.2 and Appendix B it is shown that the increase in the fire spread probability that is related to the wooden façade is small as compared to several other factors, such as properties of the rooms (*e.g.*, the room shapes and sizes), or the properties of the windows (*e.g.*, the window shapes and sizes and their construction details), *etc*. With respect to fire spread two storeys upwards, the probability is notably higher for a wooden façade than a non-combustible façade. This difference is, however, totally irrelevant, because it pertains to so low absolute probabilities values that can for any practical purposes be regarded as equal to zero, *i.e.*, according to the results the spread of fire two storeys upwards is a pure matter of chance. A potential, but not likely, fire scenario is fire spread upwards one storey at a time, the last ignited storey acting as the source of the fire spread to second storey above. The above remarks apply also this fire scenario: its absolute magnitude is negligible and any other factors relevant for fire spread than the difference in the façade material combustibility have a more strong impact on the fire spread probability.

In the example building, there is only a shallow roof void with only a small amount of combustibles and a reinforced concrete slab protecting the apartments of the uppermost storey from a potential fire in the roof structures. Hence, the potential spread of fire to the roof structures does not put the occupants in the building to any threat and thus any increase in the number roof fires that may result from installing of a wooden façade to the example building is irrelevant for the occupant fire safety. However, the potential increase in the number roof fires that may result from installing of a wooden façade may give rise to increased property losses and decrease safety at work of the rescue personnel and actually these hazards become notable only if also the roof structure is altered so that there will be an attic or a roof void with significant amount of combustible construction materials (*e.g.*, roof trusses). Thus, if there is also a roof renovation, one should pay attention to the fire safety of the eaves and the attic or roof void. The relevant fire safety measures are improving the fire performance of the eaves (see 3.2.3 or Hietaniemi *et al*. 2003) and appropriate compartmentation of the attic of the roof void.

If improving of fire safety is set as one of the goals in the renovation project of the example building, the fire safety measures should be focussed to the most influential actions that increase the occupant safety of life. As detailed above, the façade material is only of secondary importance with respect to occupant life safety and there are several simple, but effective ways to improve the occupant life safety such as keeping the walls and near surroundings of the building clear of any significant sources of ignition (intentional or unintentional), *e.g.*, waste containers and waste container shelters, car parking structures, *etc*.; keeping the stairway free on any combustible materials or items, including prams, sledges, *etc*.; keeping the cellars and other such rooms locked. In addition, there are several technical devices that improve fire safety considerably, such as appropriate smoke exhaust systems in the stairway, hard-wired (not battery-driven) fire detectors and alarming systems. Yet, it is a sad to acknowledge that fire deaths in Finland are mainly a multi-dimensional social problem and as such, controllable only to a certain extent by technical regulations; indeed, finding the multi-disciplinary measures to reduce the fire-death rate in Finland to the average European level is one of the main challenges of fire safety work in Finland.

The fire damage due to potential external ignitions can be reduced efficiently by designing and executing the wooden façade so that upward flame propagation is reduced which in practise can be realised by installing fire stops into the air ventilation slot of the façade (see Section 3.2.3). In this way, the fire spread up to the eaves and the roof structures becomes delayed which considerably increases the likelihood that the fire brigade will be able to suppress the fire before it reaches the eaves.

4.4.2 Recommended fire safety solutions for the example building

The starting point here is that there is a wooden façade installed either to replace the old concrete façade or on top of it, with the both cases necessitating an air ventilation gap behind the wooden cladding. If the present roof structure, a shallow roof void with small amount of combustibles, is changed in the renovations to, *e.g.,* a pitched roof, one should pay attention o the following issues:

- The eaves should be made using a fire-retarding construction (see Figure 6);

- The attic or the roof void must be divided to fire-resistant compartments;

- Shelters for waste containers or cars should be kept away from the walls of the building. There should not also be any other fixed construction near the building. These conditions should be written in the building licence.

If the renovation involves only installation of the wooden façade, but the roof is left unchanged, then one should take the following items in to account:

- Shelters for waste containers or cars should be away from the walls of the building. There should also not be any other fixed construction near the building. These conditions should be written in the building licence.

- Yet, if there are only minor changes made to the roof structure, it is advisable to install the appropriate fire-resistant constructions to divide the shallow roof void into compartment[14], because this facilitates the suppression efforts and enhances safety at work of firemen.

If the renovation involves installing of the wooden façade and a change of roof to a flat roof without any roof void, then one should take the following items in to account:

- Shelters for waste containers or cars should be away from the walls of the building. There should not also be any other fixed construction near the building. These conditions should be written in the building licence.

If there are windows in the external walls of the staircases, these external walls should be made out of materials which contribute to fire to a very limited extent (or better) even though wood can be use in small quantities. A very effective way to improve the safety of occupants is to install smoke vents that can be activated from the first storey or the basement.

---

[14] The material usage in such improvement would be small.

5. Generalisation of the results

In the previous Chapter we analyse the fire risks of the example building, *i.e.*, a relatively low (3–4 storeys high) concrete-framed residential multi-storey building built in the 1960's and 1970's that belongs to the fire class P1 and is located at 8 km distance from one of the major fire stations in Helsinki, and which in a façade renovation has been retrofitted by a wooden façade. The results of the analysis show, that in the case of the particular example building analysed, as compared to a concrete façade, a wooden façade gives a small increase in the probability of fire spread to the apartment one storey above, but that this increase is insignificantly small both statistically as well as when it is compared to the influence of the changes in the operational preconditions of the fire services.

Although quite homogeneous in their architectural design, the residential suburb multi-storey buildings built in the 1960's and 1970's are not identical, but have differences in the room and openings lay outs and sizes as well as furnishings and other customised features dependent of the occupants. In this Chapter we analyse how the most typical changes in the building details, such as sizes and shapes of room and windows, affect the results we obtained for the example building. We emphasise that in this Chapter – as in the previous Chapters – we address only the fire scenarios in which the flames become into contact with the façade material, not the most fatal fire scenarios in the P1-fire-class residential multi-storey buildings in which the occupant/occupants perish due to smoke or heat inside the apartment-of-fire-origin or in the stairway while attempting an escape.

The question that we address in his Chapter is that whether the positive results obtained for the example building are of more general validity or whether they apply only that particular building due to its some specific feature. The approach we proceed to employ is a comparative one: we weigh at the fire safety level related to installing a wooden façade against the influence on the fire safety of some other factors. The fire safety is quantified as before in terms of the probability of fire spread or in terms of the height of the external flames.

5.1 The influence of the characteristic features of the example building

The gables of the example building have no window and thus, the façades on these walls are allowed to be made fully of wood according to the Environmental Guide 39 [Ympäristöministeriö 2003]. In some building there may windows and in this case, one issue that has not emerged in the study of our example building is the question whether the spread of the fire to neighbouring construction works is limited. If the distance of the gable to another building is more than 8 m, then the potential of spread of the fire to the neighbouring building is deemed to be limited. If the distance, however, is less than 8 m., then additional considerations are required. The Part E1 of the NBCF gives a firewall with fire resistance of EI-M 120 as an alternative for the sufficient safety distance. The other option is, naturally, to employ the performance-based approach similar to the study presented in this report.

If the buildings are so closely located that the spread of fire is 'obvious', one should use the firewall – or show by calculations and potential additional fire safety measures that the spread of fire after all is not 'obvious'. Yet, the basic requirements of the firewall can be relaxed, if the buildings on the site can be treated as an entity and that this entity fits within the requirements on the maximum area and number of people of the particular fire class of the buildings that make up this entity. As we are dealing with buildings in the fire class P1, there are no restrictions set upon the maximum area or the number of people and the 'single-entity approach' can be applied and normal compartmentation is valid as long as one takes into account the potential asymmetry of the external walls as well as the influence of the windows. Here, the guidelines given in the Environmental Guide 39 [Ympäristöministeriö 2003] for one-family houses belonging to the fire class P3 are applicable to an appropriate extent when ones estimates the influence of the window size and fire resistance to potential fire spread.

Yet another architectural feature that is missing from our example building is re-entrant corners. In there are such features in the building studied, the influence of these details on the potential fire spread must be investigated.

The external walls of the stairways in the example building have windows, which are a bit indented as compared to the rest of the façade. In such case it is feasible to construct the external walls of the stairways of a different material than the rest of the façade without breaking the architectural unity of the whole façade. Since there are windows on the external walls of the stairways, the cladding material of these walls should mainly be constructed of materials which contribute to fire to a very limited extent (or better) even though wood can be use in small quantities, *e.g.*, in window frames and other details.

The roof of the example building is made of rough tongue and groove boarding covered by felt roofing. The roof slopes slightly towards the centre of the roof and there is a shallow roof void with a reinforced concrete slab as a floor of the void. This concrete slab protects the apartments underneath from a potential fire on the roof. As there are no protruding eaves, the probability of fire spread to the roof void is small. If the building examined has a pitched roof with an attic or roof void, one must for reasons of property damage and firemen safety pay attention to the reduction of the probability of fire spread to the attic or the roof void: the fire measures include installing proper fire stopping to the air ventilation gaps of the façade, improving the fire performance of the eaves and appropriate compartmentation of the attic of the roof void (see 3.2.3). The last two items, improving the eaves and the void compartmentation, are relevant even in the cases where the façade is made of non-combustible material, because a room fire in the uppermost or second uppermost apartments may readily spread to the attic or the roof void via the eaves.

5.2 The influence of general building characteristics

5.2.1 Impact of room and window characteristics on fire spread probabilities

Different buildings vary according to their room and window sizes and shapes. The influence of these factors is studied by considering the following four cases: case A is the example building and the other cases are different variants of room and windows sizes with non-combustible façade:

A) Rooms and windows are similar to those of the example building. Wooden façade (the case analysed in Chapter 4).

B) The plans of the rooms are a square-shaped with areas equal to the room areas of the example building. Windows are similar to the windows in the example building. Non-combustible façade.

C) The plans of the rooms are similar to the example building. Windows are wide, extending the whole width of the rooms. Non-combustible façade.

D) The dimensions of the room have been swapped so that the width equals to depth of rooms of the example building *et vice versa* and the window width is doubled as compared to the example building. Non-combustible façade.

Note that the variants B, C and D have a non-combustible façade and thus satisfy the fire classes and numerical criteria given in the regulations and guidelines of part E1 of the National Building Code of Finland.

Figure 16 shows the probabilities of spread of a fire in an apartment to apartments above for these four cases. It is seen that the influence of the wooden façade to fire spread upwards is smaller that the influence of changes in the room or window sizes.

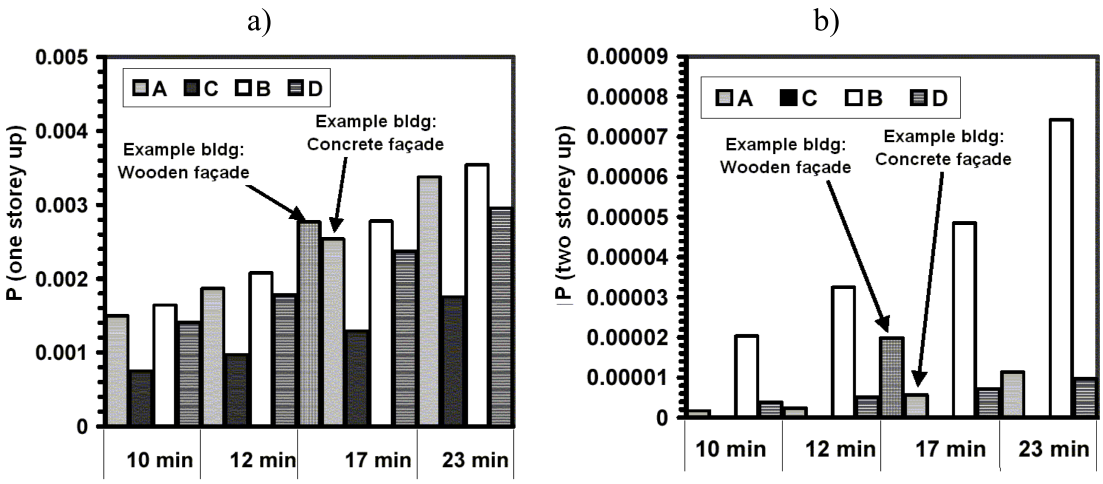


Figure 16. Probabilities of spread of a fire in an apartment to apartments above for the four cases A, B, C and D explained in the text (a 3–4 storey residential building belonging to the fire class P1): a) probability of fire spread one storey upwards and b) probability of fire spread two storeys upwards. The results obtained for the example building with and without the wooden façade are denoted with arrows. Case A has rooms and windows similar to the example building and cases B, C and D are variants of the example building: case B has square-shaped rooms with the same area, case C has similar room shape and size, but has wide windows with width equal to the room width and case D corresponds to a case with the width and depth of the rooms swapped and with a doubled window width. The probabilities are grouped according to the fire brigade operation times which here corresponds to the average time delay from the alarming to the beginning of extinguishing. It can be seen that the differences related to room or window geometry or the fire brigade operation times can have a more pronounced influence on the fire spread probability than installing a wooden façade.

5.2.2 Further analysis of the impact of the building characteristics

The risk analysis presented above shows that installing a wooden façade to a typical suburb residential multi-storey building built in the 1960's and 1970's, exemplified by our example building, does not cause a significant increase in the probability of fire spread; actually moderate changes in the general building characteristics may have a bigger impact on the fire spread probability than the wooden façade.

The most important factor affecting the spread of an apartment fire to apartments above the room-of-fire-origin is the size of the external flames. Thus, we focus on the flame height in the further analysis presented in this section of the influence of different factors.

Appendix B presents a brief discussion on the factors that affect the height of the external flames, ending up with the conclusion that the increment of the external flame height due to the wooden façade is small as compared to both the mean flame height and the differences related to variability in the several factors that affect any fire scenario. In this Section we present a similar study but in a more systematic manner by analysing each influential factor separately, *i.e.*, in turn each factor allowed vary within moderate limits while all the other factors are kept fixed. For example, one study involves varying the room size uniformly between 12 m^2 and 20 m^2 and another involves varying the room shape, *etc*. The number of calculations for each parameter variation was 200, one hundred for a non-combustible façade and one hundred for a wooden façade.

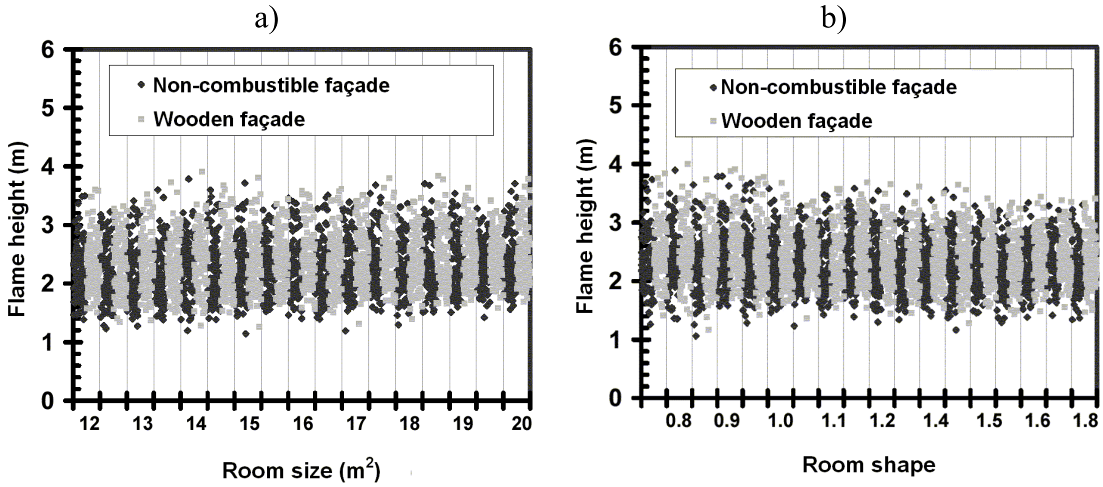


Figure 17. The influence on the external flame height of the a) room size (floor area) and b) room shape (room depth divided by room width). The dark grey markers denote a non-combustible façade and the light grey markers denote a wooden façade. Neither the room size nor the room shape has a notable influence on the flame height. It is also seen that the results for the non-combustible and the wooden façade are practically the same indicating the negligible influence of the combustibility of the façade to the flame height.

