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Abstract: This report contains several case studies where trade-offs have been made between prescriptive code requirements and the installation of fire sprinklers. The case studies cover design situations as use of combustible wall and façade materials, extended travel distance to exits, reduced requirements on fire ratings as well as the combination of trade-offs. The report uses verifications methods presented in previous research initiatives and evaluates their applicability to common fire safety design situations.

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Preface

This report has been prepared within a Swedish project on fire safety design with sprinklers. The report is financed by the following organisations:

- SBUF, Development Fund of the Swedish Construction Industry
- Sprinklerfrämjandet, Swedish Sprinkler Association

This work is closely linked to a Nordic project on fire safety design in sprinklered buildings coordinated by SP Technical Research Institute of Sweden through Birgit Östman. Earlier results are reported in Verifying Fire Safety Design in Sprinklered Buildings, Report 3150, LTH 2011. The Nordic project will also result in a Nordic Technical Specification with the working title Fire Safety Engineering – Verification of fire safety design in buildings.

Representatives from the Nordic project have been able to provide comments. The support from all persons and organisations involved are gratefully acknowledged.

Summary

This report is a product by a Nordic research initiative with the objective of presenting thoroughly worked out case studies on the application of the verifications methods presented in past research initiatives on the subject. It is known that fire sprinklers add several benefits to a building as the system has a high probability of extinguishing or controlling the fire. Statistics states that the system is able to operate effectively in 90-95 % of all fires large enough to serve a potential threat to the building and its occupants. However, little information and guidance have been available to be used when verifying trade-offs between prescriptive code requirements and the optional installation of fire sprinklers in a building.

The report contains several cases studies where newly developed the verification method are applied to common design situations. Three different verification methods are used; qualitative risk assessment, quantitative assessment with deterministic analysis and quantitative assessment with probabilistic analysis. The selection of verification method is a part of the fire safety design process and it is dependent on the complexity of the trial design, as well as the extent of the deviation from the prescriptive requirements. The report covers four design situations; the use of combustible linings in an apartment building, extended travel distance to exits in a retail store, reduced fire rating on windows in an office building and combustible façade materials in an apartment building. The specific requirements and needs of verification when combining these trade-offs is addressed specifically.

It is shown that fire sprinklers most likely will extinguish or control the fire, despite the use of combustible wall linings. However, in order for the system to be effective linings with at least a Euroclass D rating must be used. The mandatory requirement on smoke detectors will facilitate successful escape when sprinklers are ineffective. Sprinklers could also allow for extended travel distance to exits as the system increases the available safe egress time. The presence of fire sprinklers will result in far less probability of fire spread to another apartment, compared to a building without fire sprinklers, despite the prescience of e.g. combustible façade material or windows with EI 30 rating (compared to EI 60). But, some concerns on air gaps in combustible facades, external fires and radiative heat transfer are presented that need to be addressed

Buildings without fire sprinklers must rely on other measures/action in order to prevent fire spread. The fire service has a very important role in the safety of non-sprinklered buildings. If the response of the fire service is not considered, sprinklered buildings will generally have up to 25 times less risk of fire become large and threatening occupants as well as the building. Thus, the dependence on the fire service to fulfil important technical requirement on fire safety is far less in a building with sprinklers compared to a non-sprinklered building.

Sammanfattning (In Swedish)

Delar av denna rapport är utgiven på svenska via SP Trätek. Rapporten har titeln "Tekniska byten i sprinklade byggnader – Fallstudier" (SP-rapport 2012:33). För information om projektet på svenska hänvisas till SP-rapport 2012:33.

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1 Introduction

1.1 Background

A Nordic research initiative on fire safety design in buildings with sprinklers were finalised in 2011 and documented in Nystedt (2011). That project had the objective of exploring different fire safety design methods and to give guidance on how to choose a relevant method for a given situation. The work was focused on verifying design alternatives in buildings with fire sprinkler systems aiming at developing a more consequent and uniform performance-based design process, which is a result of a specification of methods, performance criteria and design scenarios.

The report also contained a few brief examples of applications. However, these examples did not provide any deep understanding of the required steps necessary to verify fire safety in buildings. The lack of detailed examples urged the need for an additional initiative on case studies where both practitioners and officials could find information on the use of the proposed verification methods for a number of design situations.

1.2 Aim and objectives

The aim of this report is to provide thoroughly worked out case studies on the application of the methods described by Nystedt (2011). The primary objective is to raise the knowledge of engineering community on the task of verification of fire safety in buildings, with emphasis on design alternatives in building with fire sprinklers. A secondary objective is to use the case studies to evaluate the methods introduced by Nystedt (2011) and give guidance on further developments in the field of fire safety engineering.

1.3 Method

The report uses the following methods (Nystedt, 2011) to verify fire safety in five different design situations (case studies):

- Qualitative risk assessment
- Quantitative assessment with deterministic analysis
- Quantitative assessment with probabilistic analysis

The design situations that are represented in the case studies are:

1. Combustible linings in an apartment building (chapter 4)
2. Extended travel distance to exits in a retail store (chapter 5)
3. Reduced fire rating on windows in an office building (chapter 6)
4. Combustible façade materials in an apartment building (chapter 7)
5. Combining trade-offs in an office building (chapter 8)

The verification of the particular design situation in each case study is carried out by following the procedure described by Nystedt (2011).

An initial qualitative design review (QDR) is carried out in order to establish building and occupant characteristics, fire hazards, trial fire safety design, selection of design method as well as verification prerequisites. The QDR identifies the appropriate verification needs and a suitable verification method, which will be applied in order to evaluate the trial fire safety design.

1.4 General limitations

The case studies presented in chapter 4 to 8 should be considered as fictitious. The do however use real data appropriate to the particular design situation. Users that are interested in applying the case studies to their own projects could use data and methods as inspiration and guidance. The users must, however, verify that the data is applicable to his/her design situation.

The case studies are specific to a certain building, e.g. "combustible linings in an apartment building" and "reduced fire rating on windows in an office building". However, the design scenarios could be applied to other buildings as well by adopting them and using appropriate input data.

Note that the intended use of this report is to provide verified case studies in buildings where sprinkler systems are used as a key fire safety feature of the building. The case studies in this report are all related to design situations where comparative criteria could be used when evaluating fire safety. Thus, only buildings where prescriptive solutions could be applied are covered by methods and findings this report.

It is the responsible of the designer to design a sprinkler system that can cope with the potential fires in the building. In many cases, the basic need of water discharge meets the requirements. But the designer needs to consider if there are fire scenarios that require either a larger water source or higher discharge rate.

2 The fire safety design process

A number of publications, e.g. NKB (1994), BSI BS 7974 (2001), SFPE (2007) and CAENZ (2008), provide information on the fire safety design process. However, these guides focus on design using fire engineering principles (i.e. an analytical approach) and there is a need for an overall description of the design process showing the relationship between the prescriptive and the analytical design approach, as proposed and outlined in Figure 2.1 below.

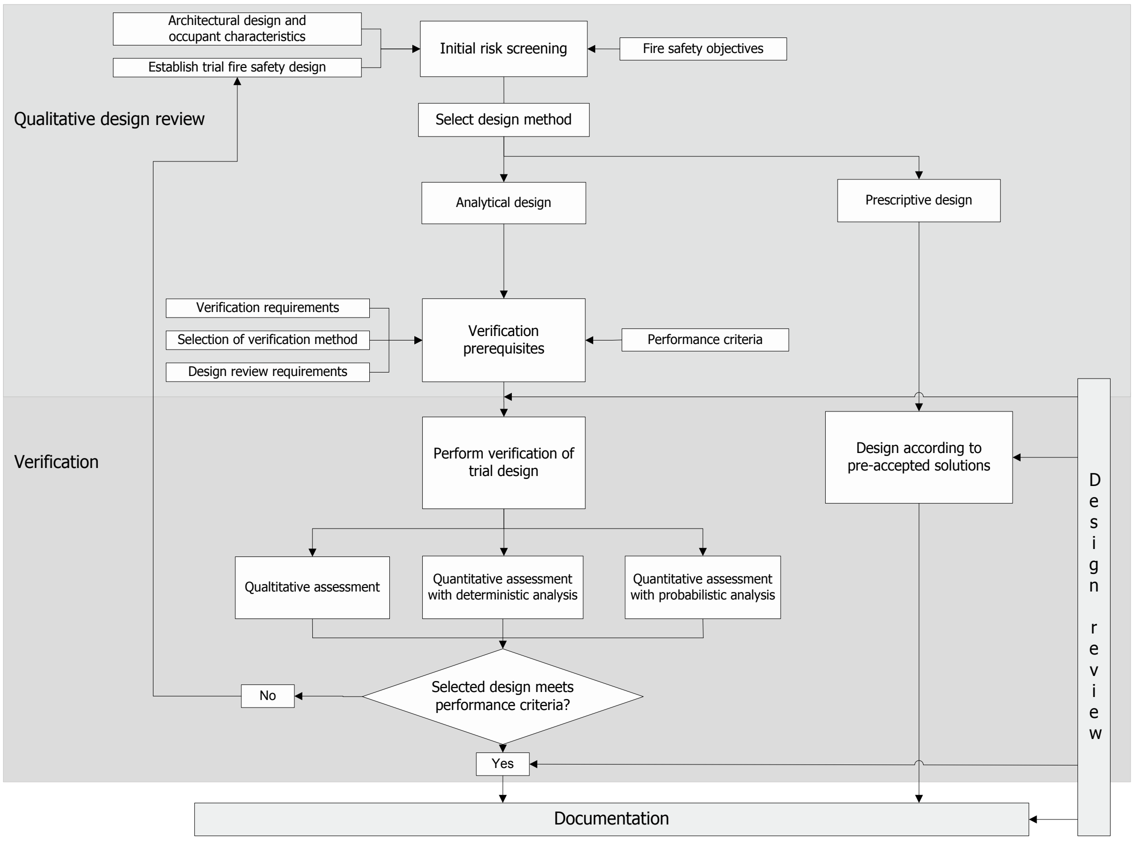

Figure 2.1 Proposed fire safety design process.