Figure 17 shows the influence on the external flame height of the room size (*i.e.*, the floor area) and the room shape (defined here as the room depth divided by the room width). It is seen that neither the room size nor the room shape have a notable influence on the flame height: as scatter of the data points reveals, the variability of the other factors has a much larger influence than the two room geometry parameters studied here. It is also seen that the results for the non-combustible and the wooden façade are practically the same indicating the negligible influence of the combustibility of the façade to the flame height. The reason why the size and shape of the room do not have a significant influence on the flame height depends on the fact that in a wide room there will most likely be wide windows and with respect to the flame height, these two factors act to compensate each other. If there is a narrow window in a wide room, then there would a high external flame, the height of which would diminish if the window would be wider (see also Figure 18a).

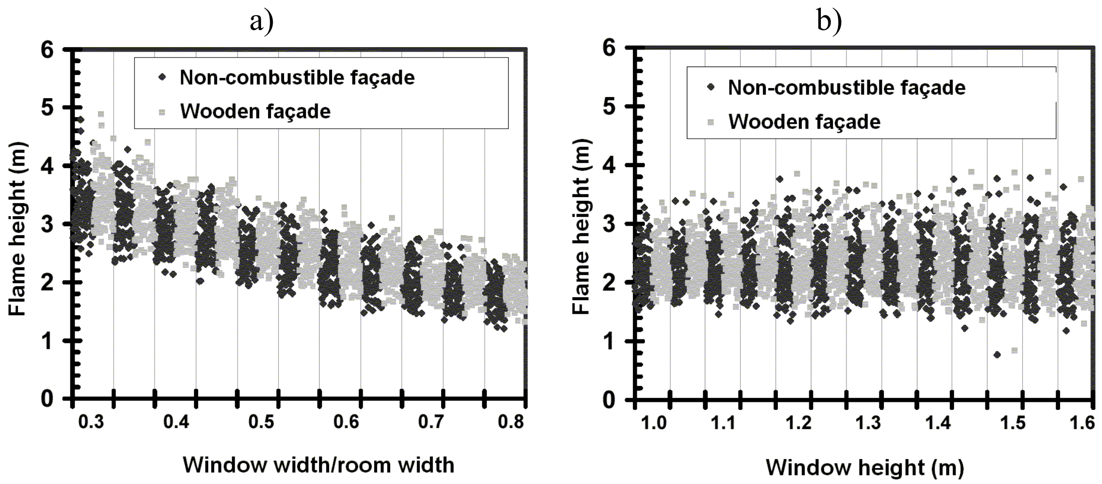


Figure 18. The influence of the window size on the external flame height: a) the window width (a relative value with respect to the room width) and b) the window height (in m). The dark grey markers denote a non-combustible façade and the light grey markers denote a wooden façade. The impact of the window height on the external flame height is clearly seen while the influence of the window height is lost in the variability of the other factors. Similarly to Figure 17, it is also seen that the results for the non-combustible and the wooden façade are practically the same indicating the negligible influence of the combustibility of the façade to the flame height.

Figure 18 shows the influence on the external flame height of the window width (here we use a relative value normalised with respect to the room width) and the window height. The impact of the window height on the external flame height is clearly seen while the influence of the window height is minute as compared in the variability of the other factors manifested by the scatter of the data points. There is however, an indirect way that the window height may become more important regarding the fire risks: it is the fact in the case of a high windows, the next window above may be located closer to the fire room window. Also in Figure 18 it is also seen that the combustibility of the façade has a negligible influence of the to the flame height as compared to influence of the other factors.

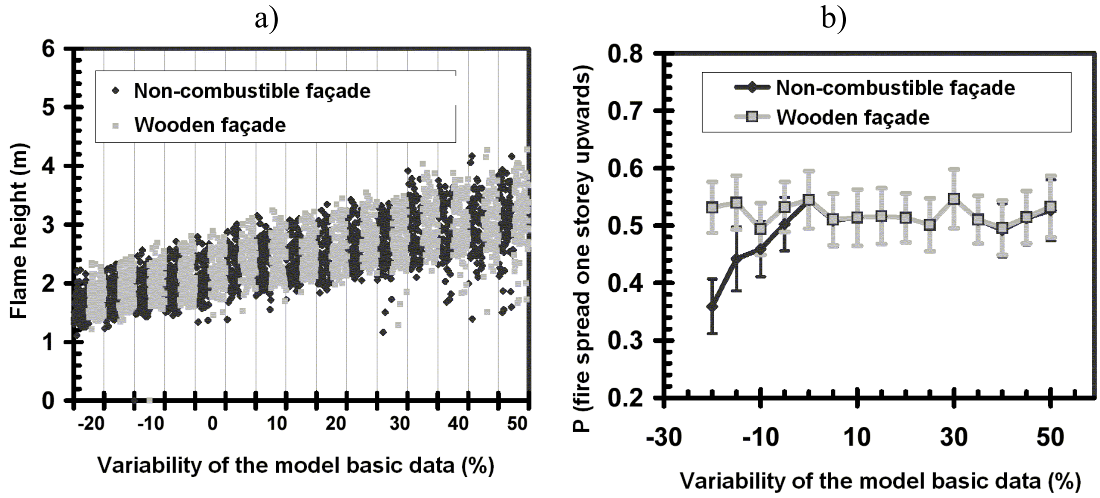


Figure 19. The influence of the variability of the model used to calculate the flame height on a) the flame height and b) the probability of an apartment fire spread to an above apartment. In the model for the flame height depends on the heat release rate and the room and window sizes and shapes, but in the reality there are also other factors not included in the model, such as the amount, combustibility and location of the fire load within the room-of-fire-origin. As an attempt to take the influence of these other factors into account, we allowed the rate of heat release to vary from -20 % to +50 % of its mean value. The dark grey markers denote a non-combustible façade and the light grey markers denote a wooden façade. It is also seen that in the flame-height results for the non-combustible and the wooden façade are practically the same reflecting that the influence of the combustibility of the façade to the flame height is negligible. With respect to the fire spread probability, results for the non-combustible and the wooden façade are practically the same except the lower end range of the heat-release-rate variability, where the results differ slightly.

In Figure 19 we study the influence on the model uncertainty on the results concerning the flame height and the probability of an apartment fire spread to an above apartment. The assessment of the magnitude of the model uncertainty is estimated on the basis of the results of Harmathy [1980/81], who presented data on enclosure fires involving cellulose-based materials which enable to assess the inherent variability of the heat release rate of fully developed fires. An estimate for the uncertainty that is in line of the findings of Harmathy [1980/81] is to allow the heat release rate to vary between -20 % and +50 % of the mean heat release rate value.

Figure 19a shows that there is a systematic variability in the flame height related to the model uncertainty, or in other words, that the inherent uncertainty of the room fire phenomenon is much stronger than any changes induced by the combustibility of a wooden façade. In addition, at each heat release rate level, the influence of other factors on the flame height, such as geometry of rooms and windows, is stronger than that of the wooden façade.

Figure 19b shows the probability of an apartment fire spread to an above apartment with to fire brigade operations modelled according to the data corresponding to the situation in Helsinki. Results for the non-combustible and the wooden façade are practically the same except the lower end range of the heat-release-rate variability, where the results differ slightly: when the heat release rate is low, the smallish contribution of the wooden façade becomes discernible. However, this situation corresponds to a case in which there is only a relatively small fire load in the room-of-fire-origin, which is turn means that the probability of breakage and fallout of the window in the room-of-fire-origin is low. This effect is not incorporated in the wooden façade results in Figure 19b and when it would be taken into account, the results for the non-combustible and the wooden façade would merge closed together.

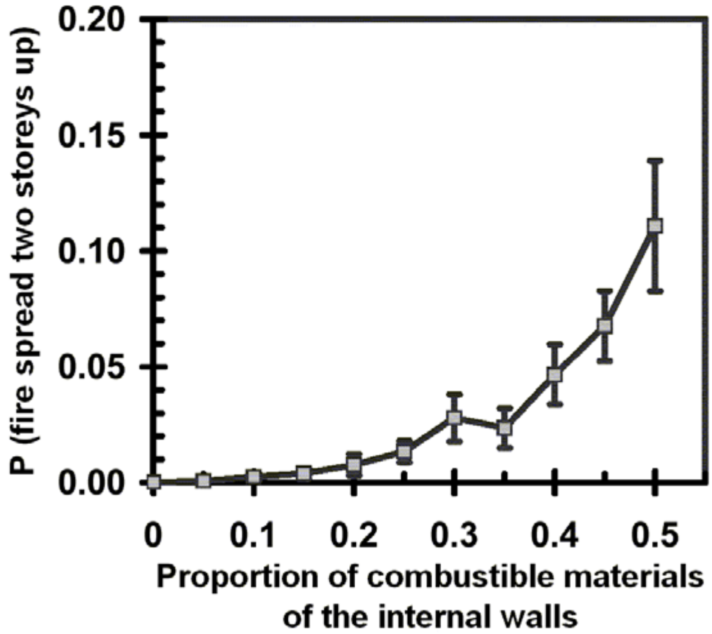


Figure 20. Influence of fire load located on the internal walls of the room-of-fire-origin of the probability of fire spread per one fire to an apartment two storeys above the room-of-fire origin. As the combustible area inside the fire room increases, the probability of fire spread to an apartment two storeys above increases drastically: for small combustible area, the probability is practically zero, but grows above 10 % when half of the internal wall area is covered with combustible material (wood).

Figure 20 demonstrates how much stronger influence the combustible material (wood) has when it is placed inside the fire room than on the façade: the figure shows the probability of fire spread per one fire to an apartment two storeys above the room-of-fire-origin. When the wooden surface is on façade, this probability is effectively zero but when the wood is placed as linings inside the room-of-fire-origin, 25 % wood coverage rises the probability to 1–2 % per one fire and when the combustible linings cover 50 % of the walls of the room, the probability exceeds 10 % per fire.

5.3 Summary of the generalisation of the results

The results given in Chapter 4 and the above Sections assert that the influence of a wooden façade on the probability of fire spread in a concrete-framed residential multi-storey building belonging to the fire class P1 is marginal and hence, does not give any significant increase in the fire risks of the building. In addition, the results given in the above Sections show that the conclusions on the fire spread probabilities presented for the selected example building are not sensitive to changes in the general features of the building or other factors considered, including the fire brigade intervention as long as one is considering a building in a city or in a suburb of a city where the basic assumptions made regarding the fire operation times hold true; buildings located in sparsely populated areas or rural areas may need a specific analysis concerning the fire brigade intervention. Thus, the results and conclusions have general validity beyond application to the selected example building.

It is noteworthy that the distance of the building to the fire station, the size and shape of windows as well as the furnishings and linings inside the apartments are more important factors than a wooden façade concerning the potential of fire spread to other apartments. Actually, the contribution to fire of a moderate-sized area of wood on the façade is so small that it is overwhelmed by the influence to the external flaming of any of the factors mentioned above. Especially, if the linings are partially or completely made of materials with the reaction-to-fire class of D-s2, d2 (*e.g.*, wood panelling and boards) – which according the regulations and guidelines of part E1 of the National Building Code of Finland is allowed in the buildings belonging to the P1 fire class – the probability of fire spread to above apartments increases drastically as compared to the case when the wood surface forms only the cladding of the external wall.

When applying the results of this report to other buildings than the selected example building presented in Section 2.2 and analysed in Chapter 4, the issues brought out in Section 5.1 should be borne in mind: The gable of the example building has no windows and hence, the there is no danger of fire spread inside the apartments. The distance of the example building from neighbouring buildings exceeds 8 m and thus, we have been able omit any considerations of safety of neighbouring buildings in case of fire. The balconies in the example building are not of a protruding type and hence, this report gives no guidance for such balconies. However, the study of the Kuortane Sports

Hotel [RTE 2003] made in parallel to this study addresses the balcony fires in some depth. Otherwise the results given concerning the example building can be applied as long as the target building is not essentially higher than the example building, *i.e.*, 3–4 storeys.

6. Conclusions

The thorough fire risk analysis of the selected example building located in the Laajasalo district in Helsinki shows that the influence of a wooden façade on the probability of fire spread from one apartment to other apartments in a concrete-framed residential multi-storey building belonging to the fire class P1 is marginal and hence, does not give any significant increase in the fire risks of the building. A relative increment of about one tenth per a fire in the probability of fire spread to an apartment above the room-of-fire-origin can be discerned from the results when one compares the example building with and without a wooden façade. If this relative change is interpreted in terms of absolute numbers, it means that if every residential multi-storey building in Finland would be retrofitted by a wooden façade, there would be one additional incident of fire spread in ten years. Such change could not by any means be distinguished from the inherent statistical fluctuations. Another way to assess the magnitude of risk associated with the installing of the wooden façade is to compare its influence to the effect of other factors. Figure 21 shows in a condensed way the results of such a comparison: it may be seen that the influence of the wooden façade is smaller than the influence of several other, non-regulated factors.

For example, if the relatively narrow-shaped rooms of the example building would be replaced by wide rooms of the same size and with correspondingly wider windows (the case 'wide rooms' in Figure 21), there expectation value of fire spread incidents would reduce by an amount of 0,07 per year and per all residential multi-storey buildings in Finland, which is of the same order of magnitude as the small increment caused by the installation of the wooden façade. If there would room-wide windows in the example building, the corresponding expectation value of fire spread incidents would of reduce by an amount of 0,5, which is much larger than the influence of the wooden façade. If the rooms in the example building would have a square-shaped plan, the expectation value of fire spread incidents would of increase by an amount of 0,1, *i.e.*, more than the effect of the wooden façade. Further, if the average fire brigade intervention time in the example building would be 12 minutes instead of 17 minutes, the expectation value of the fire spread incidents would of decrease by more than 0,3. This example concerning the influence of the fire brigade operations is very relevant to the example building, because a change of such magnitude – though in the other direction – was in fact caused by the closing down the Herttoniemi Fire Station, located much closer to the example building than the Mellunkylä Fire Station. The impact on the fire safety in the example building of this action is considerably higher than the influence of installation of a wooden façade.

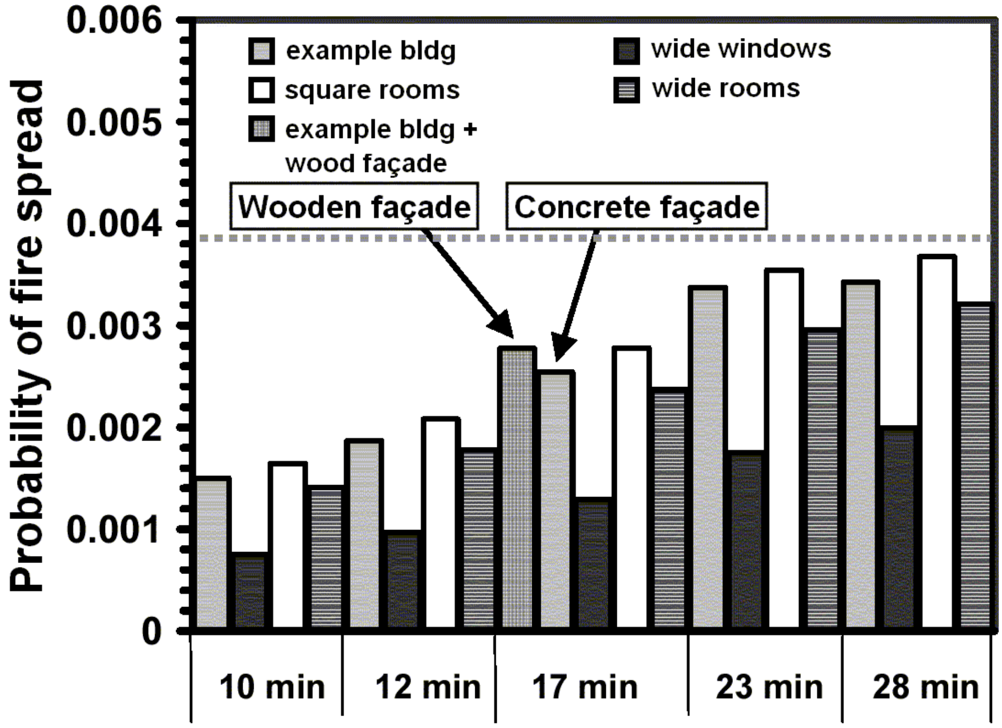


Figure 21. Probability of spread of an apartment fire in a residential 3–4 storey building belonging to the P1 fire class. The horizontal axis shows time lag of alarming to the start of the fire brigade intervention. It can be seen that the influence of the geometry of the room and windows as well as the distance to the fire brigade cause larger changes in the fire-spread probability than the installation of a wooden façade. The dotted horizontal line depicts a risk level below which the fire spread risks as evaluated using our model in buildings resembling the example building remain if they are designed and executed according to the prescriptions of the part E1 of the NBCF. The labels 'Concrete façade' and 'Wooden façade' refer to the example building before and after the installation of the wooden façade.

The results obtained for the example building can be applied to other residential multi-storey buildings built in the 1960's and 70's belonging to the fire class P1 provided that the buildings considered are reasonably similar to the example building, *e.g.*, so that the number of storeys does not differ much from the example building and that the assumptions made on the operation of the fire brigade remain valid.

This study reveals that when one considers the overall fire safety of residential multi-storey buildings that belong to the fire class P1, the role of the combustibility of the façade material is very small, provided of course that the façade is designed and executed using the state-of-art knowledge on appropriate fire stops and eaves fire protection and compartmentation of the potential attic or roof void spaces. With respect to safety of life in the compartment-of-fire origin, by far the most important issue is to reduce the number of ignitions. In prevention of fatal and non-fatal casualties that may occur beyond the compartment-of-fire origin, control and mitigation of the smoke spread seems as the most important technical action. In particular, the spread of smoke to the stairway should be prevented as efficiently as possible and provisions should be made for effective removal of any smoke that has potentially spread to the stairway. One effective measure to improve the fire safety within and beyond the compartment-of-fire origin would be installation of more reliable fire detectors and alarms than the present battery-operated smoke detectors, *e.g.*, by changing to hard-wired systems. Any of these actions is independent of the of the combustibility of the façade material, since the spread of fire and smoke takes place inside the building not affected by the external cladding of the building. The potential hazards related to external ignition of the combustible façade material can be reduced in an efficient way by removing any combustibles from the vicinity of the building.

Epilogue

In this study we have carried out a fire risk analysis concerning the impact on fire safety of an installation of a wooden façade to a residential suburb multi-storey building that belongs to the fire class P1 defined in the National Building Code of Finland. The risk analysis and the associated fire simulations are made using state-of-the-art techniques in the fire safety sciences and technology. The results of the study reveal that with respect to the overall fire safety of the P1-class residential multi-storey buildings, the role of the combustible wood as the façade material is insignificant: as is inevitable, the calculations bring out a small increment in the probabilities of fire spread from the room-of-fire-origin to the apartments above, but this increment is small as compared to the influence of several other factors which are not regulated by the Finnish Fire Regulations. The relatively small amount of wood with a Euroclass D performance level on the façade that is likely to contribute the external flaming would cause a much higher risk if it was installed as a lining inside the apartment-of-fire-origin. It is shown that the results obtained for the selected example building can be generalised to other buildings with reasonably similar characteristics.

The statistics survey carried out shows that external spread of a fire from one apartment to another is very rare in buildings that belong to the fire class P1, which naturally means that the associated risks to life are very small. By far the most typical fire scenario is fire that is limited to the compartment-of-fire-origin or a part of it and casualties are due to smoke inhalation and potentially also due to heat exposure that takes place in the compartment-of-fire-origin or in the stairway during an attempt to escape the fire. If there is any spreading beyond the compartment-of-fire-origin, it involves smoke spread to the stairway. Thus, in protection of life such fire safety measures that influence the fire development inside the building are emphasised, not those that involve the façade. Structural detailing of the wooden façade and the associated constructions, *e.g.*, the eaves, is effective in decreasing the potential property losses caused by fire spread on the façade: fire stops that hinder the occurrence of the shaft effect in the air ventilation gap needed behind the wooden cladding can be realised with simple constructional parts and the eaves can be constructed so that it retards the fire spread into the potential attic or roof void space via the eaves. A fire-resistant eaves is needed even if the façade is made of non-combustible materials if it is desired to prevent spread of a fire in the apartments of the uppermost storey into the attic or roof void space. Appropriate compartmentation of the potential attic or roof void space safeguards against uncontrolled fire spread within these spaces which greatly facilities fire fighting and provides safety to the firemen. The most efficient way to prevent the consequences of potential fire spread on the façade is to reduce the probability of external ignitions by removing any combustibles such as waste containers, waste container shelters or cars from the vicinity of the building.

References

Anon. 2002. The Potential Benefits of Fire Safety Engineering in the European Union. Final report of the EC contract EDT/01/503480 (the BeneFEU – Benefits of Fire Safety Engineering in the EU project). UK: Warrington Fire Research. 180 p.

Back, G., Beyler, C.L., DiNenno, P. & Tatem, P. 1994. Wall Incident Heat Flux Distributions Resulting from an Adjacent Fire. In: Kashiwagi, T. (ed.). Fire Safety Science – Proceedings of the Fourth International Symposium. Ottawa, Canada, July 13–17, 1994. Boston, USA: International Association for Fire Safety Science. Pp. 241–252.

CEN 2002. Eurocode 1: Actions on Structures – Part 1–2: General Actions – Actions on structures exposed to fire. Brussels: CEN. EN 1991-1-2:2002 E. 59 p.

Hakkarainen, T., Oksanen, T. & Mikkola, E. 1996. Puujulkisivujen paloturvallisuus sprinklatuissa kerrostaloissa [Fire safety of wooden façades in sprinklered multi-storey buildings]. Espoo: VTT Tiedotteita 1736. 29 p. + app. 16 p. ISBN 951-38-4892-2. (In Finnish)

Hakkarainen, T., Oksanen, T. & Mikkola, E. 1997. Fire behaviour of façades in multi-storey wood-framed houses. Espoo: VTT Research Notes 1823. 42 p. + app. 16 p. ISBN 951-38-5098-6.

Hakkarainen, T. & Oksanen, T. 2002. Fire Safety Assessment of Wooden Façades. Fire and Materials, Vol. 26, No. 1, pp. 7–27.

Harmathy, T.Z. 1980/81. Some Overlooked Aspects of the Severity of Compartment Fires. Fire Safety Journal, Vol. 3, pp. 261–271.

Hietaniemi, J., Baroudi, D., Korhonen, T., Björkman, J., Kokkala, M. & Lappi, E. 2002. Yksikerroksisen teollisuushallin rakenteiden palonkestävyyden vaikutus paloturvallisuuteen. Riskianalyysi ajasta riippuvaa tapahtumapuumallia käyttäen [The influence on the fire safety of the fire resistance of the load-bearing structures of a single-storey industial hall. Risk analysis using Time-Dependent Event trees]. Espoo: VTT Tiedotteita – Research Notes 2123. 95 p. + app. 51 p. ISBN 951-38-5935-5; 951-38-5936-3. http://www.vtt.fi/inf/pdf/tiedotteet/2002/T2123.pdf (In Finnish)

Hietaniemi, J., Hakkarainen, T., Huhta, J., Jumppanen, U.-M., Kouhia, I., Vaari, J. & Weckman, H. 2003. Ontelotilojen paloturvallisuus. Ontelopalojen leviämisen katkaiseminen [Fire safety of cavity spaces – Prevention of fire spread in building voids]. Espoo: Tiedotteita 2202. 168 p. + app. 52 s. ISBN 951-38-6156-2; 951-38-6157-0. http://www.vtt.fi/inf/pdf/tiedotteet/2003/T2202.pdf (In Finnish)

Hietaniemi, J., Hostikka, S., & Korhonen, T. 2004. Probabilistic Fire Simulation. In: Almand, K.H. (Ed.). Proceedings of the 5th International Conference on Performance-Based Codes and Fire Safety Design Methods. October 6–8, 2004. Luxembourg. Bethesda, MD. USA. 2004. Society of Fire Protection Engineers. Pp. 280–291.

Hostikka, S., Keski-Rahkonen, O. & Korhonen, T. 2003. Probabilistic Fire Simulator. Theory and User's Manual for Version 1.2. Espoo: VTT Publications 503. 72 p. + app. 1 p. ISBN 951-38-6235-6; 951-38-6236-4. http://www.vtt.fi/inf/pdf/publications/2003/P503.pdf

Hostikka, S. & Keski-Rahkonen, O. 2003. Probabilistic simulation of fire scenarios. Nuclear Engineering and Design, Vol. 224, pp. 301–311.

Kokkala, M., Mikkola, E., Immonen, M., Juutilainen, H., Manner, P. & Parker, W.J. 1997. Large-scale upward flame spread tests on wood products. Espoo: VTT Research Notes 1834. 29 p. + app. 116 p. ISBN 951-38-5114-1.

Korhonen, T., Hietaniemi, J., Baroudi, D. & Kokkala, M. 2003. Time-Dependent Event-Tree Method for Fire Risk Analysis: Tentative Results. In: Evans, D. (Ed.). Fire Safety Science – Proceedings of the Seventh International Symposium. Worcester, MA, USA, June 16–21, 2003. Boston, MA, USA: International Association for Fire Safety Science. Pp. 321–332.

Lattimer, B.Y. 2002. Heat fluxes from fires to surfaces. In: DiNenno, P.J., Drysdale, D., Beyler, C.L. & Walton, W.D. (ed.). SFPE Handbook for Fire Protection Engineering, 3. Edition. Pp. 2/269–296.

Law, M. & O'Brien, T. 1981. Fire safety of bare external structural steel. Constrado. ISBN 0 86200 026 2.

Ministry of the Environment. 2002. E1 of the National Building Code of Finland – Fire safety in buildings. Helsinki: Ministry of the Environment. 41 p.

Mowrer, F.W. 1998. Window Breakage Induced by Exterior Fires. Gaithersburg, MD, USA: National Institute of Standards and Technology. 40 p. (NIST-GCR-98-751.)

Oleszkiewicz, I. 1990. Fire Exposure to Exterior Walls and Flame Spread on Combustible Cladding. Fire Technology, Vol. 26, pp. 357–375.

Peacock, R.D., Forney, G., Reneke, P., Portier, R. & Jones, W.W. 1993. CFAST, The consolidated model of fire growth and smoke transport. Gaithersburg, MD, USA: National Institute of Standards and Technology. (Technical Note 1299). 246 p.

RTE. 2003. Kuortaneen liikuntahotellin julkisivun puuverhoilun vaikutus paloturvalli–suuteen [The influence of the wooden facade on the fire safety of the Sports Hotel in Kuortane]. Espoo: VTT Rakennus- ja yhdyskuntatekniikka. Tutkimusseloste RTE3339/03. (In Finnish)

Schild, D., Wiederkehr, R. & Bart, B. 2004. Optimisation of wooden façades for fire restistance. In: Proceedings of International Symposium on Advanced Timber and Timber-Composite Elements for Buildings. 27–29 October 2004, Firenze, Italy. Firenze, Italy: COST Action E29: Innovative Timber & Composite Elements for Buildings. 11 p.

Särdqvist, S. 1998. Real Fire Data. Fires in non-residential premises in London 1994–1997. Lund: Lund University. 59 p. (Report 7003) ISSN 1102-8246, ISRN LUTVDG/TVBB--7003-SE.

Tillander, K. & Keski-Rahkonen, O. 2000a. Palokunnan saatavuuden merkitys rakennuksen paloriskitarkastelussa [The influence of fire department intervention in a building fire risk analysis]. Espoo: VTT Tiedotteita 2013. 200 p. + app. 55 p. ISBN 951-38-5634-8; 951-38-5635-6. http://www.vtt.fi/inf/pdf/tiedotteet/2000/T2013.pdf (In Finnish)

Tillander, K. & Keski-Rahkonen, O. 2000b. The influence of fire department intervention to the fire safety of a building assessed using fire risk analysis. In: Almand, K.H. (ed.). Proceedings of the 3rd International Conference on Performance-Based Codes and Fire Safety Design Methods. Lund, Sweden, 15–17 June 2000. Lund: Lund University. Pp. 247–256. ISBN 1-58716-018-8.

Tillander, K. 2004. Utilisation of statistics to assess fire risks in buildings. Espoo: VTT Publications 537. 224 p. + app. 37 p. ISBN 951-38-6392-1; 951-38-6393-X. http://www.vtt.fi/inf/pdf/publications/2004/P537.pdf

Valonen, K., Männikkö, S., Rajaniemi, K., Ellisaari, J., Saarsalmi, O. & Hämäläinen, J. 2004. Asumiskäytössä olleen koulurakennuksen palo Jyväskylän maalaiskunnassa ja viisi muuta paloa 20.4.–20.5.2003 [School Building in Residential Use Catches Fire in Jyväskylä RuRal Municipality in Finland; Five other Fires over the Period from April 20 to May 20, 2003]. Helsinki: Onnettomuustutkintakeskus. 77 p. ISBN 951-836-137-1. (In Finnish)

Ympäristöministeriö. 2003. Rakennusten paloturvallisuus & Paloturvallisuus korjaus-rakentamisessa [Fire safety in buildings and in renovation]. Helsinki: Ympäristö-ministeriö: Ympäristöopas 39. 160 p. ISBN 952-11-1375-8. (In Finnish)

Appendix A: Statistical survey

Summary of the results

Fires ignited in apartments

The total number fires in residential multi-storey buildings recorded to the PRONTO accident database between years 1996–2001 is 2856, which corresponds to an average number of fires of 476 per year (with the 95 % confidence interval equalling 432–520 fires). The annual average of the number of fires with interior origin is 425 fires (the 95 % confidence interval equals 385–466 fires). Of these fires only 3 % was recorded to have spread to several fire compartments at the time of fire brigade arrival. 74 % of the interior ignitions were limited to the room-of-fire-origin or a part of it. First-aid extinguishing was able extinguish 14 % of the fires and in 8 % of the cases first-aid extinguishing limited the fire development.

Of all the fires during the six years 1996–2001 included in our survey, only in 2 % of the incidents (48 fires) there was a recording that the flames had come out of the window of the room-of-fire-origin. Three fires of these 48 incidents spread to the apartment above the room-of-fire-origin by breaking its windows. Normalised by the total number of the fires in residential multi-storey buildings (2856 fires), the proportion of fires spreading to the apartment above the room-of-fire-origin is about one out of thousand.