The design process in Figure 2.1 is discussed in more detail in the sub-sections below with emphasis on the qualitative design review, verification, design review and documentation.

2.1 Qualitative design review

The fire safety design process starts with the qualitative design review and the initial risk screening which should be conducted no matter which principal design method (prescriptive or analytical) that is selected at a later stage. The initial risk screening could vary in extent depending on the complexity of the building and its intended use as well as on the proposed deviations from prescriptive design.

The initial risk screening is conducted by collecting relevant information on e.g. architectural design and occupant characteristics, as well as on specific fire hazards. The following list could be used in the qualitative design review and additional information could be found in BS 7974 (BSI, 2001):

- Architectural design
  - Size, type of construction, number of floors, etc.
  - Available escape routes
  - Fire service response time and accessibility
  - Distance to neighbouring property
- Occupants
  - Number and distribution
  - Mobility and state of wakefulness
  - Familiarity with the building
- Fire hazards
  - Flammable liquids storage
  - Combustible building materials
  - Potential sources of ignition
- Other factors
  - Planning constraints (e.g. listed building of historical interest)
  - Future changes of layout or that may be anticipated
  - Climate factors as snow, wind, rain and extreme temperatures

The selection of principal design method could not take place until the architectural design and the occupant characteristics have been reviewed and a trial design solution has been established. The trial design should involve fire safety features from all relevant major barrier groups and most commonly the trial design is a combination of prescriptive solutions and measures designed analytically, as shown in Table 2.1.

Table 2.1 Example of a trial design solution.

Barrier	Measure	Requirements
Prevent ignition	Insulation of smoke exhausts	Prescriptive design
	Furniture clothing	Relevant standard
Control fire growth	Incombustible surface finishes	Prescriptive design
Control smoke spread	Smoke management system	Analytical design

Table 2.1 Example of a trial design solution. (cont.)

Barrier	Measure	Requirements
Limit fire spread within building	Fire compartmentation	Prescriptive design
Prevent fire spread to other buildings	Separation between buildings	Prescriptive design
Means of escape	Several independent escape routes	Analytical design
	Alarm and notification system	Prescriptive design
	Smoke control	Analytical design
Facilitate rescue service operations	Stand pipes	Prescriptive design
	Fire fighting lift	Analytical design
Prevent structural collapse	Structural steel protected by intumescing paint	Prescriptive design

If a pure prescriptive design solution is selected, the design process is finalized by describing relevant requirements and solutions in the design documentation. However, if there is a need for (or demand of) an analytical approach, the design process continues by establishing fire scenarios and the prerequisites for verification. This work consists of an evaluation of the verification requirements, the selection of verification method and the requirements on design review. The selection of measures to be included in the trial design should be made with a basis in the prescribed design solution, in order to make sure that all necessary aspects on fire safety are being addressed.

2.2 Available design methods

As mentioned in the previous section and shown in Figure 2.1, two principal methods are available when designing fire safety in a building:

- Prescriptive design
- Analytical design

Prescriptive design use general recommendations and approved documents to establish the fire safety design. The design method does not allow for deviations from these recommendations and documents, and the need for verification is limited. The designer must ensure that the proposed building and its intended use fits in the regulatory system for prescriptive design by considering architectural design, occupant characteristics and relevant fire safety objectives.

Prescriptive design often has its origin in previous building regulations. It is practically the same method for design as the one being used previous to the performance-based building regulations. A number of design alternatives are usually allowed within the scope of prescriptive design and these are well described in the general recommendations in the building regulations. E.g. it is possible to extend the maximum travel distance to an escape route in Swedish buildings equipped with sprinklers by one third, compared to buildings without sprinklers.

If there is a need for deviations from the prescribed solutions, the engineer could employ an analytical design method to show that the proposed design meets all relevant performance criteria. The objective for the designer is now to verify that the building meets the design criteria by the use of other so called verification methods. But the key point is to show that the regulation requirements still are met.

The fire safety features of a building are commonly designed by a mixture of prescribed solutions and those verified by the use of analytical methods. Most often, the design solution resulting from the prescriptive method is used as a starting point. If any of these solutions are too expensive or in conflict with other design objectives then modifications are made to varying degrees. Such modifications are referred to as technical design alternatives, i.e. deviations from the prescriptive solutions. The concept of design alternatives is quite simple. One fire safety feature is added to the building and another is subtracted (or minimized), but the overall safety level remains within what is acceptable, see Figure 2.2. Naturally, an added safety feature must fulfil the same purpose as the removed feature.

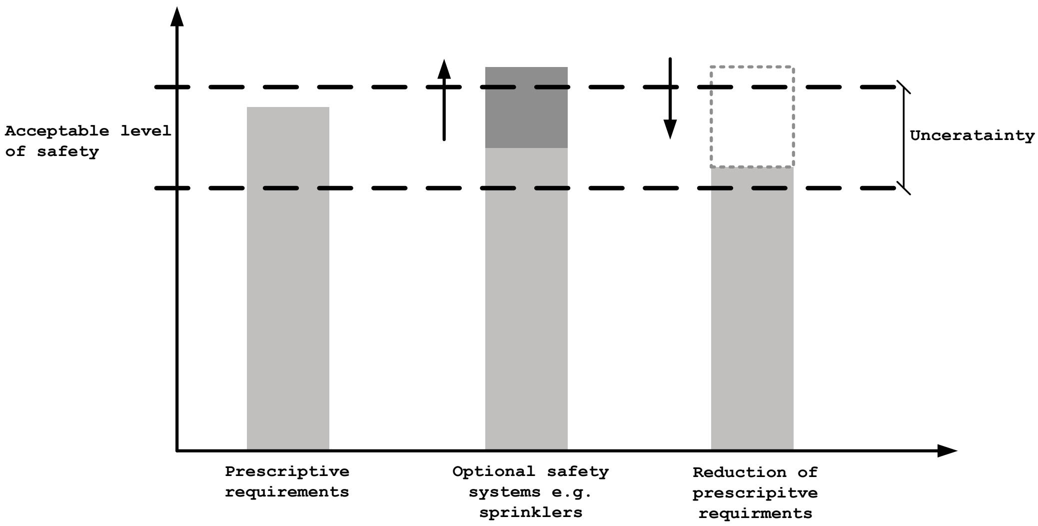

Figure 2.2 Principle of optimisation of fire safety in buildings.

For example, when installing a sprinkler system in a building, design alternatives on other safety measures such as compartmentation, fire ratings on load-bearing structures, exit width etc., could be allowed. However, this requires a verification that that the performance requirements in the regulations are met.

It is necessary to evaluate how the attributes of the proposed fire features relate to the ones resulting of a prescriptive design solution. Such attributes are e.g. function, human action/performance, complexity of the fire safety strategy, complexity of the fire protection system, flexibility, sensitivity, reliability, and vulnerability (Lundin, 2005).

2.3 Verification

There are a number of verification methods available to be used when evaluating a trial design and the selection of method is dependent on which deviations from the prescribed solutions that are proposed. Most of them are based on the use of risk equivalency. Naturally, all relevant performance requirements must be met in order to show sufficient safety and it is the roll of the designer to verify that the proposed design solution has equivalent safety. Nystedt (2011) outlines the following methods:

- Qualitative risk assessment
- Quantitative assessment with deterministic analysis
- Quantitative assessment with probabilistic analysis

The selection of verification method is mainly influenced by the following variables:

- Voluntarily or required[1] use of an analytical approach.
- The number of design alternatives compared to a prescriptive design solution.
- The complexity and robustness of the trial fire safety design solution.

Qualitative risk assessment has limited applicability and could only be used if the deviations from prescriptive design are limited and the performance of the proposed solution is well documented in e.g. test results, research publications and relevant regulations in other countries. Thus, qualitative risk assessments could only be used if:

- The design is uncomplicated, affects few people and prescriptive solutions are mostly used.
- Limited and well understood deviation from prescriptive design, where limited deviation is defined as one or two design alternatives.

All other design situations demand that the engineer presents "evidence" of equivalent safety. Such evidence could consist of testing and various levels of quantitative assessment. These methods could naturally be combined with each other. Therefore, quantitative assessment (either deterministic or probabilistic analysis) should be used if:

[1] In certain buildings a prescriptive approach to the design of fire safety measures is not valid. In Swedish and Norwegian building regulations this is the case for the design of certain high-risk buildings, such as high-rises and extensive underground structures.

- The design of the building is complicated and "new" solutions to comply with the fire safety objectives are chosen.
- Several and/or dependant fire safety measures are affected by design alternatives.
- Proposed design alternatives affect several major barrier groups.

Complicated objects are referred to as buildings which are large and difficult to survey. The trial design is built up be a number of technical systems with unclear function, purpose and interdependence. If "new" measures are adopted the importance of thoroughly verification is great as there is a lack of experience in the operation of these systems. Additional information on these methods is given in Nystedt (2011).

2.4 Design review and documentation

Analytical design has a need for a more extensive design review than prescriptive design. Design review should be carried out throughout the design process and the demands for review should be established at an early stage. The degree of design review depends on the complexity of the proposed solutions and ranges from a simple self-check to the use of an independent third party peer-review.

There is a need to document the verification as the process moves forward a final design solution. The first document to be produced is the so called fire engineering design brief, which could be finalised after the qualitative design review. The second document often referred to as the design documentation includes both the design brief and the complete verification of sufficient safety. In order to ensure an effective design process there is a need for a review of the fire engineering design brief before the verification of the trial design is conducted. A review at this early stage minimises potential surprises (and changes to the design) in a later stage of the process. Usually the requirements on the documentation follow the degree of fire safety design complexity and the choice of verification method.

3 Fire sprinkler systems

This chapter provides information on fire sprinkler systems that is generic to all case studies. Additional information on fire sprinkler systems regarding their design, effectiveness and how they influence the fire development is found in Nystedt (2011).

3.1 Type of fire sprinkler systems

The majority of sprinkler systems are designed to control a fire by cooling fire gases, the fire surface and pre-wetting surrounding material to stop it spreading. The design intent is that the fire is finally extinguished by the fire service or staff using portable equipment. In reality, in many cases, the design intent is exceeded, and the fire is actually extinguished by the sprinkler system.

This report considers two different types of sprinkler systems namely conventional and residential fire sprinkler systems. Conventional sprinklers could be used in various locations such as offices, retail stores, hospitals etc. Residential sprinklers are to be used in family houses, apartment buildings, nursing homes, hotels etc. Conventional fire sprinkler systems are built with a higher degree of robustness than residential fire sprinkler system. These increased requirements on the system are necessary to cope with the diverse fire scenarios that could take place in these buildings. On the other hand, residential fire scenarios are well defined and occur in rooms with smaller geometry.

It is assumed that a sprinkler system designed according to the appropriate standard (e.g. NFPA 13, EN 12845 or NFPA 13R and INSTA 900-1) is suitable to control/suppress a fire in that location. However, most standards on residential fire sprinkler systems (INSTA 900-1 and NFPA 13R) allows for a limited water source, e.g. a duration of 10 or 30 minutes, compared to conventional systems which require a duration of 60 or 90 minutes. If a design alternative includes a trade-off on measures that limits fire spread within and between buildings or prevents structural collapse, the duration of the water source needs to be extended if residential sprinklers are used. The duration should then be comparable with the requirements in EN 12845 using an appropriate hazard classification.

3.2 The characteristics of fire sprinkler system as a fire safety feature

CAENZ (2008) discusses fire safety measures in terms of barriers related to the fire development in a building, i.e., prevent ignition, control fire growth, control smoke spread, limit fire spread within building, prevent fire spread to other buildings, means of escape, facilitate rescue operations and prevent structural collapse. Fire sprinklers are designed to either control or suppress the fire. By doing so, fire sprinklers, fulfil an important task in the building fire safety system, enabling design alternatives from other traditional fire safety measures. Table 3.1 indicates whether fire sprinklers are a suitable safety measure to a specific barrier group or not.

Table 3.1 Evaluation of fire sprinklers as a safety measure for a specific barrier group.

Barrier group	Design alternative with sprinkler possible?
Prevent ignition	No
Control fire growth	Yes
Control smoke spread	Yes
Limit fire spread within building	Yes
Prevent fire spread to other buildings	Yes
Means of escape	No
Facilitate rescue service operations	No
Prevent structural collapse	Yes

Table 3.1 shows that fire sprinklers can be used to allow design alternatives from safety features regarding control fire growth, control smoke spread, limit fire spread within and between buildings and prevent structural collapse. Despite the presence of sprinklers, the building must be designed to have a minimum set of means for escape for the occupants to execute rapid egress. Examples of such measures are sufficient exit width, signage, emergency lightning, notification systems, etc. Fire sprinklers cannot replace such barriers, but they could be used to lower some requirements within the group when balancing the ASET vs. RSET equation.

Fire sprinkler could not replace means necessary to facilitate rescue service operations. Such measures are needed especially in case of sprinkler failure and must be kept at an appropriate level. Note that the measures included in this barrier group are those related to rescue operations within the building. Some countries do allow for design alternatives regarding e.g. reduced fire flow and longer hydrant spacing as well as longer distance from fire stations, narrower streets, fewer parking restrictions, longer cul-de-sacs, reduced turnaround radius, etc.

3.3 The role of fire sprinkler systems in relation to different aspects on fire safety

Lundin (2005) provides extensive information on how address and analyse the influence of a particular fire safety measure (such as fire sprinklers) on the different aspects on fire safety. Two different tools are proposed by Lundin (2005):

1. A tool to analyse the structure of the fire protection system in the building. This is a tool to identify which part of the fire safety strategy is affected by a design alternative. This is done by analysing the structure of the total fire protection system in the building and the impact when the system is changed.

2. A tool to analyse the purpose of the performance requirements. In building legislation and building regulations the purpose must be well understood to ensure that the demands of society in terms of fire safety are fulfilled. If several functional requirements are affected by the design alternative, several analyses may be needed, and different design scenarios and acceptance criteria may be required. This tool is used to establish the various cause-effect relations between each safety measure and the demands in the building regulations.

The first tool focuses on the impact that the proposed changes have on the fire safety strategy, related to a prescriptive solution. Fire sprinkler systems are used to motivate design alternatives on other safety features and it is necessary to show that the added safety system is in a qualitative balance with the subtracted system. The matrix in Figure 3.1 could be used illustrate the effects of design alternatives on the structure of the fire protection system, when a trial design is compared to the prescriptive requirements. Fire sprinklers are designed to either control or extinguish the fire. By doing so fire sprinklers is considered to be an added fire safety measures (A_1) to the barrier groups on "control fire growth", "control smoke spread", "limit fire spread within a building", "prevent fire spread to other buildings" and "prevent structural collapse". No removed measures (R_i) are included in the matrix, but the trade-offs in chapter 4 to 8 should be considered as such.

Purpose of the fire safety measure (linked to the major barrier groups)	**Trade-off**					
	Added measure			Removed measure		
	A_1	A_2	...	R_1	R_2	...
Measures to prevent ignition						
Measures to control fire growht	+					
Measures to control smoke spread	+					
Measures to limit fire spread within a building	+					
Measures to prevent fire spread to other building	+					
Allow rapid egress						
Facilitate rescue service operations						
Prevent structural collapse	+					

Figure 3.1 The effects of fire sprinklers (A_1) on the structure of the fire protection system. The tool is adapted from Lundin (2005) and slightly modified.

The practical use of the matrix in Figure 3.1 is simple as removed measures are denoted with a "-" and added measures are denoted with a "+". The matrix does not provide the designer with quantitative information, however several conclusions can be drawn (Lundin, 2005):

- By regarding the vertical spread in the position of the + and – signs it is easy to determine whether the design alternative affects one or several types of safety measures. If the spread is significant, the original safety measure is likely to have been replaced by another type of risk-reducing measure belonging to a different barrier group. This calls for an extensive analysis, since the structure of the protection system has been modified. It is necessary to check that the new safety measure provides protection for all the safety objectives covered by that removed.
- If there is imbalance between the total number of + and – signs in the vertical direction the numbers of independent barriers, i.e. the defence in depth, is likely to be reduced. The fire protection required by the prescriptive method is generally designed with defence in depth in mind, which results in a combination of measures aimed at the various major barrier groups. A vertical spread in the signs also indicates that it is important to check whether measures with multiple purposes have been removed without adequate compensation.
- If there is imbalance between the total number of + and – signs in the horizontal direction or in the horizontal and vertical directions, great care must be taken. This is an indication that the protection relies on a smaller number of safety measures, and that the risk of common-cause failure has increased. Each single reduction may appear negligible, but together, they can have serious implications on safety.

Another important aspect in identifying verification requirements is that the purpose of the performance requirement affected by the design alternative is well understood, otherwise it is difficult to choose models and criteria that measure the effect on the safety appropriately. The matrix in Figure 3.2 could be used to assist the designer in identifying the impact of the design alternative on the safety goals represented by functional requirements on fire safety. Again, since fire sprinklers are designed to either control or extinguish the fire, they have a positive influence on all functional requirements.

Functional requirements in NKB (1994)	Trade-off					
	Added measure			Removed measure		
	A_1	A_2	...	R_1	R_2	...
The load-bearing capacity of the construction can be assumed for a specific period of time	+					
The generation and spread of fire and smoke within the construction is limited	+					
The spread of fire to neighbouring construction works is limited	+					
People in the construction on fire can leave it or be rescued by other means	+					
The safety of fire and rescue service personnel is taken into consideration	+					

Figure 3.2 Investigation of the effect of fire sprinklers (A_1) on the functional requirements of fire safety. The tool is adapted from Lundin (2005) and slightly modified.

The purpose of the matrix in Figure 3.2 is to investigate whether the added and removed measures have effects on several technical requirements, which is an indication of multiple purposes of a technical requirement. It is of utterly importance to stress that the building regulations do not allow for design alternatives between the different functional requirements. If a "-" sign appears without any "+" sign for a specific technical requirement this must be interpreted as a warning. One possible consequence of the design alternative is that the safety effect of the measure removed has not been adequately compensated for. The designer must ensure that the trial design solution offers a balance regarding the technical requirements, i.e., both + and – signs in the horizontal direction. The verification could then focus on showing that the safety level is sufficient.

There are some attributes of the fire safety system that could not be evaluated in quantitative terms. Lundin (2005) present such a list containing attributes as function, human action/performance, complexity of the fire safety strategy, complexity of the fire protection system, flexibility, sensitivity, reliability, and vulnerability. The designer needs to address these attributes when comparing the trial design with the prescriptive design solution, by answering questions as:

- Is the effectiveness of the added protection system dependent on human action?
- Is the design alternative characterized by the reduction or elimination of several independent safety measures and replaced by a single measure?
- Is the added safety measure dependent on several sub-systems functioning correctly?
- Does the design alternative have the necessary degree of flexibility to cope with possible fires in the building?

- How sensitive is the fire protection to the use of the building, e.g. when sports arenas are used for exhibitions or concerts?
- How will the function of the protection system be affected by time and to what extent are service and maintenance necessary?
- How vulnerable is the added protection system on power failure, cold and windy conditions, software failure, etc?

When the answer is "Yes" to any of the questions above, the designer needs to be careful on provide information on how to ensure e.g. that human action will be effectuated when needed and to which degree there is a need for more flexibility. Additional information on these attributes is found in Lundin (2005).

4 Case study: Combustible linings in an apartment building

This chapter contains a case study where fire sprinklers are used as compensatory measure to allow for combustible linings in an apartment building. The case study could be applied to other buildings as well, but the data and the results presented in this chapter are specific to apartment buildings.