Fires ignited in balconies

Frequency of fires initiating in balconies

The total number of exterior ignitions of fires in residential multi-storey buildings between years 1996–2001 is 308. Of these fires 243 fires started in the balcony, leaving 65 fires to the category of "other external ignitions than balcony fires". The proportion of balcony fires is thus 8,5 % (243/2856) of all fires and four out of five external ignitions take place in the balcony. The annual average number of balcony fires is 40 (with the 95 % confidence interval equalling 29–54 fires).

The consequences of the 243 fires in balconies include, *e.g.*, the following damage:

- 25 fires spread into the apartment (or broke part of the windows);
- 2 fires spread also horizontally;
- 3 fires spread to the eaves or roof structures;

- 8 fires exhibited notable fire spread judging by the recorded damage to the contents of the building larger than 10 000 FIM (about 1 700 euros) and/or the recorded fire spread categorised as the whole room-of-fire-origin.

The role first-aid extinguishing in the balcony fires may summarised as follows: in 59 cases the first-aid extinguishing was able to put out the fire, in 25 cases the first-aid extinguishing was able to limit the fire, in 7 cases the first-aid extinguishing had no influence on the fire development. In other words, in 91 incidents (38 %) there has been an attempt first-aid extinguishing and 64 % of the attempts have been successful (*i.e.*, 24 % of all balcony fires). It should be noted that the proportion of 38 % of the first-aid extinguishing attempts can be interpreted so that at least this percentage of the fires has been detected relatively quickly.

One can conclude that about 10 % of fires starting in the balcony spread inside the apartment. First-aid extinguishing was attempted in about 40 % of the balcony fires and 90 % of these attempts were successful. Thus it may estimated that roughly 30 % of fires starting in the balconies are extinguished by first-aid extinguishing and further, that about 15 % of fires initiated in the balcony and which are not put out by the first-aid extinguishing spread inside the apartment.

When assessing the risks related to balcony fires, one must take into account the fact that not every apartment has a balcony and scale the ignition frequency of fires initiating in the balcony in an appropriate way.

According to Statistics Finland (Tilastokeskus) in year 1999 there were 1 079 926 apartments in residential multi-storey buildings in Finland with the average size of the apartments equalling 56,1 m^2. The total area of residential multi-storey buildings, including in addition to the area of apartments also the area of stairways, attics and basements, in Finland in year 1999 was 78 730 420 m^2 [Tilastokeskus 2001]. By dividing the annual average number of fire by the number of apartments in residential multi-storey buildings one obtains the ignition frequency in residential multi-storey buildings per one apartment equal to $4{,}4\times10^{-4}$ fires/year and, further by diving the ignition frequency by the average apartment size, one obtains $7{,}9\times10^{-6}$ fires/(m^2·year) for the annual specific ignition frequency in residential multi-storey buildings. One may obtain an estimate for the annual specific ignition frequency in residential multi-storey buildings also by dividing the annual average number of fires (476) by total area of apartments in residential multi-storey buildings in Finland in year 1999 (78 730 420 m^2) which gives $6{,}0\times10^{-6}$ fires/(m^2·year). This is a bit smaller frequency than that obtained by using the area of the apartments since here there are included also the other areas besides the areas of the apartments. By assuming that 2/3 of apartments have a balcony (corresponding to 719 951 balconies in year 1999) we obtain $5{,}6\times10^{-5}$ fires/year for the annual frequency of balcony fires and, further, by assuming that the average size of the balconies is approximately 10 % of the area of the apartment we obtain the value 10×10^{-6} fires/(m^2·year) for the annual specific ignition frequency in balconies of residential multi-storey buildings. Thus, the annual specific ignition frequency of balconies is close to the annual specific ignition frequency of apartments.

Causes of fire initiated in balconies

Of the fires initiated in the balcony, 98 fires (40 %) started from a candle product and 85 incidents (35 %) originated from smoking. The origin of the fires initiated from candle products was typically inappropriate use of the product (*e.g.*, unguarded burning on a combustible substrate). In 24 (10 %) incidents the ignition reason was not recorded. The 7 incidents in which there was remark that a balcony table or other such object had burner are potentially fires actually originating from a candle product. Smoking may be the origin of the three incidents in which a flowerbox in the balcony was recorded to have burned because such boxes are sometimes used as ashtrays.

Results on the influence of the façade material

In buildings with façade classified as a 1/I or B-s1,d0 material (e.g., coated non-combustible board products), the portion of external ignitions of all fires is smaller than in buildings with façade classified as a 2/- or D-s2,d2 material (*e.g.*, wood) or -/- material . The portions are the following: class 1/I: ca.10 % and classes 2/- and -/-: 15–20 %. A similar difference emerges when one uses the building fire class (P1, P2 or P3) as the determinant factor: in buildings belonging to the fire class P1 the percentage of exterior fires of all fires is ca. 10 % and in buildings belonging to the fire classes P2 and P3 about 15 %. The coincidence between the percentages evaluated either on the basis of the façade material fire classification or the fire class of the building stems from the fact that in practise, these two factors describe the same thing, *i.e.*, the façades in the class P1 buildings belong mainly to the reaction-to-fire class 1/I while in the buildings belonging to the fire classes P2 and P3 it is quite rare that the façades are constructed of a 1/I material. In addition, buildings belonging to the classes P2 and P3 are on the average lower than buildings in the class P1 and thus they have fewer apartments per unit area (or circumference).

Assessment of the uncertainties involved in the statistical data

Fires in residential multi-storey buildings can be assumed to be independent incidents in which case their number within a certain period of time is distributed according to the Poisson distribution. When N is the average number from a Poisson distribution, its standard deviation equals $\sqrt{N}$ and a simple estimate for the 95 % confidence interval equals $\left(\sqrt{N} \pm 0{,}98\right)^2$ (*e.g.*, for the annual average number of fires in residential multi-storey buildings $N = 425$, the 95 % confidence interval equals [385,466]). This estimate is based on the assumption that $\sqrt{N}$ is distributed according to the normal distribution which is a valid assumption when N is large enough. When N is small (of the order of some tens), then the estimation of the 95 % confidence interval is more difficult and in fact it is still under debate how to present a Poisson distributed random quantity when he number of observations N is small.

Tabulation of the data obtained in the search runs from the PRONTO database

Below we present tables of the data obtained in the search runs of the PRONTO database aimed at establishing the influence of building characteristics to fire spread both in internal and external ignitions. The focal point of the investigation was the role of the façade material in the fire development in residential multi-storey buildings.

Multi-storey buildings vs. other buildings

In the following, a 'multi-storey building' is defined so that small buildings such as one-family house, saunas, and other such small buildings are excluded from the data. Such definition 'multi-storey building' gives a larger sample than a reach run using the PRONTO category of 'multi-storey buildings'. We employed the former definition in order to obtain more buildings with wooden or other combustible façade in our sample. The results of the PRONTO search runs are presented in Tables A1–A5.

Table A1. Multi-storey buildings: proportion of external ignitions in buildings belonging to the different fire classes. Entry 'all' denotes the number of all relevant multi-storey-building fires, 'P1–P3 total' means the number of fires in which the fire class of the building has been recorded in the relevant field in the PRONTO inquire format. It is interesting to note that the fire class of the building is recorded in almost all fires recorded in the PRONTO system.

multi-storey buildings	ext	tot	external ignitions (%)	all buildings	ext	tot	external ignitions (%)
P1	361	3630	9.94 %	**P1**	562	5331	10.54 %
P2	63	415	15.18 %	**P2**	216	1337	16.16 %
P3	170	1252	13.58 %	**P3**	1726	12454	13.86 %
P1-P3 total	594	5297	11.21 %	**P1-P3 total**	2504	19122	13.09 %
all	597	5311	11.24 %	**all**	2512	19171	13.10 %
no record (%)	0.50 %	0.26 %		**no record (%)**	0.32 %	0.26 %	

Table A2. Proportion of external ignitions in residential multi-storey buildings.

residential multi-storey buildings	ext	tot	external ignitions (%)	all buildings	ext	tot	external ignitions (%)
P1	242	2 582	9.37 %	**P1**	562	5331	10.54 %
P2	8	64	12.50 %	**P2**	216	1337	16.16 %
P3	9	212	4.25 %	**P3**	1726	12454	13.86 %
sum	259	2858	9.06 %	**sum**	2504	19122	13.09 %
all	261	2 864	9.11 %	**all**	2512	19171	13.10 %
no record (%)	0.77 %	0.21 %		**no record (%)**	0.32 %	0.26 %	

Table A3. Multi-storey buildings: proportion of external ignitions categorised according to the reaction-to-fire classification of the façade material. It is seen that the recording of the reaction-to-fire classification of the façade material is missing relative often.

multi-storey buildings	ext	tot	external ignitions (%)	all buildings	ext	tot	external ignitions (%)
01_1/I	298	2857	10.43 %	**01_1/I**	650	5552	11.71 %
02_1/II	3	39	7.69 %	**02_1/II**	15	133	11.28 %
03_1/-	9	52	17.31 %	**03_1/-**	44	280	15.71 %
04_2/-	149	736	20.24 %	**04_2/-**	1011	6418	15.75 %
05_-/-	25	142	17.61 %	**05_-/-**	397	2494	15.92 %
sum	484	3826	12.65 %	**sum**	2117	14877	14.23 %
all	597	5311	11.24 %	**all**	2512	19171	13.10 %
no record (%)	18.93 %	27.96 %		**no record (%)**	15.72 %	22.40 %	

Table A4. Multi-storey buildings: proportion of external ignitions categorised according to the reaction-to-fire classification of the façade material and the fire class of the building.

multi-storey buildings:						
	external ignitions			**all fires**		
walls	**P1**	**P2**	**P3**	**P1**	**P2**	**P3**
01_1/I	248	25	25	2378	197	280
02_1/I	1	1	1	9	13	17
03_1/-	3	2	4	15	18	19
04_2/-	25	16	106	71	69	594
05_-/-	2	5	18	14	14	114
sum	279	49	154	2487	311	1024
all	361	63	170	3630	415	1252
no record (%)	22.71 %	22.22 %	9.41 %	31.49 %	25.06 %	18.21 %
	external ignitions (%)			**P1-P3**		
walls	**P1**	**P2**	**P3**	**ext.**	**all**	**external ignitions (%)**
01_1/I	10.43 %	12.69 %	8.93 %	298	2857	10.43 %
02_1/I	11.11 %	7.69 %	5.88 %	3	39	7.69 %
03_1/-	20.00 %	11.11 %	21.05 %	9	52	17.31 %
04_2/-	35.21 %	23.19 %	17.85 %	149	736	20.24 %
05_-/-	14.29 %	35.71 %	15.79 %	25	142	17.61 %
sum	11.22 %	15.76 %	15.04 %	484	3826	12.65 %
all	9.94 %	15.18 %	13.58 %	597	5311	11.24 %
no record (%)				18.93 %	27.96 %	

Table A5. All building types: proportion of external ignitions categorised according to the reaction-to-fire classification of the façade material and the fire class of the building.

all buildings						
	external ignitions			all fires		
walls	P1	P2	P3	P1	P2	P3
01_1/I	387	111	152	3446	717	1385
02_1/I	1	8	6	13	41	79
03_1/-	6	5	33	40	44	196
04_2/-	33	40	935	122	207	6081
05_-/-	6	10	379	48	61	2380
sum	433	174	1505	3669	1070	10121
all	562	216	1726	5331	1337	12454
no record (%)	22.95 %	19.44 %	12.80 %	31.18 %	19.97 %	18.73 %
all buildings						
	external ignitions (%)			P1-P3		
walls	P1	P2	P3	ext.	all	external ignitions (%)
01_1/I	11.23 %	15.48 %	10.97 %	650	5552	11.71 %
02_1/I	7.69 %	19.51 %	7.59 %	15	133	11.28 %
03_1/-	15.00 %	11.36 %	16.84 %	44	280	15.71 %
04_2/-	27.05 %	19.32 %	15.38 %	1011	6418	15.75 %
05_-/-	12.50 %	16.39 %	15.92 %	397	2494	15.92 %
sum	11.80 %	16.26 %	14.87 %	2117	14877	14.23 %
all	10.54 %	16.16 %	13.86 %	2512	19171	13.10 %
no record (%)				15.72 %	22.40 %	

The data in the tables above reveals that the proportion of external ignitions is smaller in buildings that belong to the fire class P1 than in buildings that belong to the fire classes P2 and P3. The type of the building (multi-storey buildings/all building types) has no influence on proportion of external ignitions ((P1 *ca.* 10 % and P2 *ca*. 15–16 %, P3 *ca*. 14 %). In residential multi-storey buildings belonging to the fire class P3[15] the proportion of external ignitions seems to be smaller, only about 5 %, but the small number of observations in this category (*ca.* 200) may introduce a relative large error marginal to this percentage.

The proportion of external ignitions is smaller in the building with the façade material ranking to the reaction-to-fire class 1/I than in buildings with the 2/- or -/- reaction-to-fire grade façades: 10 % vs. 20 % for multi-storey buildings, residential multi-storey buildings 10 % vs. 15 % and 12 % vs. 16 % for all buildings.

[15] According to the National Building Code of Finland these building can have only two storeys.

In the statistical data, most (106/147) of the multi-storey buildings with the façade material in the reaction-to-fire class 2/- belong to the fire class P3 whereas most (248/298) of the multi-storey buildings with the façade material in the reaction-to-fire class 1/I belong to the fire class P1, *i.e.*, the fire classes P1-P3 and the reaction-to-fire classes façade material have strong correlation and cross-comparison between the influences of these two factors is not meaningful. Thus the differences observed in the comparison between the different façade materials may actually reflect the differences between the buildings in the fire classes P1 and P3, which are pronounced: the buildings in the fire class P3 are relatively small having no more than 2 storeys while the buildings in the fire class P1 are big and may have many storeys.

The sample that includes all buildings gives similar results as the sample in which the small buildings have been excluded (our 'multi-storey' data), *i.e.*, in the building fire class P1, the façades are made building materials belonging to the reaction-fire-class 1/I and in the building fire class P3, the façades are made building materials belonging to the reaction-fire-class 2/-. Yet, there are also façades with the 1/I ranking in the building fire classes P2 and P3 (P1 and P3 both about 11 % external ignitions, P2 about 15 % external ignitions).

Residential multi-storey buildings vs. all other buildings

In the following presentation, buildings are classified as residential multi-storey buildings and other buildings. The total number of fires in the residential multi-storey buildings in the years 1996–2001 recorded to the PRONTO system is 2 864 fires. Of these fires 9 % (261 fires) are recorded as external ignitions.

Summarising remarks

The building fire class

More than 90 % of the residential multi-storey buildings belong to the fire class P1. External ignitions make up 9 % of the fires in the class P1 buildings whereas the proportion of external ignitions is smaller in the building fire class P3. In all building fires, the corresponding proportions were 11 % for the building fire class P1 and 14 % for the building fire class P3.

The extent of fire spread

When considering external ignitions, the PRONTO entries ’fire/smoke did not spread inside the building’ and ’fire/smoke spread into one compartment inside the building’ can be combined with the external ignitions.

All buildings: in fires with internal origin of ignition, comparing the extent of fire spread at the arrival of the fire brigade and at the end of the incident, there is a *ca*. 1–2 % difference in the fires that have been recorded to have spread beyond the compartment-of-fire-origin. This is true also to external ignitions with the exception that for the cases with the reaction-to-fire class 1/II, the difference was 14 % (yet, here the number of cases is only 16 and thus, the result is not statistically significant).

The first-aid extinguishing

The proportion of fires extinguished by the first-aid extinguishing is slightly higher in residential multi-storey buildings than in other buildings. Taking into account statistical uncertainty, the difference is small.