4.1 Qualitative design review

4.1.1 Architectural design and occupant characteristics

The building in the case study is an ordinary apartment building with four storeys. It is built of wood and has three apartments on each floor. The occupants in the building (app. 30-40 people) are expected to be familiar with it and be able to escape by themselves. They are, however, not assumed to be awake at all times. People are able to escape from the building through the main stairwell (placed in its own fire compartment). If the stairwell is blocked by smoke, occupants should remain in their apartments and wait for assistance of the fire service. The fire service has an intervention time that is less than 10 minutes and the shortest distance to neighbouring buildings is app. 15 m.

4.1.2 Fire hazards and other factors

The fire load in dwellings is well established and consistent. It is unlikely that the fire will spread to adjacent fire compartments and those injured by the fire are most commonly in the apartment where the fire started.

All apartments have windows in two directions making a wind-aided projection of flames possible in the event of a fully developed fire. The fire safety features are not sensitive to snow, rain or extreme temperatures.

4.1.3 Trial fire safety design

The trial fire safety design of the building complies mainly with the prescriptive requirements of apartment buildings found in the building code. A residential fire sprinkler system will be installed in the building as a complementary fire safety measure and the design team proposes a deviation from the prescriptive requirements on surface finishes. The code requirement on wall and ceiling linings for apartment buildings is normally Euroclass C, but the architect proposed a use of combustible linings in Euroclass D.

Table 4.1 outlines the main fire safety features of the building.

Table 4.1 Trial design solution for the apartment building.

Barrier	Measure	Requirements
Prevent ignition	Insulation of kitchen extract ducts	Prescriptive design
Control fire growth	Combustible surface finishes (Euroclass D[2])	Analytical design
Control smoke spread	Fire dampers	Prescriptive design
Limit fire spread within building	Fire separating structures (EI 60)	Prescriptive design
	Residential fire sprinkler system[3]	Relevant standard
Prevent fire spread to other buildings	Safety distance to neighbouring building	Prescriptive design
Means of escape	Smoke alarm	Prescriptive design
	Main stairwell	Prescriptive design
	Assistance by fire service from windows	Prescriptive design
Facilitate rescue service operations	Access to building	Prescriptive design
	Smoke vent in stairwell	Prescriptive design
Prevent structural collapse	Structural elements protected by wood-based boards (R 60)	Prescriptive design

4.1.4 Selection of design method

Since the design team proposes a deviation from prescriptive design, there is a need to verify that the trial design offers sufficient safety in case of fire. Analytical design will be used to perform the verification.

4.1.5 Verification prerequisites

The verification requirements are identified by the use of the tools provided by Lundin (2005), see Figure 4.1 and Figure 4.2. Additional information on how to use these tools, including the influence of fire sprinklers on the different aspects on fire safety, is provided in section 3.3.

[2] The prescriptive code requirement is Euroclass C.
[3] The residential fire sprinkler system is a complementary fire safety measures.

Purpose of the fire safety measure (linked to the major barrier groups)	Trade-off					
	Added measure			Removed measure		
	A_1	A_2	...	R_1	R_2	...
Measures to prevent ignition						
Measures to control fire growht	+			-		
Measures to control smoke spread	+					
Measures to limit fire spread within a building	+					
Measures to prevent fire spread to other building	+					
Allow rapid egress						
Facilitate rescue service operations						
Prevent structural collapse	+					

Figure 4.1 Identification of the effects of the trial design in comparison with the prescriptive code requirements. Note that A_1 is the residential fire sprinkler system and R_1 is linings in Euroclass D.

A short evaluation of Figure 4.1 states that there is imbalance in "added" and "removed" measures and the positive side as fire sprinklers is a multifunctional measure that influences several barrier groups in a positive way. There is a balance in the number of measures "added" and "removed", which makes the task of verification easier.

Functional requirements in NKB (1994)	Trade-off					
	Added measure			Removed measure		
	A_1	A_2	...	R_1	R_2	...
The load-bearing capacity of the construction can be assumed for a specific period of time	+					
The generation and spread of fire and smoke within the construction is limited	+			-		
The spread of fire to neighbouring construction works is limited	+					
People in the construction on fire can leave it or be rescued by other means	+					
The safety of fire and rescue service personnel is taken into consideration	+					

Figure 4.2 Investigation on the effect of the added and removed fire safety measures on the functional requirements. Note that A_1 is the residential fire sprinkler system and R_1 is linings in Euroclass D.

Figure 4.2 indicates that there is a balance among the added and removed safety features. No safety features has been removed that hasn't been compensated for. To conclude, a check list on different attributes of the fire safety system is presented.

Table 4.2 Evaluation of attributes of the fire safety system.

Attribute	Answer
Is the effectiveness of the added protection system dependent on human action?	No
Is the design alternative characterized by the reduction or elimination of several independent safety measures and replaced by a single measure?	No
Is the added safety measure dependent on several sub-systems functioning correctly?	No
Does the design alternative have the necessary degree of flexibility to cope with possible fires in the building?	Yes
How will the function of the protection system be affected by time and to what extent are service and maintenance necessary?	Fire sprinklers need maintenance according as outlined in the relevant standard
How vulnerable is the added protection system on power failure, weather conditions, software failure, etc?	Not particular vulnerable

The design alternative is considered to be properly verified by the use of a qualitative assessment method as:

- The design is uncomplicated, affects few people and prescriptive requirements are mostly used.
- The design alternative only has one deviation from prescriptive design, i.e. fire sprinklers as a compensation for linings in Euroclass D.

The verification of the trial design will thus be done be collection evidence that fire sprinklers are a suitable “replacement” of linings with higher fire performance than materials of Euroclass D. The verification will be performed by qualitatively assess the design alternative and its performance in the event of fire. The key task in the qualitative assessment is to collect proof that combination of fire sprinklers and linings in Euroclass D is better at “controlling fire growth” than linings in Euroclass C (without sprinklers present). Some key analysis tasks to be answered are:

- What role has surface linings in the initial fire development?
- How does the fire development differ in a room with linings in Euroclass C, compared to a room with linings in Euroclass D?
- How will fire sprinklers influence the fire development in a room with linings in Euroclass D?

The verification is documented in section 4.2.

4.2 Verification by qualitative assessment

4.2.1 The role of linings in the initial fire development

In most cases the contents of a building have more influence on the size and growth rate of a fire than the fabric of the walls and ceilings. Combustible linings in Euroclass C or D will result in a more severe fire as it continues to grow and eventually spread to the linings. Most fires in smaller rooms or fire compartments result in untenable conditions prior to the ignition of the linings (Nystedt, 2003). The initial fire will most likely start in the building content and grow due to the spread to additional combustible parts of the contents as well as the linings.

Sundström et.al (2009) states that most up-holstered furniture have a fire performance that corresponds to the one of products with a Euroclass D rating. Höglander et. al (1997) states that the fire growth rate of combustible linings is related to the size of the ignition source. For small ignition sources (up to 100 kW) the fire growth rate of the linings is slow to medium (0.009 to 0.012 kW/s^2). But, if the ignition source is larger than 160 kW the growth rate becomes ultra-fast (0.19 kW/s^2). The role of the linings in the initial fire development could not be neglected and is of special concern in smaller rooms as the distance between the initial fire and the lining most likely is shorter than in larger rooms.

The control of lining materials contributes to the functional requirements on fire safety as the further a fire spreads beyond the object of origin, the worse the fire becomes and the greater the likelihood of loss of life (and property) becomes. Therefore, keeping the fire small will result in less loss of life. Control of linings will influence the time available for building occupants to escape.

Fire Code Reform Centre (1998) states that fires in small enclosures usually start with the ignition of building contents and once a fire becomes established, flashover might occur and the whole room becomes involved in a relatively short time, probably before linings have become involved in the fire. The contribution of lining materials in small rooms as a source of spread of flame to other parts of the building might not be significant.

Conservative estimates show that the response time of a sleeping adult to an alarm is 30 seconds and that it takes a further 30 seconds to evacuate the unit. The room will therefore be evacuated within 90 seconds of the fire starting. If the room were to reach flashover within 120 seconds of the fire starting (as with Euroclass D), the occupants would be well clear of the fire by the time flashover occurred (Fire Code Reform Centre, 1998).

4.2.2 Differences between Euroclass C and Euroclass D

A product with a Euroclass C rating is assumed to have “limited contribution to fire” and example of products that comply with this rating is gypsum boards with different types of surface linings such as walk cover of paper, or paint. A product with a Euroclass D rating is considered to have “acceptable contribution to fire” and wood products with a thickness of more than 10 mm and a density of more than 400 kg/m^3 have this rating. Products get their rating by being exposed to a 100 kW flame in a room fire test during the first 10 minutes and 300 kW in another 10 minutes. If there is a flash-over within the first two minutes, the product fails the test by acquiring a Euroclass E, which is an unsatisfactory performance to be used in buildings. The product will get a Euroclass D rating if flash-over occurs after 2 minutes, but before 10 minutes. If flash-over occur after 10 min the product performs according to Euroclass C. It could be noted that products in Euroclass B and A, both do not result in flash-over. The difference between them is that Euroclass A products are non-combustible.

There is quite a remarkable difference in fire performance when comparing products in Euroclass C with those in and Euroclass D. However, as stated in section 4.2.1 above, the difference becomes less significant in a furnished room where other combustibles have a large role in the fire development. However, both products will cause flash-over and their contribution to the fire development could be significant. The main difference is the time to reach flash-over which corresponds to the fire growth rate of the lining. Sprinklers must act quickly enough to prevent flash-over and sprinkler capabilities are described in section 4.2.3 below.

4.2.3 Sprinkler capabilities

Nystedt (2011) shows statistics on sprinkler performance from several sources. The success rate of sprinklers in apartment buildings is high, app. 96 %. Upon on sprinkler actuation, the fire will most likely be put out. Only 3 % of the fires have flame damage outside the room of origin. The smaller room, the more effective is the sprinkler system in dispersing water on the fire and room surfaces.

Arvidson (2000) has conducted fire tests for a residential fire scenario where the fire development as well as the fire effluents has been measured for a non-sprinklered scenario with linings in Euroclass B and a sprinklered scenario with linings in Euroclass D. The source of ignition was an upholstered armchair. The residential fire sprinkler system managed to control the fire despite the combustible linings and the major conclusion presented by Arvidson (2000) is that the fire is less severe in the sprinklered scenario with combustible linings than it is in the non-sprinklered scenario with linings that has very limited contribution to the fire.

Australian research (Fire Code Reform Centre, 1998) showed that life safety is not threatened by the use of combustible linings (comparable to Euroclass D). The research concludes that “sprinklers are perhaps the only fire safety system the optional presence of which can affect the burning of linings” and they illustrate the findings by several experiments concluding that “sprinklers can prevent wall linings in corridors from spreading fire and causing untenable conditions”. However, the Fire Code Reform Centre (1998) recognise that “even in buildings protected by sprinklers, it is important to ensure that sprinklers are not overwhelmed by rapid fire spread via highly flammable materials”. Materials with worse fire performance than Euroclass D should not be allowed.

4.3 Conclusions

Various research initiatives show that sprinklers will influence the fire development in buildings, no matter if the linings are combustible or not. However, the location and function of sprinklers might affect walls and ceilings differently. In some cases, rapid fire spread across the ceiling might overwhelm the sprinklers, while the slower spread of fire up and across walls will be suppressed.

Sprinklers will extinguish or control the fire, despite the use of combustible wall linings. In order for the system to be effective linings with at least a Euroclass D rating must be used. If the sprinkler system is ineffective (app. 4 % of the fires in apartment buildings) the linings will eventually be involved in the fire. But, if the apartment is equipped with smoke detectors (mandatory requirement), occupants will most likely be able to escape despite ineffective sprinklers and combustible wall linings. Special attention needs to be given to designs where combustible linings are to be used in ceilings as it is unclear whether the fire sprinklers will be effective in such cases.

5 Case study: Extended travel distance to exits in a retail store

This chapter contains a case study where fire sprinklers are used as a compensatory safety measure in a building where the prescribed travel distance to exits is exceeded. Most prescriptive codes allow for some extension in the travel distance if the building is fitted with sprinklers. In Sweden, the allowed extension is one third to the prescriptive requirement, i.e. 40 m instead of 30 m in a retail store. The case study goes beyond the allowable extension and shows how fire safety can be verified. The case study could be applied to other buildings as well, but the data and the results presented in this chapter are specific to retail stores.

5.1 Qualitative design review

5.1.1 Architectural design and occupant characteristics

The building is a retail store with two stories with a total floor area of 1 100 m^2. Sketches of the building layout are shown in Figure 5.1.

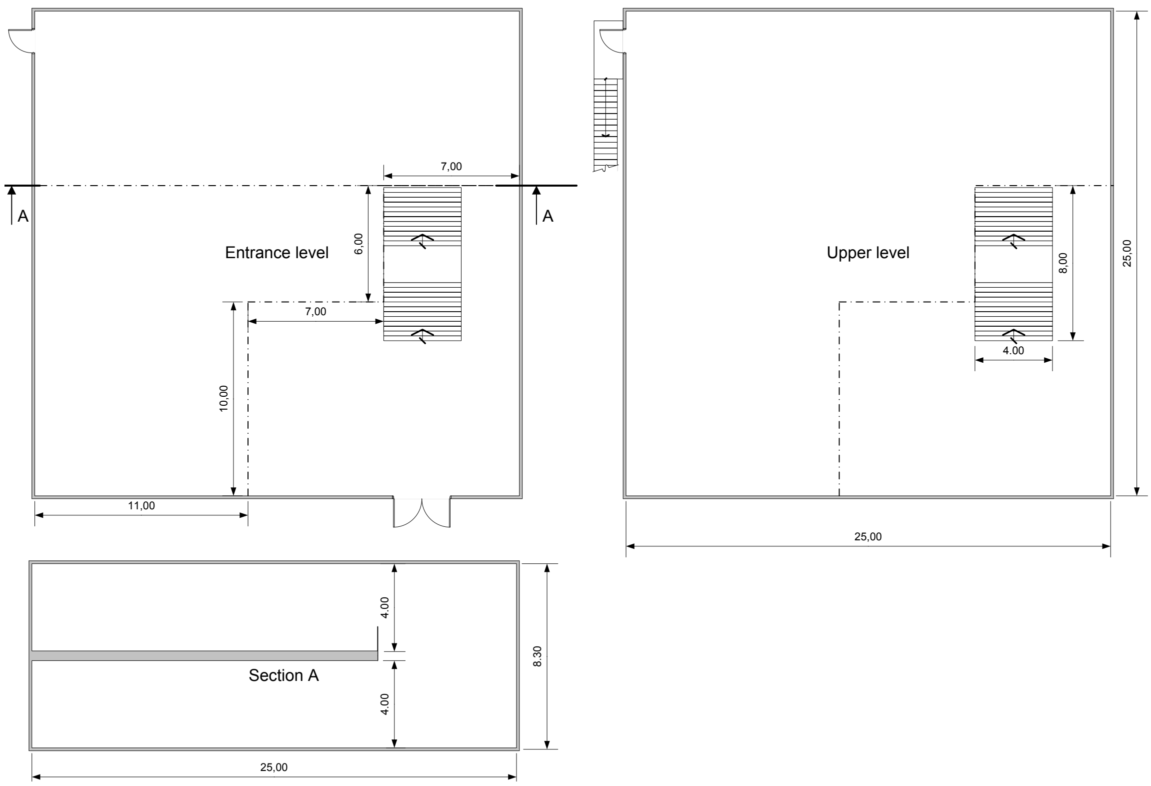

Figure 5.1 Layout of the retail shop.

The ceiling height is 4.0 m on both floors. There is a large opening between the two floors. The occupants in the building are of different age and have different ability to move. It is likely that there will be disable (mobility-impaired) people present. Occupants are not expected to be familiar with the building, especially the location of exits apart from the main entrance. The occupant load is, according to code requirements, 0.5 people per m^2.

The total number of occupants is assumed to be 540 people, distributed on each floor as shown below.

- The entrance level has a floor area of 600 m^2 resulting in 300 occupants.
- The upper level has a floor area of 480 m^2 resulting in 240 occupants.

The fire service has an intervention time that is less than 10 minutes and the distance to neighbouring buildings is app. 25 m.

5.1.2 Fire hazards and other factors

There are several issues to be addressed in the building:

- A high occupant load results in a potential large consequence in the event of fire.
- Furnishing could result in decreased visibility and people are not familiar with the building.
- The large opening between the floors is unfavourable for fires initiated on the entrance level as it results in larger spill plumes. Spill plumes will increase the volume of the smoke and decrease the available safe egress time on the upper level.
- A large part of the escape capacity is located in the entrance level resulting in relative long escape times from the upper level.

5.1.3 Trial fire safety design

The trial fire safety design complies mostly with the requirements according to prescriptive design. The exception is the travel distances on the upper level which are app. 50 m (calculated according to code requirements).

The building has two exits from the entrance level, where one is the main entrance (1.8 m door width) and one is a rear fire exit (1.2 m door width). There is a stair with a width of 1.8 m from the upper floor to the entrance level. The upper floor does also have one exit (1.2 m width) direct to the outside.

The building is equipped with an automatic fire alarm and a public notification system. The fire alarm has smoke detectors and the notification system is an automatically activated voice alarm. The systems are designed according to relevant standards. The building is also equipped with an automatic conventional fire sprinkler system, designed according to relevant standards. The building is not divided into several fire compartments.

Table 5.1 outlines the main fire safety features of the building.

Table 5.1 Trial design solution for the retail store.

Barrier	Measure	Requirements
Prevent ignition	-	-
Control fire growth	Surface finishes with low combustibility (Euroclass B)	Prescriptive design
Control smoke spread	-	-
Limit fire spread within building	Fire sprinkler system[4]	Relevant standard
Prevent fire spread to other buildings	-	-
Means of escape	Fire alarm	Relevant standard
	Voice alarm	Relevant standard
	Two exists from entrance level	Prescriptive design
	One exit from upper level[5]	Analytical design
Facilitate rescue service operations	Access to building	Prescriptive design
Prevent structural collapse	Structural elements of concrete (R 30)	Prescriptive design

5.1.4 Selection of design method

Since the design team proposes a deviation from prescriptive design, there is a need to verify that the trial design offers sufficient safety in case of fire. Analytical design will be used to perform the verification.

5.1.5 Verification prerequisites

The verification requirements are identified by the use of the tools provided by Lundin (2005), see Figure 5.2 and Figure 5.3.

[4] The fire sprinkler system is a complementary fire safety measures.

[5] The prescriptive code requirement would result in two exits from the upper level.

Purpose of the fire safety measure (linked to the major barrier groups)	Trade-off					
	Added measure			Removed measure		
	A_1	A_2	...	R_1	R_2	...
Measures to prevent ignition						
Measures to control fire growht	+					
Measures to control smoke spread	+					
Measures to limit fire spread within a building	+					
Measures to prevent fire spread to other building	+					
Allow rapid egress				-		
Facilitate rescue service operations						
Prevent structural collapse	+					

Figure 5.2 Identification of the effects of the trial design in comparison with the prescriptive code requirements. Note that A_1 is the fire sprinkler system and R_1 is the extended travel distance to exits from the upper level.

A short evaluation of Figure 5.2 states that there is imbalance in "added" and "removed" measures on the positive side as fire sprinklers is a multifunctional measure that influences several barrier groups in a positive way. A fire sprinkler system is not a measure that makes escape for rapid. However, fire sprinklers do result in longer available safe egress time and thus can an extended travel distance to exits be motivated. Finally, there is a balance in the number of measures "added" and "removed", which makes the task of verification easier.

Functional requirements in NKB (1994)	Trade-off					
	Added measure			Removed measure		
	A_1	A_2	...	R_1	R_2	...
The load-bearing capacity of the construction can be assumed for a specific period of time	+					
The generation and spread of fire and smoke within the construction is limited	+			-		
The spread of fire to neighbouring construction works is limited	+					
People in the construction on fire can leave it or be rescued by other means	+					
The safety of fire and rescue service personnel is taken into consideration	+					

Figure 5.3 Investigation on the effect of the added and removed fire safety measures on the functional requirements. Note that A_1 is the fire sprinkler system and R_1 is the extended travel distance to exits from the upper level.