Attic

Residential multi-storey buildings: a used attic is rarer in cases with external ignition.

In most cases (31 %) there is no attic or roof void space, the proportion is a bit larger than in internal ignition cases.

Role of surface fire performance

Residential multi-storey buildings: The portion of fires in which the surface material contributed to the fire is about twice as high in incidents with external ignition than with internal ignition.

Reaction-to-fire classification of the façade material

Residential multi-storey buildings: the portion of the class 2/- in external ignitions is 10 % and in internal ignitions 5 %. The 1/I: external ignitions 68 %, internal ignitions 61 %. (It should be noted that in 31 % of the fires with internal origin and in 20 % of fires with external origin, the reaction-to-fire classification of the façade material was not recorded.)

Table A6. Building fire class.

	Number of fires			Percentages		
Building fire class	Internal ignitions	External ignitions	Total	Internal ignitions	External ignitions	Total
P1	2 340	242	2 582	90 %	93 %	90 %
P2	56	8	64	2 %	3 %	2 %
P3	203	9	212	8 %	3 %	7 %
Not recorded	4	2	6	0.2 %	0.8 %	0.2 %
Total	**2 603**	**261**	**2 864**			

Table A7. Ignition location.

	Number of fires			Percentages		
Ignition location	Internal ignitions	External ignitions	Total	Internal ignitions	External ignitions	Total
Contents inside the building	2 263		2 263	87 %		79 %
Structures inside the building	323		323	12 %		11 %
Movable property in the vicinity of the building		166	166		64 %	6 %
External structures of the building		95	95		36 %	3 %
Not recorded	17		17	0.7 %		0.6 %
Total	**2 603**	**261**	**2 864**			

Table A8. Development phase of the fire at the arrival of the fire brigade.

	Number of fires			Percentages		
Development phase of the fire at the arrival of the fire brigade	Internal ignitions	External ignitions	Total	Internal ignitions	External ignitions	Total
Ignition	1 317	106	1 423	51 %	41 %	50 %
Burning phase	858	107	965	33 %	41 %	34 %
Cooling phase	376	45	421	14 %	17 %	15 %
Soot fire	3		3	0.1 %	0.0 %	0.1 %
Fire extinguished/self-extinguished	35	3	38	1 %	1 %	1 %
Not recorded	14		14	0.5 %		0.5 %
Total	**2 603**	**261**	**2 864**			

Table A9. Extent of fire spread at fire brigade arrival.

	Number of fires			Percentages		
Extent of fire spread at fire brigade arrival	Internal ignitions	External ignitions	Total	Internal ignitions	External ignitions	Total
Part of the room-of-fire-origin	1 693	58	1 751	65 %	22 %	61 %
Whole room-of-fire-origin	373	11	384	14 %	4 %	13 %
Whole compartment-of-fire-origin	141	3	144	5 %	1 %	5 %
Spread to several fire compartments	35	2	37	1 %	1 %	1 %
No fire/smoke spread inside the building	40	112	152	2 %	43 %	5 %
Fire/smoke spread into one compartment of the building	112	41	153	4 %	16 %	5 %
Fire self-extinguished or extinguished/no fire gases	180	31	211	7 %	12 %	7 %
Not recorded	29	3	32	1 %	1 %	1 %
Total	**2 603**	**261**	**2 864**			

Table A10. Extent of fire spread at end of the incident.

	Number of fires			Percentages		
Extent of fire spread at end of the incident	Internal ignitions	External ignitions	Total	Internal ignitions	External ignitions	Total
Part of the room-of-fire-origin	1 515	61	1 576	58 %	23 %	55 %
Whole room-of-fire-origin	408	10	418	16 %	4 %	15 %
Whole compartment-of-fire-origin	276	6	282	11 %	2 %	10 %
Spread to several fire compartments	81	4	85	3 %	2 %	3 %
Spread to another building	1		1	0.04 %		0.03 %
No fire/smoke spread inside the building	32	113	145	1 %	43 %	5 %
Fire/smoke spread into one compartment of the building	106	36	142	4 %	14 %	5 %
Fire self-extinguished or extinguished/no fire gases	73	16	89	3 %	6 %	3 %
Not recorded	111	15	126	4 %	6 %	4 %
Total	**2 603**	**261**	**2 864**			

Table A11. First-aid extinguishing and its influence.

	Number of fires			Percentages		
First-aid extinguishing equipment and its influence on the fire development	Internal ignitions	External ignitions	Total	Internal ignitions	External ignitions	Total
No first-aid extinguishing equipment	1 514	130	1 644	58 %	50 %	57 %
First-aid extinguishing equipment not used	435	44	479	17 %	17 %	17 %
First-aid extinguishing equipment extinguished the fire	368	54	422	14 %	21 %	15 %
First-aid extinguishing equipment limited the fire	209	22	231	8 %	8 %	8 %
First-aid extinguishing had no effect	61	9	70	2 %	3 %	2 %
First-aid extinguishing equipment did not work	4	1	5	0.2 %	0.4 %	0.2 %
Not recorded	12	1	13	0.5 %	0.4 %	0.5 %
Total	**2 603**	**261**	**2 864**			

Table A12. Attic.

	Number of fires			Percentages		
Attic	Internal ignitions	External ignitions	Total	Internal ignitions	External ignitions	Total
Attic in use	599	33	632	23 %	13 %	22 %
attic not in use	338	37	375	13 %	14 %	13 %
Roof void space	628	75	703	24 %	29 %	25 %
No attic or roof void space	608	81	689	23 %	31 %	24 %
Not recorded	430	35	465	17 %	13 %	16 %
Total	**2 603**	**261**	**2 864**			

Table A13. Role of surface fire performance.

	Number of fires			Percentages		
Role of surface fire performance	Internal ignitions	External ignitions	Total	Internal ignitions	External ignitions	Total
Retarded the fire	1 096	129	1 225	42 %	49 %	43 %
No effect	1 145	71	1 216	44 %	27 %	42 %
Accelerated the fire	221	43	264	8 %	16 %	9 %
Not recorded	141	18	159	5 %	7 %	6 %
Total	**2 603**	**261**	**2 864**			

Table A14. Reaction-to-fire class of the exterior walls.

	Number of fires			**Percentages**		
Reaction-to-fire class of the exterior walls	Internal ignitions	External ignitions	Total	Internal ignitions	External ignitions	Total
1/I	1 595	177	1 772	61 %	68 %	62 %
1/II	8	1	9	0.3 %	0.4 %	0.3 %
1/-	17	4	21	0.7 %	1.5 %	0.7 %
2/-	140	25	165	5 %	10 %	6 %
-/-	24	3	27	0.9 %	1.1 %	0.9 %
Not recorded	819	51	870	31 %	20 %	30 %
Total	**2 603**	**261**	**2 864**			

External ignitions in all buildings in years 1996–2001
(PRONTO, place of ignition recorded using code 03 or 04)

Table A15. Extent of fire spread at fire brigade arrival.

Extent of fire spread at fire brigade arrival	**Reaction-to-fire class of the facade material**				
	1/I	**1/II**	**1/-**	**2/-**	**-/-**
Part of the room-of-fire-origin	141	2	14	199	52
Whole room-of-fire-origin	29		4	104	83
Whole compartment-of-fire-origin	38	3	5	279	120
Spread to several fire compartments	13	1		37	6
Spread to another building	4		1	31	18
No fire/smoke spread inside the building	247	6	11	185	63
Fire/smoke spread into one compartment of the building	100	2	5	137	46
Fire self-extinguished or extinguished/no fire gases	75	2	3	89	26
Total	**647**	**16**	**43**	**1 061**	**414**

Table A16. Extent of fire spread at fire brigade arrival.

Extent of fire spread at fire brigade arrival	Reaction-to-fire class of the facade material				
	1/I	1/II	1/-	2/-	-/-
Part of the room-of-fire-origin	22 %	13 %	33 %	19 %	13 %
Whole room-of-fire-origin	4 %		9 %	10 %	20 %
Whole compartment-of-fire-origin	6 %	19 %	12 %	26 %	29 %
Spread to several fire compartments	2 %	6 %		3 %	1 %
Spread to another building	1 %		2 %	3 %	4 %
No fire/smoke spread inside the building	38 %	38 %	26 %	17 %	15 %
Fire/smoke spread into one compartment of the building	15 %	13 %	12 %	13 %	11 %
Fire self-extinguished or extinguished/no fire gases	12 %	13 %	7 %	8 %	6 %
No spread beyond fire compartment	**97 %**	**94 %**	**98 %**	**94 %**	**94 %**

Table A17. Extent of fire spread at end of the incident.

Extent of fire spread at end of the incident	Reaction-to-fire class of the facade material				
	1/I	1/II	1/-	2/-	-/-
Part of the room-of-fire-origin	141	2	13	187	61
Whole room-of-fire-origin	28	1	4	112	74
Whole compartment-of-fire-origin	34		7	294	125
Spread to several fire compartments	26	2	1	47	8
Spread to another building	4	1	1	25	17
No fire/smoke spread inside the building	242	6	10	182	61
Fire/smoke spread into one compartment of the building	96	2	3	123	37
Fire self-extinguished or extinguished/no fire gases	34	1	4	44	14
Total	**605**	**15**	**43**	**1 014**	**397**

Table A18. Extent of fire spread at end of the incident.

Extent of fire spread at end of the incident	**Reaction-to-fire class of the facade material**				
	1/I	**1/II**	**1/-**	**2/-**	**-/-**
Part of the room-of-fire-origin	23 %	13 %	30 %	18 %	15 %
Whole room-of-fire-origin	5 %	7 %	9 %	11 %	19 %
Whole compartment-of-fire-origin	6 %		16 %	29 %	31 %
Spread to several fire compartments	4 %	13 %	2 %	5 %	2 %
Spread to another building	1 %	7 %	2 %	2 %	4 %
No fire/smoke spread inside the building	40 %	40 %	23 %	18 %	15 %
Fire/smoke spread into one compartment of the building	16 %	13 %	7 %	12 %	9 %
Fire self-extinguished or extinguished/no fire gases	6 %	7 %	9 %	4 %	4 %
No spread beyond fire compartment	**95 %**	**80 %**	**95 %**	**93 %**	**94 %**

Table A19. Extent of fire spread at fire brigade arrival.

Extent of fire spread at fire brigade arrival	**Attic**			
	Attic in use	**Attic not in use**	**Roof void space**	**No attic**
Part of the room-of-fire-origin	48	102	118	170
Whole room-of-fire-origin	15	51	47	111
Whole compartment-of-fire-origin	49	124	67	213
Spread to several fire compartments	11	21	19	14
Spread to another building	15	11	4	24
No fire/smoke spread inside the building	66	153	141	221
Fire/smoke spread into one compartment of the building	43	97	77	97
Fire self-extinguished or extinguished/no fire gases	19	56	67	77
Total	**266**	**615**	**540**	**927**

Table A20. Extent of fire spread at fire brigade arrival.

Extent of fire spread at fire brigade arrival	**Attic**			
	Attic in use	**Attic not in use**	**Roof void space**	**No attic**
Part of the room-of-fire-origin	18 %	17 %	22 %	18 %
Whole room-of-fire-origin	6 %	8 %	9 %	12 %
Whole compartment-of-fire-origin	18 %	20 %	12 %	23 %
Spread to several fire compartments	4 %	3 %	4 %	2 %
Spread to another building	6 %	2 %	1 %	3 %
No fire/smoke spread inside the building	25 %	25 %	26 %	24 %
Fire/smoke spread into one compartment of the building	16 %	16 %	14 %	10 %
Fire self-extinguished or extinguished/no fire gases	7 %	9 %	12 %	8 %
No spread beyond fire compartment	**90 %**	**95 %**	**96 %**	**96 %**

Table A21. Extent of fire spread at end of the incident.

Extent of fire spread at end of the incident	**Attic**			
	Attic in use	**Attic not in use**	**Roof void space**	**No attic**
Part of the room-of-fire-origin	40	111	115	169
Whole room-of-fire-origin	21	52	46	108
Whole compartment-of-fire-origin	52	127	75	211
Spread to several fire compartments	17	29	28	19
Spread to another building	11	7	5	25
No fire/smoke spread inside the building	67	146	133	227
Fire/smoke spread into one compartment of the building	37	86	67	90
Fire self-extinguished or extinguished/no fire gases	14	22	35	37
Total	**259**	**580**	**504**	**886**

Table A22. Extent of fire spread at end of the incident.

Extent of fire spread at end of the incident	**Attic**			
	Attic in use	**Attic not in use**	**Roof void space**	**No attic**
Part of the room-of-fire-origin	15 %	19 %	23 %	19 %
Whole room-of-fire-origin	8 %	9 %	9 %	12 %
Whole compartment-of-fire-origin	20 %	22 %	15 %	24 %
Spread to several fire compartments	7 %	5 %	6 %	2 %
Spread to another building	4 %	1 %	1 %	3 %
No fire/smoke spread inside the building	26 %	25 %	26 %	26 %
Fire/smoke spread into one compartment of the building	14 %	15 %	13 %	10 %
Fire self-extinguished or extinguished/no fire gases	5 %	4 %	7 %	4 %
No spread beyond the fire compartment	**89 %**	**94 %**	**93 %**	**95 %**

Table A23. Extent of fire spread at fire brigade arrival.

Extent of fire spread at fire brigade arrival	**Building fire class**					
	P1	**P2**	**P3**	**P1**	**P2**	**P3**
Part of the room-of-fire-origin	40	111	115	22 %	24 %	17 %
Whole room-of-fire-origin	21	52	46	4 %	5 %	12 %
Whole compartment-of-fire-origin	52	127	75	2 %	4 %	26 %
Spread to several fire compartments	17	29	28	1 %	5 %	3 %
Spread to another building	11	7	5	0.4 %	1 %	3 %
No fire/smoke spread inside the building	67	146	133	44 %	34 %	17 %
Fire/smoke spread into one compartment of the building	37	86	67	15 %	17 %	12 %
Fire self-extinguished or extinguished/no fire gases	14	22	35	12 %	10 %	8 %
No spread beyond the fire compartment				**99 %**	**94 %**	**94 %**

Table A24. Extent of fire spread at end of the incident.

Extent of fire spread at end of the incident	Building fire class					
	P1	**P2**	**P3**	**P1**	**P2**	**P3**
Part of the room-of-fire-origin	126	49	305	24 %	24 %	18 %
Whole room-of-fire-origin	29	7	223	6 %	3 %	13 %
Whole compartment-of-fire-origin	11	11	482	2 %	5 %	28 %
Spread to several fire compartments	8	16	71	2 %	8 %	4 %
Spread to another building	2	2	47	0.4 %	1 %	3 %
No fire/smoke spread inside the building	242	73	302	46 %	36 %	18 %
Fire/smoke spread into one compartment of the building	74	33	191	14 %	16 %	11 %
Fire self-extinguished or extinguished/no fire gases	31	12	77	6 %	6 %	5 %
No spread beyond the fire compartment	**523**	**203**	**1 698**	**98 %**	**91 %**	**93 %**

Internal ignitions in all buildings in years 1996–2001
(PRONTO, place of ignition recorded using code 01 or 02)

Table A25. Extent of fire spread at fire brigade arrival.

Extent of fire spread at fire brigade arrival	Reaction-to-fire class of the facade material				
	1/I	**1/II**	**1/-**	**2/-**	**-/-**
Part of the room-of-fire-origin	2974	56	102	1913	669
Whole room-of-fire-origin	624	22	43	1218	562
Whole compartment-of-fire-origin	343	16	42	1433	577
Spread to several fire compartments	132	5	6	195	68
Spread to another building	8		2	49	25
No fire/smoke spread inside the building	112	4	6	68	26
Fire/smoke spread into one compartment of the building	275	5	15	152	65
Fire self-extinguished or extinguished/no fire gases	448	11	22	325	101
Total	**4 916**	**119**	**238**	**5 353**	**2 093**

Table A26. Extent of fire spread at fire brigade arrival.

Extent of fire spread at fire brigade arrival	**Reaction-to-fire class of the facade material**				
	1/I	**1/II**	**1/-**	**2/-**	**-/-**
Part of the room-of-fire-origin	60 %	47 %	43 %	36 %	32 %
Whole room-of-fire-origin	13 %	18 %	18 %	23 %	27 %
Whole compartment-of-fire-origin	7 %	13 %	18 %	27 %	28 %
Spread to several fire compartments	3 %	4 %	3 %	4 %	3 %
Spread to another building	0 %	0 %	1 %	1 %	1 %
No fire/smoke spread inside the building	2 %	3 %	3 %	1 %	1 %
Fire/smoke spread into one compartment of the building	6 %	4 %	6 %	3 %	3 %
Fire self-extinguished or extinguished/no fire gases	9 %	9 %	9 %	6 %	5 %
No spread beyond the fire compartment	**97 %**	**96 %**	**97 %**	**95 %**	**96 %**

Table A27. Extent of fire spread at end of the incident.

Extent of fire spread at end of the incident	**Reaction-to-fire class of the facade material**				
	1/I	**1/II**	**1/-**	**2/-**	**-/-**
Part of the room-of-fire-origin	2810	50	93	1772	624
Whole room-of-fire-origin	635	21	50	1128	534
Whole compartment-of-fire-origin	519	18	49	1631	648
Spread to several fire compartments	211	7	10	251	78
Spread to another building	8		2	45	25
No fire/smoke spread inside the building	103	6	5	76	27
Fire/smoke spread into one compartment of the building	246	8	13	152	57
Fire self-extinguished or extinguished/no fire gases	172	5	5	126	47
Total	**4 704**	**115**	**227**	**5 181**	**2 040**

Table A28. Extent of fire spread at end of the incident.

Extent of fire spread at end of the incident	**Reaction-to-fire class of the facade material**				
	1/I	**1/II**	**1/-**	**2/-**	**-/-**
Part of the room-of-fire-origin	60 %	43 %	41 %	34 %	31 %
Whole room-of-fire-origin	13 %	18 %	22 %	22 %	26 %
Whole compartment-of-fire-origin	11 %	16 %	22 %	31 %	32 %
Spread to several fire compartments	4 %	6 %	4 %	5 %	4 %
Spread to another building	0 %	0 %	1 %	1 %	1 %
No fire/smoke spread inside the building	2 %	5 %	2 %	1 %	1 %
Fire/smoke spread into one compartment of the building	5 %	7 %	6 %	3 %	3 %
Fire self-extinguished or extinguished/no fire gases	4 %	4 %	2 %	2 %	2 %
No spread beyond the fire compartment	**95 %**	**94 %**	**95 %**	**94 %**	**95 %**

Table A29. Extent of fire spread at fire brigade arrival.

Extent of fire spread at fire brigade arrival	**Attic**			
	Attic in use	**Attic not in use**	**Roof void space**	**No attic**
Part of the room-of-fire-origin	1149	1849	1751	2191
Whole room-of-fire-origin	387	714	680	826
Whole compartment-of-fire-origin	416	756	560	827
Spread to several fire compartments	105	128	109	80
Spread to another building	10	31	16	33
No fire/smoke spread inside the building	53	101	71	104
Fire/smoke spread into one compartment of the building	81	192	151	145
Fire self-extinguished or extinguished/no fire gases	133	305	293	363
Total	**2 334**	**4 076**	**3 631**	**4 569**

Table A30. Extent of fire spread at fire brigade arrival.

Extent of fire spread at fire brigade arrival	**Attic**			
	Attic in use	**Attic not in use**	**Roof void space**	**No attic**
Part of the room-of-fire-origin	49 %	45 %	48 %	48 %
Whole room-of-fire-origin	17 %	18 %	19 %	18 %
Whole compartment-of-fire-origin	18 %	19 %	15 %	18 %
Spread to several fire compartments	4 %	3 %	3 %	2 %
Spread to another building	0 %	1 %	0 %	1 %
No fire/smoke spread inside the building	2 %	2 %	2 %	2 %
Fire/smoke spread into one compartment of the building	3 %	5 %	4 %	3 %
Fire self-extinguished or extinguished/no fire gases	6 %	7 %	8 %	8 %
No spread beyond the fire compartment	**95 %**	**96 %**	**97 %**	**98 %**

Table A31. Extent of fire spread at end of the incident.

Extent of fire spread at end of the incident	**Attic**			
	Attic in use	**Attic not in use**	**Roof void space**	**No attic**
Part of the room-of-fire-origin	1020	1749	1618	2111
Whole room-of-fire-origin	380	667	659	809
Whole compartment-of-fire-origin	503	914	701	935
Spread to several fire compartments	148	178	156	116
Spread to another building	11	28	15	34
No fire/smoke spread inside the building	62	96	65	99
Fire/smoke spread into one compartment of the building	80	182	147	122
Fire self-extinguished or extinguished/no fire gases	58	114	108	150
Total	**2 262**	**3 928**	**3 469**	**4 376**

Table A32. Extent of fire spread at end of the incident.

Extent of fire spread at end of the incident	**Attic**			
	Attic in use	**Attic not in use**	**Roof void space**	**No attic**
Part of the room-of-fire-origin	45 %	45 %	47 %	48 %
Whole room-of-fire-origin	17 %	17 %	19 %	18 %
Whole compartment-of-fire-origin	22 %	23 %	20 %	21 %
Spread to several fire compartments	7 %	5 %	4 %	3 %
Spread to another building	0 %	1 %	0 %	1 %
No fire/smoke spread inside the building	3 %	2 %	2 %	2 %
Fire/smoke spread into one compartment of the building	4 %	5 %	4 %	3 %
Fire self-extinguished or extinguished/no fire gases	3 %	3 %	3 %	3 %
No spread beyond fire compartment	**93 %**	**95 %**	**95 %**	**97 %**

Table A33. Extent of fire spread at fire brigade arrival.

Extent of fire spread at fire brigade arrival	**Building fire class**					
	P1	**P2**	**P3**	**P1**	**P2**	**P3**
Part of the room-of-fire-origin	3226	625	3834	68 %	56 %	38 %
Whole room-of-fire-origin	461	129	2283	10 %	12 %	22 %
Whole compartment-of-fire-origin	205	90	2428	4 %	8 %	24 %
Spread to several fire compartments	43	49	348	1 %	4 %	3 %
Spread to another building	6	3	88	0 %	0 %	1 %
No fire/smoke spread inside the building	97	30	230	2 %	3 %	2 %
Fire/smoke spread into one compartment of the building	238	62	327	5 %	6 %	3 %
Fire self-extinguished or extinguished/no fire gases	480	123	643	10 %	11 %	6 %
No spread beyond fire compartment				**99 %**	**95 %**	**96 %**

Table A34. Extent of fire spread at end of the incident.

Extent of fire spread at end of the incident	**Building fire class**					
	P1	**P2**	**P3**	**P1**	**P2**	**P3**
Part of the room-of-fire-origin	3042	601	3563	67 %	58 %	36 %
Whole room-of-fire-origin	514	125	2148	11 %	12 %	22 %
Whole compartment-of-fire-origin	356	112	2789	8 %	11 %	28 %
Spread to several fire compartments	105	72	447	2 %	7 %	5 %
Spread to another building	7	1	86	0 %	0 %	1 %
No fire/smoke spread inside the building	95	33	232	2 %	3 %	2 %
Fire/smoke spread into one compartment of the building	216	53	316	5 %	5 %	3 %
Fire self-extinguished or extinguished/no fire gases	178	44	287	4 %	4 %	3 %
No spread beyond fire compartment				**98 %**	**93 %**	**95 %**

References of Appendix A

Tilastokeskus. 2001. Rakennukset, asunnot ja asuinolot 1999 [Statistics Finland. 2001. Buildings, dwellings and housing conditions 1999]. Helsinki: Tilastokeskus. ISBN 951-727-911-6. (In Finnish)

Appendix B: Considerations on the size of the external flames

Introduction

If during a room fire the window (or windows) of the room break and fallout, the hot gases and flames vent out creating external flaming. Because a fraction of the gases that vent out are combustible hydrocarbon compounds combustion takes place also outside the room-of-fire-origin when the combustible hot gases become into contact with oxygen. Provided that the temperature of the external flames is high enough at the level of the window of the apartment above the room-of-fire-origin, it is possible that the fire spreads into the above apartment either so that the windows of the apartment break or that heat radiated by the external flames that penetrates the window pane (or panes) is strong enough to ignite items inside the apartment.

The hazard of fire spread to spaces above the room-of-fire-origin depends on the vertical extent and temperature distribution of the externally venting hot gases and flames. These factors in turn depend on the strength of the fire, *i.e.*, the burning and heat release rate. If a concrete façade with negligible contribution to fire is replaced by a wooden one that has non-negligible contribution to fire, the strength of the fire grows and thus, in principle also the probability of the fire spread to the apartments above increases. The study presented in this Appendix reveals that the added contribution to fire from the wood façade is negligible as compared to the magnitude of a typical room fire as well as the variability in the magnitude of the fire arising from other factors involved.

Flame height in a typical room fire and the contribution of a wooden façade

The model

The height of the flames venting out of the room fire vary a lot depending on the fire scenarios and the phases of the fires. During certain time intervals it is possible to determine an average flame height: Figure B1a shows a typical external flame in a fire experiment carried out at VTT and Figure B1b shows a schematic model for the flame shape during the fully developed room fire (the Law model, Eurocode 1991-1-2, Appendix B). That particular model has been development on the basis of several fire tests and it has been successfully applied to characterise external flaming during the past 20 years.

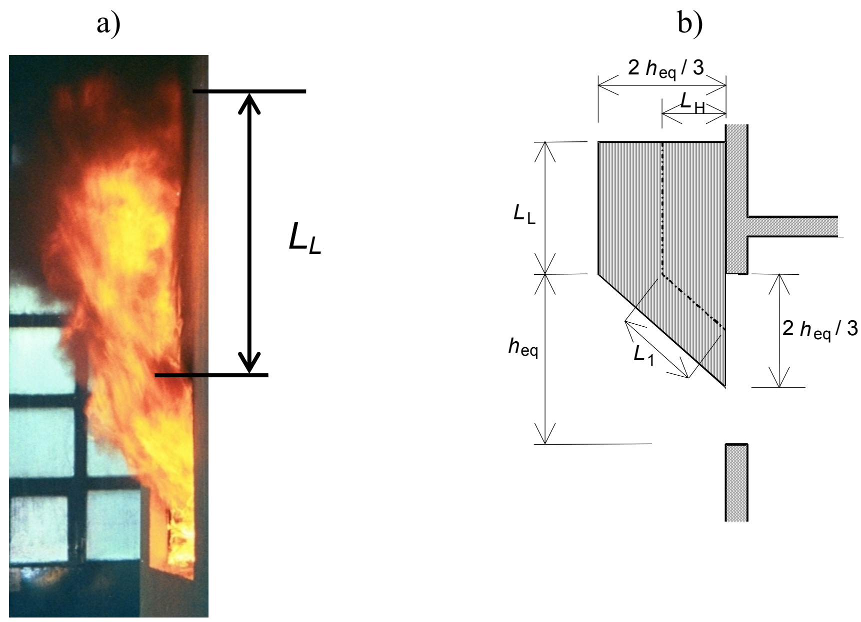


Figure B1. Height of external flames. a) External flaming in a fire experiment and b) schematic presentation according to the Eurocode 1991-1-2, Appendix B.

The height L_L (in meters) shown in Figure B1b depends on the heat release rate $\dot{Q}$ and the opening size (height h and width w) as follows:

$$L_L = 1{,}9\left(\frac{\dot{Q}}{w}\right)^{2/3} - h\ .$$

Here, the unit of the heat release rate is megawatts (MW).

To establish the maximum height of the flames, one must determine the maximum heat release rate. There are two separate cases:

- if the opening is small, the heat release rate of the fire is limited by the amount of oxygen that can flow into the fire room (ventilation-controlled fire),
- if the opening is large, the heat release rate of the fire is limited by the amount of the fuel surfaces that can contribute to the fire and how much heat these surfaces can release (fuel-limited fire).

Living room windows are typically quite large, often large enough so that the fire gets enough oxygen through the window and the heat release rate is fuel-limited. In this case the determining factors are the amount and combustibility of the fire load, which in practise depends on how strong the contribution of the furniture to the fire is (*e.g.*, is the majority of the furniture made of plastics or cellulosic materials) and how large surfaces are there that are able to produce combustible vapours (*e.g.*, a half-full bookshelf may burn more vigorously than a completely full one because of the larger surface area of the former).

Because the magnitude of a typical room fire depends on the quality and quantity of the fire load in the room, it is evident that maximum strength of fire varies a lot from one incident to another: one can imagine one household with a functionalist but ascetic furnishing characterised by chairs and tables made of chrome plated steel and with minimum amount of paddings and decorations and another household with large upholstered furniture with thick paddings and floors covered with comfortable thick carpets. While in the former case the maximum heat release may be only a few megawatts, it may in the latter case rise up to twenty megawatts.

An example

In the following we consider an example of a room fire in the enclosure with the 4×5 m^2 plan and furnishings as shown in Figure B2. Data needed to establish the heat release rate can be found, *e.g.*, from results of fire experiments carried at VTT using upholstered furniture (the CBUF project) and in literature (*e.g.*, during the last decade the role of furniture in room fires has been studied intensively in the New Zealand). On the basis of these data sources one can estimate the following maximum heat release rates for different pieces of furniture:

- a sofa: 3 MW,
- an upholstered chair: 1,5 MW,
- a carpet: 3 MW,
- floor: 2 MW,
- a shelf with a TV set: 0,8 MW,
- a table: 0,1 MW.

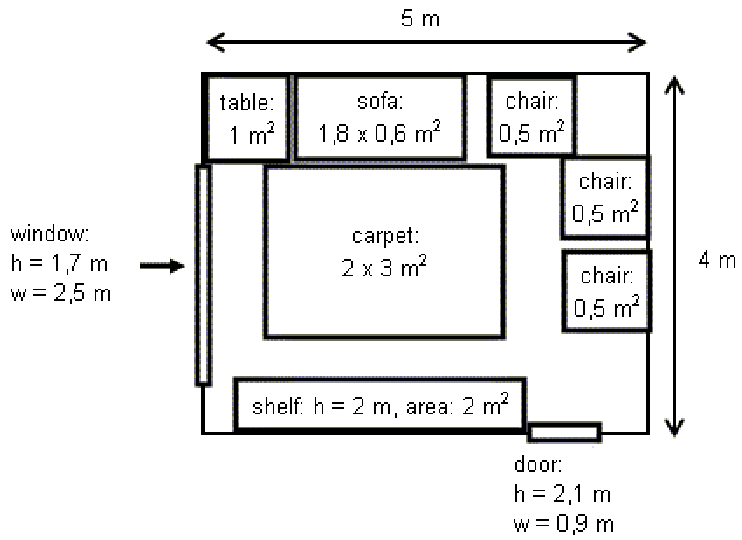


Figure B2. A simple plan of a living room with furnishings.