Figure 5.3 indicates that there is a balance among the added and removed safety features. No safety features has been removed that hasn't been compensated for. To conclude, a check list on different attributes of the fire safety system is presented.

Table 5.2 Evaluation of attributes of the fire safety system.

Attribute	Answer
Is the effectiveness of the added protection system dependent on human action?	No
Is the design alternative characterized by the reduction or elimination of several independent safety measures and replaced by a single measure?	No
Is the added safety measure dependent on several sub-systems functioning correctly?	No
Does the design alternative have the necessary degree of flexibility to cope with possible fires in the building?	Yes
How will the function of the protection system be affected by time and to what extent are service and maintenance necessary?	Fire sprinklers need maintenance according as outlined in the relevant standard
How vulnerable is the added protection system on power failure, weather conditions, software failure, etc?	Not vulnerable

The design alternative is considered to be properly verified by the use of a quantitative assessment with deterministic analysis as:

- It must be verified that the available safe egress time (ASET) is longer than the required safe egress time (RSET).
- The potential consequences of sprinkler failure must be analysed to ensure the safety of occupants as the building is classified as a place of assembly (more than 150 people).

The verification of the trial design will thus by quantifying fire development and egress time. The building is considered to be safe if the building is possible to evacuate prior the onset of untenable conditions. The key task is to quantify the fire development and the time available for escape. The result will be compared with the time required for escape. Some key analysis tasks to be answered are:

- Which fire scenarios should be considered?
- What conditions are considered untenable to occupants?
- How long time is available for escape (ASET)
- How long time is required for complete escape (RSET)?

The verification is documented in section 5.2.

5.2 Verification by quantitative assessment with deterministic analysis

5.2.1 Design fires and life safety criteria

According to Nystedt (2011) the safety in the sprinklered and non-sprinklered scenario could be assessed by analysing only one of the scenarios. If the building complies with the so called "robustness scenario" one could assume that it has satisfactory performance in the sprinklered scenario as well. This assumption is valid if the sprinkler system is activated prior a heat release of 5 MW. The actuation of the sprinkler system is dependent on the sprinkler head characteristics, the fire growth rate, the spacing of sprinkler heads and the ceiling height. A quick estimate on the actuation time indicates that the first sprinkler head will activate[6] app. 2.3 min after the fire start resulting in a heat release of app. 1 MW prior to actuation. Thus the assumption that analysis of the performance for the robustness scenario (when sprinklers are not available) will be sufficient to assess the safety in the building.

Nystedt (2011) does not provide quantified information on the characteristics of the design fire to be used in the robustness scenario. Instead, some ideas are presented and it is considered that the robustness scenario ought to represent more average conditions as it only occurs when the sprinkler system is considered to be unavailable (app. 5 % of the fires). In this case study, the design fire for the robustness scenario should be regarded as a more a less rapidly growing fire with average combustion characteristics and an unaltered maximum heat release rate. The robustness scenario is thus considered to have the characteristics shown in Table 5.3

Table 5.3 Characteristics of the design fire for the robustness scenario.

Parameter	Values
Fire growth rate	0.012 kW/s^2 (medium)
Maximum heat release rate	10 MW
Soot production[7]	0.06 g/g
Heat of combustion	30 MJ/kg

[6] The actuation time is estimated by the use of the Detact-t2 (Evans et. al, 1985) software based on a sprinkler head with an activation temperature of 68° C and a RTI-value of 50 $(ms)^{1/2}$. Each sprinkler head covers 12 m^2 and the ceiling height is 4.0 m. The fire growth rate is considered to be 0.047 kW/s^2 (fast fire growth).

[7] The value of the soot production is based on a combination of 50 % wood-based material and 50 % plastic material.

Due to the large opening between the floors it is not possible to assess where the fire should be placed in order to sufficiently stress the fire safety features. Will a fire on the entrance level have more severe consequences than a fire on the upper level due to the possibility of a large spill plume? Thus, there is a need to analyse two fire locations – a fire at the entrance level and a fire on the upper level.

Nystedt (2011) proposes a life safety criterion of at least 5 m visibility for the robustness scenario. The data in Table 5.3 will be used to quantify the fire development by the use of a computational fluid dynamics model designed for fire and smoke transport (see section 5.2.2). The time to reach untenable conditions (less than 5 m visibility) will be compared with the output of the egress analysis (see section 0). The result is presented in section 5.3.

5.2.2 Fire development calculations

The fire development have been calculated by the use of a computational fluid dynamics model – Fire Dynamics Simulator (FDS, version 5.5.3) developed by NIST (McGrattan et. al., 2010). The software quantifies the transportation of smoke and heat in the building. The building (i.e. the domain in the fire simulation) is divided into app. 750,000 cells (0.2 x 0.2 x 0.2 m). The dimensionless heat release rate Q^* is 1.2 and the resolution of the fire $D^*/\delta x$ is 12. Reference value on Q^* is 0.3 to 2.5 and 10 to 20 on $D^*/\delta x$ is 12 (Nystedt et. al., 2011). An illustration of the model is shown in Figure 5.4.

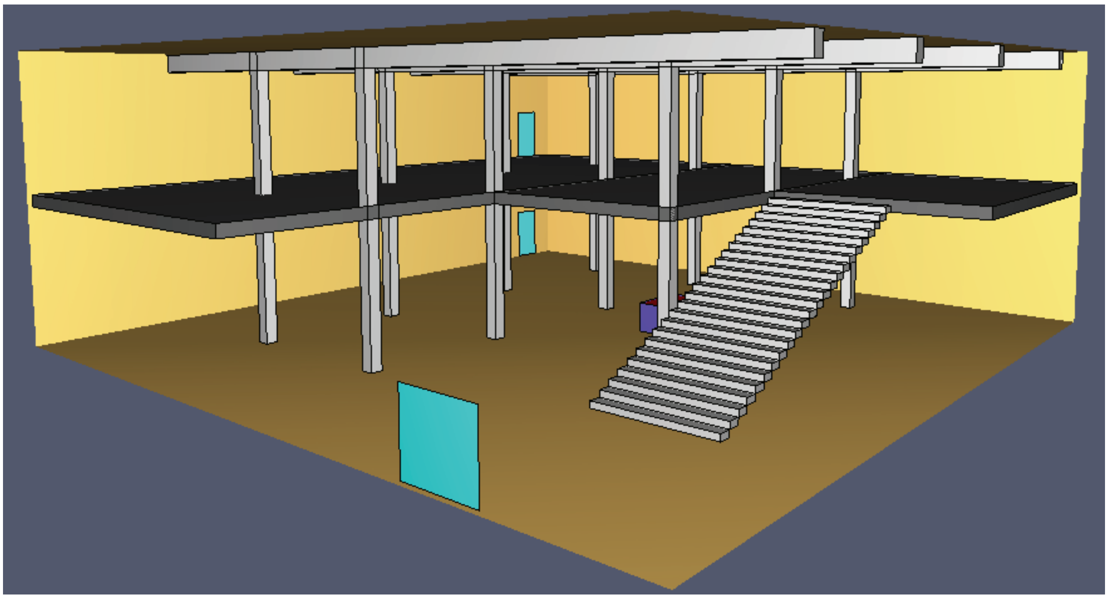

Figure 5.4 Model of building used in the fire simulation.

The results of the fire development calculations are presented in Table 5.4 below. Note that the proposed life safety criterion for the robustness scenario is a visibility at least 5 m (Nystedt, 2011). The time to reach a visibility less than 10 m is presented as it is a reference value for non-sprinklered buildings in many building codes. Note that visibility is measured towards illuminated signs.

Table 5.4 Available safe egress time. Note that the visibility criterion is the only criterion on untenable conditions that is relevant for these scenarios.

Location of fire	ASET (visibility < 10 m)	ASET (visibility < 5 m)
Entrance level	Entrance level: 320 s Upper level: 270 s	Entrance level: 360 s Upper level: 320 s
Upper level	Entrance level: N/A Upper level: 240 s	Entrance level: N/A Upper level: 260 s

Note that the fire alarm (i.e. smoke detectors) will actuate at 30 s. This output is required in the egress analysis in section 5.2.3.

5.2.3 Egress analysis

The required safe egress time (RSET) is a function of the time from ignition to alarm (Δt_a) and the time required from alarm for occupants to evacuate to a place of safety (Δt_{evac}).The evacuation time is divided into a pre-movement time (Δt_{pre}) and a travel time (Δt_{trav}). The alarm time is dependent on the type of detection system in the building and the pre-movement time is dependent on the type of notification system. The travel time is a function of the number of people (N), the flow through exits (f) and the available exit width (Δw). Equations used in assessing RSET are shown below.

$$RSET = \Delta t_a + \Delta t_{pre} + \Delta t_{trav}$$

$$\Delta t_{trav} = \frac{N}{f\,\Delta w}$$

The alarm time is provided by the fire development calculations in section 5.2.2 and has a value of 30 s. The pre-movement time in a retail store where there is an informative voice alarm is assumed to be 60 s as stated by Frantzich (2001). The flow through openings is assumed to be 1person / [m s]. It is necessary to link the egress with the fire scenarios in terms of the possibility of any exits being blocked by the fire.

A fire at the entrance level is assumed to block the rear exit. It is also assumed that no persons from the upper level will use the stair to the entrance level as the smoke spread through the large opening between the floors is quite significant. Available exit width from the entrance level is 1.8 m and 1.2 m from the upper level. A fire at the upper level is assumed to block the exit direct to the outside, while the stair to the entrance level is available. Available exit width from the upper level is 1.8 m. There is no need to calculate RSET on the entrance level as untenable conditions will not occur here (see Table 5.4).

Table 5.5 shows RSET for the two egress scenarios.

Table 5.5 Required safe egress time.