It is obvious that in fires in different apartments, *e.g.*, the maximum heat release rate of a sofa is not exactly 3 MW, but rather of the order on magnitude of 3 MW with the exact value depending on the construction and materials of the sofa as well as such factors that how many pillows there are on the sofa and of which material the pillows are made of, *etc*. There are several other factors that affect the process of burning and thus, even if two similar sofas are burned in as similar conditions as possible, the heat release rates will be different. This is true for the items in the room and as a result, the variability of the factors rises to a very significant role. In any serious assessment of fire safety, the uncertainties can not be ignored but they must be acknowledged and even more, the uncertainties must be included into the modelling which leads to probabilistic description of the fire.

In the body of this report, the uncertainties are analysed and quantified with care. In this Appendix, however, we are considering only an example, and thus we can take a shortcut in assessing the uncertainties and assign an uncertainty of ±20 % (minimum and maximum values differ by 20 % of the mean value) to all the heat release rate values given above. Variability of this order of magnitude is a typical one: for example in one study carrier out in New Zealand, the variability corresponding to the 95 % confidence interval (2 × standard deviation) of the maximum value of the heat release rate in a study of burning of upholstered chairs was equal to 20 %.

The size of the opening created by the breakage and fallout of the window of the room-of-fire-origin is not a well-defined quantity: its maximum size coincides with the size of the window pane, but the lower bound of the opening size may vary considerably. In addition, the size of the window varies from one building to another. In this study we assume that the opening height may vary between 1,5–1,9 m (uniform distribution) and the opening width may vary between 2–3 m (uniform distribution). Any ventilation via the door is ignored: this is not a very restrictive assumption done merely for sake of exactness in the fire scenario description.

The influence of a wooden façade to the flame height can be taken into account by adding the contribution of the burning part of the façade to the room fire heat release rate. The magnitude of this added heat release rate can be estimated on the basis of the area of the part of the façade that contributes to the fire and the specific rate of heat released per unit area of the burning wood surface. In this study we assume – as confirmed by experimental observations – that the part of the façade that contributes to the fire is the area between the window of the room-of-the -fire-origin and the window of the apartment above the room-of-the -fire-origin with the width approximately equal to the width of the windows. The specific rate of heat released per unit area of burning wood surface depends, *e.g.*, on the degree of charring and the availability of oxygen. We take as the maximum value of the heat release per unit area the value of 0,12 MW/m^2 observed in steady-state burning of wood in well-ventilated conditions (*e.g.*, in the cone calorimeter). As the minimum value we take 0,05 MW/m^2, which corresponds to burning of wood in poorly ventilated conditions (since the room fire consumes a lot of oxygen, the conditions above the fire room may typically correspond to poorly ventilated conditions).

We consider the following three scenarios differentiated by the shape of the rooms and the combustibility of the façade (wood or not):

1. Non-combustible façade, square room with mean width and depth of the room equal to 4,5 m. Both dimensions varying ±0,5 m around their mean values (uniform distribution).
2. Non-combustible façade, wide room with the mean width of the room equal to 5,5 m and the depth equal to 3,7 m, giving the same area of the room as in scenario 1. Both dimensions vary within ±0,5 m around their mean values (uniform distribution).
3. Combustible façade with fire performance as described above. Room dimensions as in scenario 1.

The calculations of the flame height were carried in the Monte Carlo mode, with the factors varying as described above. The number of Monte Carlo runs was 5000 in each scenario.

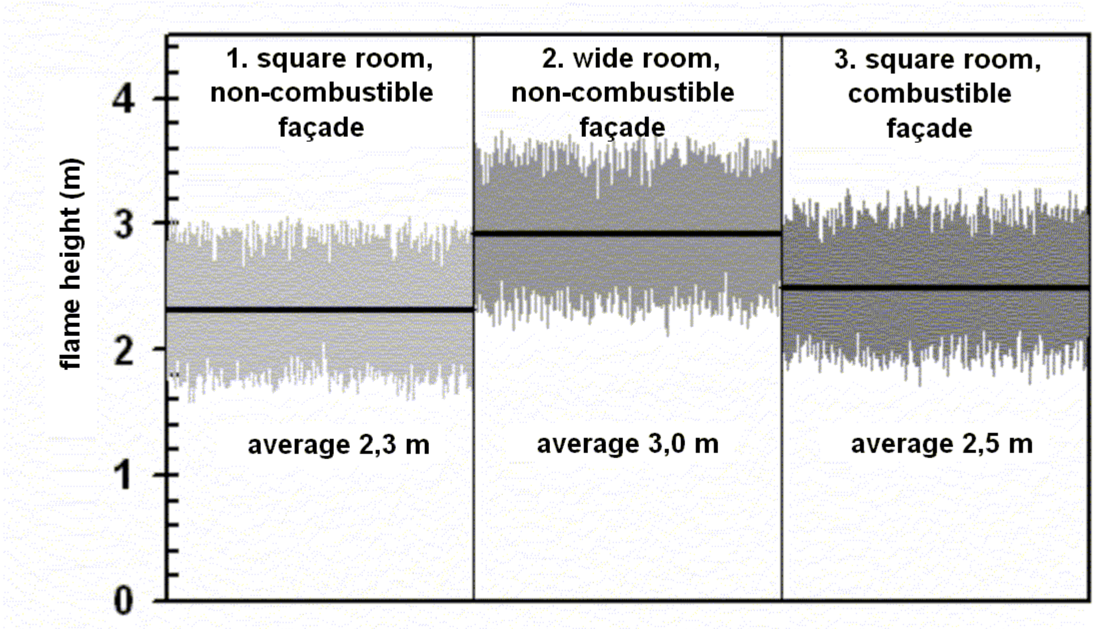


Figure B3. Flame heights in the three different scenarios considered in the Appendix. The shaded areas show the scatter of the values around the mean value (denoted with the solid black line).

The calculated flame heights are shown in Figure B3. It is seen that

- the differences in the flame height due to the influence of the wooden façade, *ca*. 0,2 m, are very small as compared to the mean flame height of about 2,5 m.
- the internal scatter of the flame heights within each scenario is about 0,6 m (2 × standard deviation), which is considerably larger than the difference in the flame heights induced by the wooden façade, *i.e*., *ca*. 0,2 m.
- a small change in the room geometry (with the room area being kept the same) causes a much larger change in the flame height than replacement of non-combustible facade material with wood.

Also the quality and quantity as well as configuration of the fire load inside the fire room have a significant influence on the external flame size. This feature is not modelled in this example, because with dimensions of the opening and the room used in this example, the fire is ventilation controlled and in this case the flame height prediction of the Law model does not include the properties or amount of the fire load in the room. The quality of the fire load has a paramount influence on the size of the external flames in particular if the fire load consists of materials that melt and form pools of burning material as then a significant portion of the pyrolysed gases can burn outside the fire room where there is oxygen available. With cellulosic materials the phenomenon is not as pronounced, because the oxygen needed in charring limits the production of pyrolysates. However, also in this case, the combustibility and configuration of the fire load has a significant influence on the heat release rate and the size of the external flames. As the results Harmathy[16] show, the variability involved can be of the order of a factor of two as compared to the average size of the external flames (with the heat release rate calculated, *e.g*., using the Law model) .

Summary

The increment of the external flame height due to the wooden façade is small as compared to both the mean flame height and the differences related to variability in fire scenarios. Thus, with respect to height of external flames in the case of a flashed-over room fire, the replacement of a non-combustible façade by a wooden façade does not cause any significant increase in the fire risks.

In this respect, the regulations that limit the combustibility of the façade material but do not in any way regulate the amount and/or combustibility of the fire load inside the apartments provide a typical example of technical regulations that have evolved through historical development: while some details, the influence of which to the risks may be relatively small may be regulated in a strict manner, some other aspects of relatively high importance may fall beyond the scope of the regulations. We emphasise that this is not to be understood as a contemptuous allegation that the law is faulty; what we want to bring forward is just a suggestion that the regulations should be regarded as a continuously evolving system which should adapt new information as it becomes available. In fire safety engineering, the risk-based approaches such as employed in this report provide a means to amend the details in the regulations that are not in balance with respect to their impact to the fire risks.

[16] Harmathy, T.Z. Some Overlooked Aspects of the Severity of Compartment Fires. Fire Safety Journal, 1980/81, Vol. 3, p. 261–271.

Appendix C: Attestation of the validity of the model used for the external fire spread

The model for the external fire spread is a combination of the Law model [CEN 2002] characterising the external flames and the model of Back *et al*. [1994], which gives the heat flux impinging to the façade. In this Appendix we show the validity of the model by comparing results obtained with the model to experimental data and observations. The first attestation of validity involves comparison of calculated heat flux values with data measured by Oleszkiewicz [1990]. The second attestation of model validity concerns *a priori* modelling of the of the full-scale wooden façade fire experiments carried out in October 2003 in Merkers near Leipzig in Germany [Schild *et al*. 2004]. In this case we compare the observations made during the experiment to the predictions of the events made by our model. In addition we compare the results of the fire CFD model FDS3 which was used as an auxiliary tool in our modelling to the Merkers full-scale experiments. Also the FDS3 results were calculated *before* the experiments.

Comparison with data of Oleszkiewicz

Figure C1 compares the heat flux values measured above the fire room window [Oleszkiewicz 1990] to the values calculated by using our model. In the experiments, the heat release rate in the fire room was varied by altering the flow rate of the fuel to the gas burner and heat flux values were measured at several heights above the window. For low rates of heat release, the calculated heat fluxes just above the window are considerably higher than the measured ones, because in these cases there were no visible flames projecting out of the window.

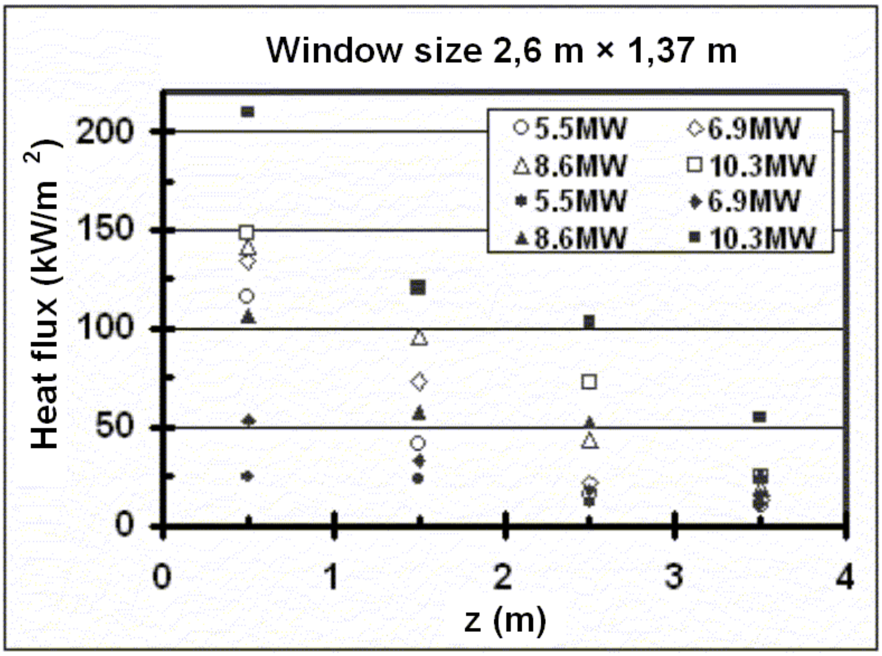


Figure C1. Heat flux to façade from to external flaming. The filled markers denote data of Oleszkiewicz [1990] and the empty markers denote results calculated using our model. It should be noted that with rates of heat release, the air flowing into the fire room was sufficient to burn out all the fuel and hence in these cases there were no visible flames outside the window.

Comparison to the observation made in the full-scale wooden façade fire experiment in Merkers, Germany, October 2003

Description of the experiments

Several full-scale wooden façade fire experiments were carried in Merkers near Leipzig in Germany towards the end of year 2003 [Schild *et al.* 2004]. The 4-storey, 14,5 m high building dating back to the days of the East-Germany was 40 m long and 10 m wide.

We consider the fire experiment carried out on 17th October 2003 in which two adjacent rooms were used as the fire source. The bigger room was 3,45 m wide, 4,2 m deep and 2,55 m high and the dimensions of the smaller room were 2,25 m × 4,2 m × 2,55 m. There was one window in each room with height of 1,25 m and width of 1,55 m in the bigger room and 1,0 m in the smaller room. The windows had two 4 mm thick glass panes separated by a distance of 1 cm attached to the same frame. The doors of the rooms were closed, but there were holes with blowers in the lower parts of the rooms that could be operated to force additional ventilation to the fires. The fire load density in the rooms was *ca*. 600–700 MJ/m^2. It consisted of cubic-shaped wooden cribs with 50 % void fraction made of sticks with dimensions of 40 mm × 40 mm × 1000 mm. In addition to the wooden cribs, there were two shallow pools of dimensions of 0,3 m × 0,6 m filled with isopropanol which acted as the primary ignition source. The windows of the fire rooms were removed before the experiment. At the beginning of the experiment, the windows of the other apartments were intact and there were cotton curtains 10 cm from the inner window pane to act as indicators of potential fire spread to these apartments.

The 13,7 m high façade had a cladding made of spruce-boards installed onto the old concrete façade. There was an air gap between the wooden cladding and the old façade (batten under the spruce-board panelling).

Comparison of FDS3 results with the observations in the Merkers experiments

For the FDS3 simulations of the Merkers experiments, the FDS3 model parameters determining the burning characteristics of the wooden façade were calibrated using data from fire experiments with wooden façades carried out at VTT [Hakkarainen *et al.* 1996, Kokkala *et al*. 1997, Hakkarainen *et al*. 1997, Hakkarainen & Oksanen 2002]. The quantity used in the calibration process was the speed of upward propagation of the flame front on a wooden wall, see Figure C2. With realistic input parameter values the FDS3 calculation gives an upward flame-spread speed of *ca*. 30 cm/min, which is in good agreement with the flame propagation rates observed in the experiments.

The FDS3 parameters were fixed to the values obtained in the calibration process and thereafter, the FDS3 was used to *predict* the development of the Merkers experiments. Comparisons between the calculations and the observations are shown in Figures C3, C4 and C5. The correspondence between the calculations and the observations is good. The apparent difference in the results in Fig. C5 is likely to be due to the differences in the amount of the fire load in the simulations and in real case. In the experiments, the fire did not spread above the second storey window that was located above the smaller room probably because to the fire load was exhausted. The FDS3 simulation predicts fire spread above the second storey window above the smaller room at about 20 minutes after the ignition, but this takes place because in the simulations there was enough fire load to sustain the fire up to 20 minutes.