Fire location	Floor	Alarm and pre-movement time	Travel time	RSET
Entrance level	Entrance	90 s	170 s	260 s
	Upper	90 s	200 s	290 s
Upper level	Entrance	N/A	N/A	N/A
	Upper	90 s	130 s	220 s

5.3 Conclusions

All building regulations require that people should be able to leave the building without getting harmed in the event of fire. Successful escape is often defined with the Available Safe Egress Time (ASET) and Required Safe Egress Time (RSET) concept as shown below:

ASET > RSET

ASET is related to the fire development and RSET is related to escape arrangements. When comparing ASET in Table 5.4 with RSET in

Table 5.5 it is concluded that safe escape is possible for all studied scenarios. The safety margin is at least 30 s. The escape arrangements proposed in the trial fire safety design solution (see section 5.1.3) have sufficient safety in the event of fire.

It is not possible to draw any general conclusions on the possibility of extended travel distances in buildings as each building is unique in terms of ceiling height, exit width, location of exits, the number of occupants, etc.

6 Case study: Reduced fire rating on windows in an office building

This chapter contains a case study where fire sprinklers are used as a compensatory safety measure in an office building where there is a reduction in the prescribed fire ratings on windows. The case study could be applied to other buildings as well, but the data and the results presented in this chapter are specific to office buildings.

6.1 Qualitative design review

6.1.1 Architectural design and occupant characteristics

The building in the case study is an office building with four storeys. It is built of concrete and has different tenants on each floor and a centrally placed atrium. The occupants in the building (app. 400 people) are expected to be familiar with it and be able to escape by themselves. A plan sketch is shown in Figure 6.1.

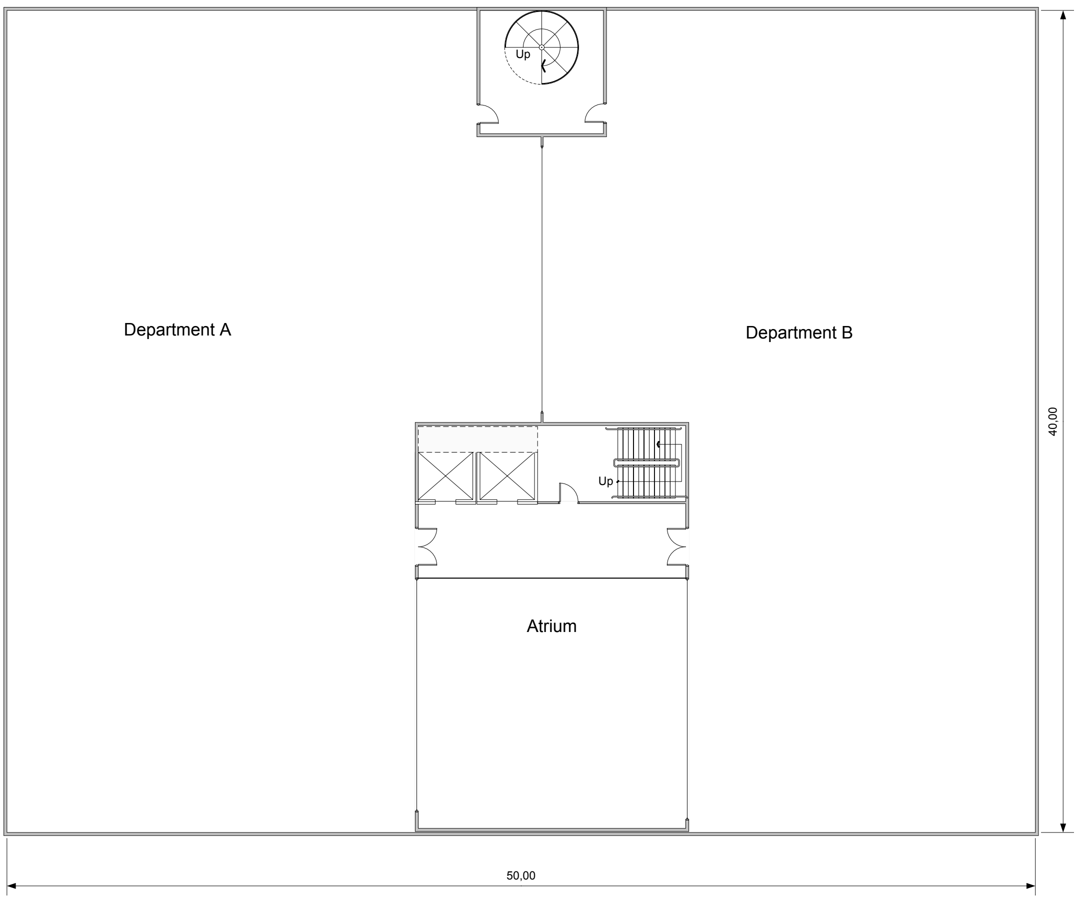

Figure 6.1 Plan sketch of the office building (upper level).

Interior glazing is used towards the atrium and between the two departments. Each department is its own fire compartment (in order to limit the size of the fire compartment). The stairwell and the atrium are also their own fire compartments. Escape is possible via the stairwell in the atrium or via the spiral staircase. The fire service has an intervention time that is less than 10 minutes and there are no other buildings nearby.

6.1.2 Fire hazards and other factors

The fire load in offices is well established and consistent. However, there is often a need for maximum design flexibility in order to adapt the building to the requirements of the tenants. The fire safety features are not sensitive to snow, rain or extreme temperatures.

6.1.3 Trial fire safety design

The trial fire safety design of the building complies mainly with the prescriptive requirements of office buildings found in the building code. A fire sprinkler system will be installed in the building as a complementary fire safety measure and the design team proposes a reduction on the fire rating of windows. The code requirement on fire rating is EI 60 and the design team would like to use windows in E 30. Table 6.1 outlines the main fire safety features of the building.

Table 6.1 Trial design solution for the office building.

Barrier	Measure	Requirements
Prevent ignition	Furniture clothing	Relevant standard
Control fire growth	Surface finishes in Euroclass B	Prescriptive design
Control smoke spread	Fire dampers	Prescriptive design
Limit fire spread within building	Fire separating structures (EI 60) Windows in E 30[8] Fire sprinkler system[9]	Prescriptive design Analytical design Relevant standard
Prevent fire spread to other buildings	-	-
Means of escape	Two stairwells	Prescriptive design
Facilitate rescue service operations	Access to building	Prescriptive design
Prevent structural collapse	Structural elements made of concrete (R 60)	Prescriptive design

[8] Windows in E 30 is a deviation from the prescriptive code requirement on EI 60.
[9] The fire sprinkler system is a complementary fire safety measures.

6.1.4 Selection of design method

Since the design team proposes a deviation from prescriptive design, there is a need to verify that the trial design offers sufficient safety in case of fire. Analytical design will be used to perform the verification.

6.1.5 Verification prerequisites

The verification requirements are identified by the use of the tools provided by Lundin (2005), see Figure 6.2 and Figure 6.3.

Purpose of the fire safety measure (linked to the major barrier groups)	**Trade-off**					
	Added measure			Removed measure		
	A_1	A_2	...	R_1	R_2	...
Measures to prevent ignition						
Measures to control fire growht	+					
Measures to control smoke spread	+					
Measures to limit fire spread within a building	+			-		
Measures to prevent fire spread to other building	+					
Allow rapid egress						
Facilitate rescue service operations						
Prevent structural collapse	+					

Figure 6.2 Identification of the effects of the trial design in comparison with the prescriptive code requirements. Note that A_1 is the fire sprinkler system and R_1 is the reduced fire ratings on windows.

A short evaluation of Figure 6.2 states that there is imbalance in "added" and "removed" measures and the positive side as fire sprinklers is a multifunctional measure that influences several barrier groups in a positive way. There is balance in the number of measures "added" and "removed", which makes the task of verification easier.

Functional requirements in NKB (1994)	Trade-off					
	Added measure			Removed measure		
	A_1	A_2	...	R_1	R_2	...
The load-bearing capacity of the construction can be assumed for a specific period of time	+					
The generation and spread of fire and smoke within the construction is limited	+			-		
The spread of fire to neighbouring construction works is limited	+					
People in the construction on fire can leave it or be rescued by other means	+					
The safety of fire and rescue service personnel is taken into consideration	+					

Figure 6.3 Investigation on the effect of the added and removed fire safety measures on the functional requirements. Note that A_1 is the fire sprinkler system and R_1 is the reduced fire ratings on windows.

Figure 6.3 indicates that there is a balance among the added and removed safety features. No safety features has been removed that hasn't been compensated for. To conclude, a check list on different attributes of the fire safety system is presented.

Table 6.2 Evaluation of attributes of the fire safety system.

Attribute	Answer
Is the effectiveness of the added protection system dependent on human action?	No
Is the design alternative characterized by the reduction or elimination of several independent safety measures and replaced by a single measure?	No
Is the added safety measure dependent on several sub-systems functioning correctly?	No
Does the design alternative have the necessary degree of flexibility to cope with possible fires in the building?	Yes
How will the function of the protection system be affected by time and to what extent are service and maintenance necessary?	Fire sprinklers need maintenance according as outlined in the relevant standard
How vulnerable is the added protection system on power failure, weather conditions, software failure, etc?	Not vulnerable

The design alternative is considered to be properly verified by the use of a quantitative assessment with probabilistic analysis as:

- The risk of fire spread must be expressed in quantitative terms as it must be ensured that the combination of fire sprinklers and reduced fire rating on windows has a sufficient safety in terms of limit fire spread within the building.
- The potential unavailability of the fire sprinkler system must be considered when the risk of fire spread is evaluated.

The verification of the trial design will thus be done quantitatively assess the risk of fire spread in the building and compare this risk with the performance of a reference building designed in accordance with the prescriptive requirements. The key task is to assess the risk of fire spread between fire compartments in the building and compare this value to the risk of fire spread in an ordinary office building that is not equipped with fire sprinklers and have a fire rating of EI 60 according the prescriptive code requirement. Some key analysis tasks to be answered are:

- What is the expected performance of the fire sprinkler system in the office building?
- What is the probability of fire spread in an office building with a fire raring of E 30?
- What is the probability of fire spread in an office building with a fire raring of EI 60?
- Are there other limitations to be considered when the insulation requirement on the windows is dropped, i.e. “E” instead of “EI”?