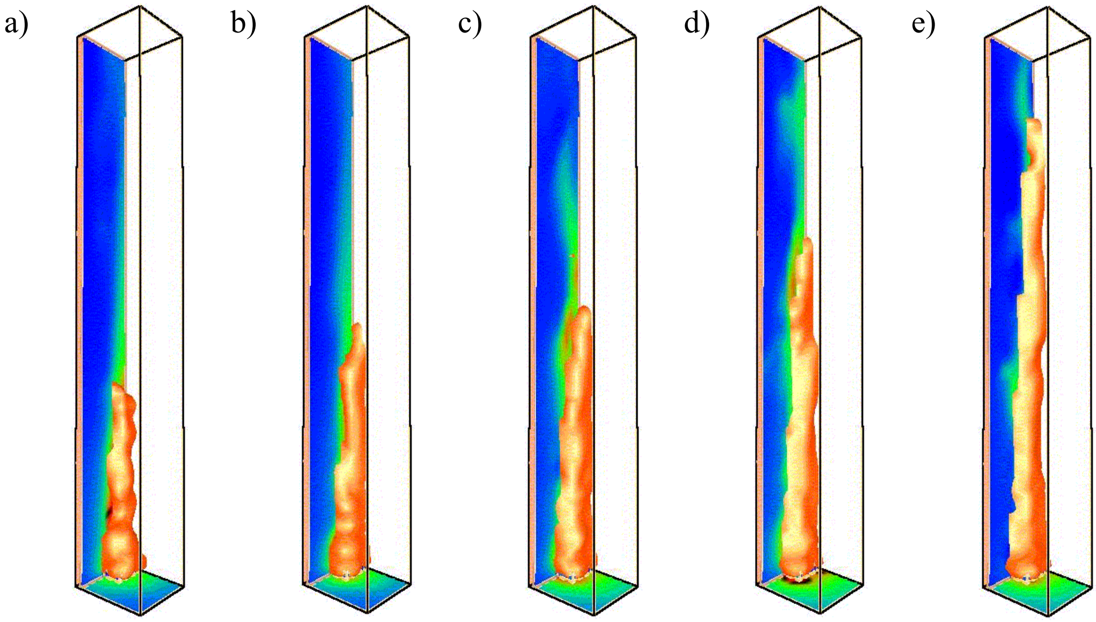


Figure C2. Calibration of the FDS model: flame front position on a wooden wall at a) 0,5 min, b) 2 min, c) 6 min, d) 12 min and e) 20 min. Analysis of the results gives an upward fire spread rate of ca. 30 cm/min, which is in good agreement with the observed values: e.g., Kokkala et al. [1997] observed flame front propagation speed of about 20–30 cm/min (300 kW burner, wall height ca. 8 m).

Figure C3. The smaller room: visual comparison of the flames observed in an early phase of the experiment (time from ignition less than 6 min) and the corresponding prediction of the FDS3 calculations.

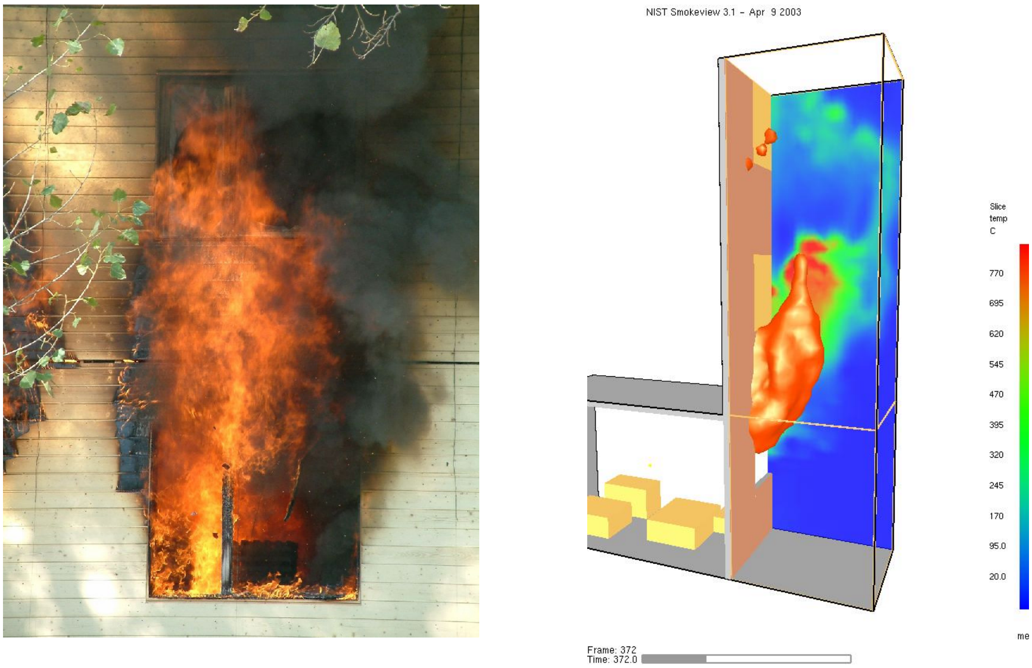


Figure C4. The larger room: visual comparison of the flames observed in an early phase of the experiment (time from ignition less than 6 min) and the corresponding prediction of the FDS3 calculations.

Figure C5. The smaller at about 20 minutes: due to the higher fire load in the simulations allowing external flaming up to and beyond 20 minutes, in the simulations there is fire spread above the second storey window, but in the experiments the fire load was exhausted before this.

Comparison of the results of the combined Law-Back model with the observations in the Merkers experiments

The Merkers full-scale experiment carried out on 17th October 2003 was modelled also using model described in Section 3.3, *i.e.*, the model established by combining the Law model [CEN 2002] for the external flame size and the model of Back *et al*. [1994]. for the heat flux to the surface exposed to the external flaming with the influence of the contribution to the fire of the façade incorporated in to the model via increased heat release rate (the average value of the specific heat release rate per unit area of the burning wooden façade was 90 kW/m^2).

It should be noted that the model results shown here are true predictions because they were carried out *before* the experiment.

The model predictions are compared to the observations made during the experiments in Tables C1 and C2. Bearing in mind the true predictive nature of the calculations, the agreement between the model results and the observations is excellent. One deviation is the predicted time of breakage of the inner pane of the window above the larger fire room: in the experiment both the inner and the outer pane broke simultaneously while the model predicts a delay between the breakages. However, this deviation is likely to be associated with the way that windows were built, *i.e.*, that first, the inner and the outer pane were attached to the same frame and secondly, that the window panes were very close to each other. In such an arrangement, the breakage of the outer pane may induce a breakage of the inner pane even though the inner pane has not heated up notably. The reports of the other experiments carried out at Merkers should shed some more light to this issue as they reveal repeated information on the performance of the windows of that particular building when exposed to external heating of flames.

In the assessment of the accuracy of the predictions it should borne in mind that glass breakage and fallout due to a fire exposure is very random process, which depends on several factors, *e.g.*, how the glass panes have been attached to the frame and whether there are small fissures originating from the manufacturing process in the glass edges.

Table C1. The smaller room: progress of the fire in the full-scale experiments carried out in Merkers, Germany 17th October 2003 and the corresponding predictions of the combined Law-Back model.

Event/factor	**Model prediction**	**Observation**
Flame height	2,1 m, *i.e.*, the flame reaches up to the half height of the window in the 2nd storey	The maximum flame height varied from the bottom to upper edge of the window in the 2nd storey (*ca.* 1,4–2,8 m).
Ignition of curtain through windows	Heat radiation that penetrates the window is not strong enough to ignite the curtains.	The curtains above the small room did not ignite.
Breakage of windows in the 2nd storey	3–6 minutes after the flames have come out of the fire room window (the outer pane after *ca.* 3 min and the inner pane after *ca.*6 min)	The outer window broke *ca*. 5 minutes after the flames have come out of the fire room window. The inner pane broke at ca. 6 minutes after the outer breaking of the outer pane. (*i.e.*, 11 min after the flames have come out of the fire room window).
Breakage of windows in the 3rd storey	The outer pane will break about 10 minutes after the flames have come out of the fire room window and the inner pane at least 7 min after the outer pane breakage.	The window in the 3rd storey did not break. It should be noted, however, that the fire ceased to spread upwards at about 12,5 minutes after the flames have come out of the fire room window.

Table C2. The larger room: progress of the fire in the full-scale experiments carried out in Merkers, Germany 17th October 2003 and the corresponding predictions of the combined Law-Back model.

Event/factor	Model prediction	Observation
Flame height	2,6 m, *i.e.*, the flame reaches almost up to the level of the upper edge of the window of the 2nd storey.	The maximum flame height varied from the halfway of the 2nd-storey window to some distance above the upper frame of the 2nd-storey window (*ca*. 2,1–2,8 m).
Ignition of curtain through windows	Heat radiation that penetrates the window may be only just strong enough to ignite the curtains, but the windows will break rapidly and the curtains will ignite because of the window breakage.	The window of the 2nd storey broke about 4 minutes after the flames have come out of the fire room window and this lead to ignition of the curtains.
Breakage of windows in the 2nd storey	3–6 minutes after the flames have come out of the fire room window so that the outer pane breaks at about 3 min and the outer pane at least 6 min after the outer pane.	The outer pane of the 2nd-storey window broke about 4 minutes after the flames have come out of the fire room window. The inner pane broke at the same time, which is probably due to the fact that the inner and outer window panes were attached to the same frame.
Breakage of windows in the 3rd storey	The outer pane will break about 7,5 minutes after the flames have come out of the fire room window and the inner pane at least 6 min after the outer pane breakage.	The outer pane broke about 8 min after the flames have come out of the fire room window and the inner pane only a short while later. The reason of the rapid breaking of the inner pane was probably related to the window structure (see above).
Breakage of windows in the 4th storey	The outer pane may shatter about 15 minutes after the flames have come out of the fire room window (provided that the fire spreads up the wall).	At end of the experiment there was a piece missing of the 4th-storey window.

Summary

The material provided in this Appendix shows that the models used in this report are valid and reproduce the real fire behaviour with sufficient accuracy, especially when compared to the large inherent uncertainties involved in the fire incidents. The model validation given in this Appendix does not include the fire services operations, which however is the most important factor in the risk-based approach used in this report. This is an intentional choice, because firstly, the statistical distributions of the Finnish fire services response times have been firmly established by Tillander & Keski-Rahkonen [2000a, 2000b] and secondly, this factor is independent of the façade material and hence does not affect the comparison of the risks related to a combustible and a non-combustible façade. Also other factors, such as the shapes of the rooms-of-fire-origin or the windows or model uncertainties, *etc*., do not have significant influence on the relative risks as shown in Chapter 5. This applies also to the perception time of the fire, which may change the absolute risk levels but not the relative risks. In any case, it should be borne in mind that we do not model the frequency of the occurrence of external fires but that information is derived from the fire statistics.

References of Appendix C

Back, G., Beyler, C.L., DiNenno, P. & Tatem, P. 1994. Wall Incident Heat Flux Distributions Resulting from an Adjacent Fire. In: Kashiwagi, T. (ed.). Fire Safety Science – Proceedings of the Fourth International Symposium. Ottawa, Canada, July 13–17, 1994. Boston, USA: International Association for Fire Safety Science. Pp. 241–252.

CEN 2002. Eurocode 1: Actions on Structures – Part 1–2: General Actions – Actions on structures exposed to fire. Brussels: CEN. (EN 1991-1-2:2002 E.). 59 p.

Hakkarainen, T., Oksanen, T. & Mikkola, E. 1996. Puujulkisivujen paloturvallisuus sprinklatuissa kerrostaloissa [Fire safety of wooden façades in sprinklered multi-storey buildings]. Espoo: VTT Tiedotteita 1736. 29 p. + app. 16 p. ISBN 951-38-4892-2. (In Finnish)

Hakkarainen, T., Oksanen, T. & Mikkola, E. 1997. Fire behaviour of façades in multi-storey wood-framed houses. Espoo: VTT Research Notes 1823. 42 p. + app. 16 p. ISBN 951-38-5098-6.

Hakkarainen, T. & Oksanen, T. 2002. Fire Safety Assessment of Wooden Façades. Fire and Materials, Vol. 26, No 1, p. 7–27.

Kokkala, M., Mikkola, E., Immonen, M., Juutilainen, H., Manner, P. & Parker, W.J. 1997. Large-scale upward flame spread tests on wood products. Espoo: VTT Research Notes 1834. 29 p. + app. 116 p. ISBN 951-38-5114-1.

Oleszkiewicz, I. 1990, Fire Exposure to Exterior Walls and Flame Spread on Combustible Cladding. Fire Technology, Vol. 26, pp. 357–375.

Schild, D., Wiederkehr, R. & Bart, B. 2004. Optimisation of wooden façades for fire restistance. In: Proceedings of International Symposium on Advanced Timber and Timber-Composite Elements for Buildings. 27–29 October 2004, Firenze, Italy. Firenze, Italy: COST Action E29: Innovative Timber & Composite Elements for Buildings. 11 p.

Tillander, K. & Keski-Rahkonen, O. 2000a. Palokunnan saatavuuden merkitys rakennuksen paloriskitarkastelussa [The influence of fire department intervention in a building fire risk analysis]. Espoo: VTT Tiedotteita 2013. 200 p. + app. 55 p. 951-38-5634-8; 951-38-5635-6. http://www.vtt.fi/inf/pdf/tiedotteet/2000/T2013.pdf (In Finnish)

Tillander, K. & Keski-Rahkonen, O 2000b. The influence of fire department intervention to the fire safety of a building assessed using fire risk analysis. In: Almand, K.H. (ed.). Proceedings of the 3rd International Conference on Performance-Based Codes and Fire Safety Design Methods. Lund, Sweden, 15–17 June 2000. Lund: Lund University. Pp. 247–256. ISBN 1-58716-018-8.

VTT WORKING PAPERS

VTT RAKENNUS- JA YHDYSKUNTATEKNIIKKA –
VTT BYGG OCH TRANSPORT – VTT BUILDING AND TRANSPORT

4 Hietaniemi, Jukka, Hostikka, Simo & Vaari, Jukka. FDS simulation of fire spread – comparison of model results with experimental data. 2004. 46 p. + app. 6 p.

6 Viitanen, Hannu. Betonin ja siihen liittyvien materiaalien homehtumisen kriittiset olosuhteet - betonin homeenkesto. 2004. 25 s.

7 Gerlander, Riitta & Koivu, Tapio. Asiantuntijapalvelu yritysten innovaatiojohtamisen kehittämiseksi Piilaakson osaamiseen tukeutuen. IMIT SV –hankkeen loppuraportti. 2004. 25 s. + liitt. 11 s.

11 Lakka, Antti. Rakennustyömaan tuottavuus. 2004. 26 s. + liitt. 15 s.

14 Koivu, Tapio, Tukiainen, Sampo, Nummelin, Johanna, Atkin, Brian & Tainio, Risto. Institutional complexity affecting the outcomes of global projects. 2004. 59 p. + app. 2 p.

15 Rönty, Vesa, Keski-Rahkonen, Olavi & Hassinen, Jukka-Pekka. Reliability of sprinkler systems. Exploration and analysis of data from nuclear and non-nuclear installations. 2004. 89 p. + app. 9 p.

18 Nyyssönen, Teemu, Rajakko, Jaana & Keski-Rahkonen, Olavi. On the reliability of fire detection and alarm systems. Exploration and analysis of data from nuclear and non-nuclear installations. 2005. 62 p. + app. 6 p.

19 Tillander, Kati, Korhonen, Timo & Keski-Rahkonen, Olavi. Pelastustoimen määräiset seurantamittarit. 2005. 123 s. + liitt. 5 s.

20 Simo Hostikka & Johan Mangs. MASIFIRE – Map Based Simulation of Fires in Forest-Urban Interface. Reference and user's guide for version 1.0. 2005. 52 p. + app. 2 p.

21 Kortesmaa, Markku & Kevarinmäki, Ari. Massiivipuu maatilarakentamisessa. Suunnitteluohje. 2005. 76 s. + liitt. 6 s.

22 Ojanen, Tuomo & Ahonen, Jarkko. Moisture performance properties of exterior sheathing products made of spruce plywood or OSB. 2005. 52 p. + app. 12 p.

27 Kevarinmäki, Ari. Konenaulojen ulosvetolujuus. 2005. 24 s. + liitt. 12 s.

31 Hietaniemi, Jukka. A Probabilistic Approach to Wood Charring Rate. 2005. 53 p.

32 Korhonen, Timo & Hietaniemi, Jukka. Fire Safety of Wooden Façades in Residential Suburb Multi-Storey Buildings. 2005. 66 p. + app. 40 p.

ISBN 951–38–6585–1 (URL: http://www.vtt.fi/inf/pdf/)
ISSN 1459–7683 (URL: http://www.vtt.fi/inf/pdf/)