The verification is documented in section 6.2.

6.2 Verification by quantitative assessment with probabilistic analysis

6.2.1 Expected performance of fire sprinklers in an office building

Fire sprinkler systems have a high degree of reliability. Nystedt (2011) presents data on sprinkler performance and it is concluded that sprinklers are 99 % effective when they operated, and they operate in 96 % of the fires. This results in a combined performance of 95 %. Thus, only 5 of 100 fires will not be readily extinguished or controlled by the sprinkler system. Lougheed (1997) demonstrates heat release rates in the order of less than 1 MW for shielded fires in sprinklered buildings. It is concluded that flash-over will not occur when the sprinkler system is available. Flames will be confined to the room of origin in 93 of 100 fires when sprinklers are present (Hall, 2010).

6.2.2 Probability of fire spread

The risk of fire spread between fire compartments is related to the possibility of having fully developed fire. Thus, if flash-over does not occur, fire spread is unlikely. Sprinklers prevent flash-over with a high degree of probability and the performance of the fire separating structure is decided according to its performance in a standardised test (EN 13501-2).

As the design alternative suggests the use of an E 30 rating instead of an EI 60 rating, it would be of interest to qualitatively express the differences between these ratings. First, the letter “E” stands for “integrity” and is measured as the time until cracks/openings or sustainable flaming. The ignition of a cotton pad must not occur. The letter “I” stands for insulation and the requirements are a limited temperature (average of 140° C, maximum of 180°) on the unexposed side. The combination “EI 60” thus means that the requirements on integrity and insulation must be met for at least 60 min exposure of a standardised exposure of heat (EN 13501-2). There are two major differences between “E 30” and “EI 60”:

- “E 30” meets the requirements on integrity for 30 min in the test oven. The temperature is app. 840° C at the failure point, which could be compared to 950 °C for “E 60”.
- The missing insulation criteria (“E”, not “EI”) results in a possibility of fire spread if there is combustible material close to the windows. Sprinkler could prevent this from happening.

Fire spread in a sprinklered office building is closely related to the availability of the sprinkler system. The risk of having a large fire (that could cause fire spread) is illustrated in the event trees in Figure 6.4 and Figure 6.5 with data from Nystedt (2011).

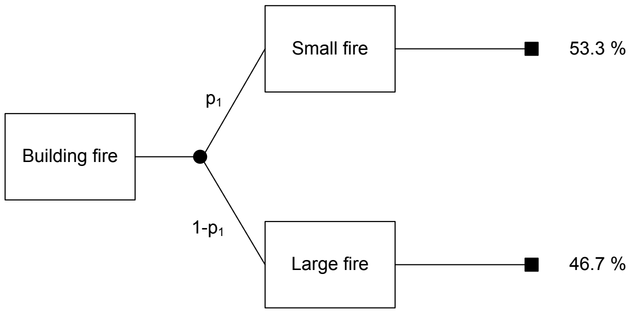

Figure 6.4 Event tree in office with no sprinkler system. Note that p_1 is 53.3 %.

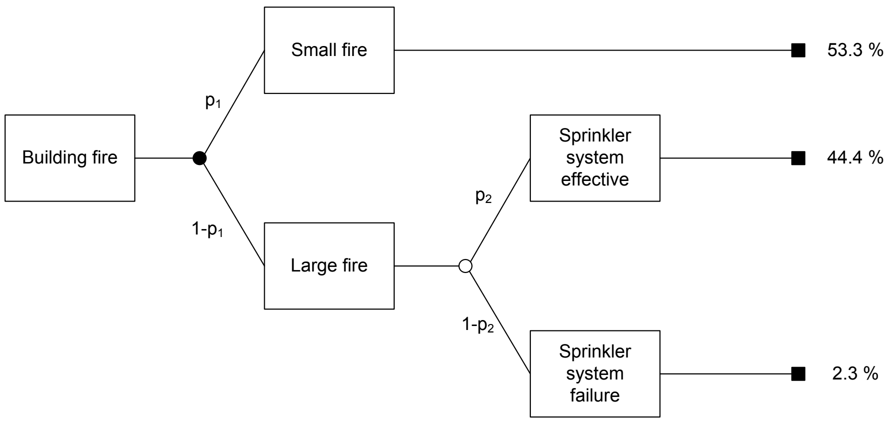

Figure 6.5 Event tree in office with sprinkler system. Note that p_1 is 53.3 % and p_2 is 95 %.

As shown in Figure 6.4 and Figure 6.5 there is a large difference in having a large fire in an office with no sprinklers (46.7 %) and an office with sprinklers (2.3 %). The next step would be to assess the likelihood of having fire spread in a fully developed office fire with windows in EI 60, compared to having windows in E 30. Initially, the focus will be to assess the likelihood of the fire duration being more severe than the performance of the structure. The fire duration is a function of the fire load, material properties and openings. As the fire load is a stochastic variable, the duration will also be a stochastic variable. The fire load for various buildings is found in Appendix E to Eurocode EN 1991-1-2 (European Standard, 2002). The fire load in office buildings has an average of 420 MJ/m^2 floor area and the 80 % fractile is 511 MJ/m^2 floor area. The fire load is considered to belong to a Gumbel distribution[10] and by using the time equivalence concept it is possible to determine the distribution of the fire duration in relation to exposure in the standard test of EN 13501-2.

$$t_{equivalent} = q_f \cdot k_b \cdot w_f$$

Where

$t_{equivalent}$ = equivalent time of fire exposure, min.

q_f = the fire load, MJ/m^2 floor area.

k_b = material properties, 0.07 min m^2 / MJ.

w_f = ventilation factor, 1.5 (conservative estimate according to CIB (1986).

It is possible to calculate which fire load that is required in order for the fire to have a certain duration. E.g. if q_f is larger than 286 MJ/m^2 floor area, the fire will last longer than 30 min. The corresponding fire load for a duration of more than 60 min is 572 MJ/m^2 floor area. The properties of the Gumbel distribution give the resulting probabilities:

- The probability that the fire load exceeds 286 MJ/m^2 floor area, and thus has a fire duration that is longer than 30 min, is 88.95 %.
- The probability that the fire load exceeds 572 MJ/m^2 floor area, and thus has a fire duration that is longer than 60 min, is 11.33 %.

As noted, a 60 min fire rating in an office building will have almost eight times less likelihood of not being able to withstand the complete fire when compared to a structure with 30 min fire rating. But, as mentioned in in Figure 6.4 and Figure 6.5 the likelihood of a flash-over is much lower in a sprinklered building, app. 20 times. The probability of failure is calculated by using the equation below.

$$P_{failure} = P_{flashover} \cdot P(S > R)$$

$$P_{failure,sprinkler} = P_{flashover,sprinkler} \cdot P(S > R)_{30\min} = 0.023 \cdot 0.8895 = 0.02$$

$$P_{failure} = P_{flashover} \cdot P(S > R)_{60\min} = 0.433 \cdot 0.1133 = 0.05$$

[10] The Gumbel distribution is a type of extreme value distribution.

6.2.3 Other aspects and limitations

The calculated probability of failure (fire spread) do not consider the possibility that the fire will spread soon after becoming fully developed due to lack of insulation of the “E 30”-rated windows. It is not unlikely that there will be combustible material on the opposite side of the window that could ignite due to heat radiation. It is generally considered that non-insulated fire rated structures reduce radiative heat transfer by 30-50 %. If the heat flux exceeds 10 kW/m^2, there is a risk of ignition of easily ignited materials. Outbound radiation could be assessed as:

$$E_{outbound} = \varepsilon \cdot \sigma \cdot T^4 \leftrightarrow T = \sqrt[4]{E/\varepsilon \cdot \sigma}$$

$$E_{inbound} = \tau \cdot F \cdot E_{outbound}$$

The emissive fraction is app. 0.75, τ is absorption by the windows (30-50 %) and F is the view factor (F = 1). The temperature in the fire compartment must thus be app. 480° in order for the inbound radiation to exceed 10 kW/m^2. Such a value is likely to occur in a fully develop fire and as a direct consequence, the probability of fire spread could be equal to 1, if the sprinkler system is unavailable. However, even if a conditional probability of 1 is used in section 6.2.2, the fire sprinkler system will still prevent fire spread twice as good as only having an EI 60 rated structure.

There is a difference in time scale that needs to be addressed. In a building without sprinklers, fire spread will most likely occur after the stipulated fire exposure or close to the end of this exposure. But, when the insulation criteria is excluded it is likely that the fire will spread when it becomes fully developed (this event requires that the sprinkler system is unavailable). People have left the building when this happens and it is most likely a question on property protection. Remember that the sprinkler system is very efficient in reducing fire costs and the system will most likely be effective in 95 of 100 fires. The system will reduce fire damage within the fire compartment, even if this ability is not given most attention in this case study.

There is also a probability that the fire rated windows have failures such as they will not be able to withstand a fire for the specified duration. Data on this subject is sparse, and it is often noted that a construction have higher performance than what is listed. Platt (1994) shows that a construction performs app. 10-25 % better that it’s rating. On the other hand, BSI states in the standard BSI 7974:2003 part 7 (BSI, 2001) that the probability of glazing having at least 75 % of the designated fire resistance standard is as low as 40 %. If these data would have been used in section 6.2.2, the benefits of sprinklers would be utterly highlighted.

6.3 Conclusions

The design target in this case study was to provide information that compares the probability of fire spread in a building with EI 30 windows and a conventional sprinkler system with a building with windows in EI 60. It is concluded that fire sprinklers alone will perform twice as good as an EI 60 window in order to prevent fire spread.

The fire sprinkler system does also provide additional benefits to the building as reduced risk to people and the building. When the sprinkler system is unavailable, fire could easily spread to the opposite side of the window due to radiative heat transfer. It is thus recommended that the furnishing of the office will provide clearance of combustible materials in the immediate vicinity of the glazed wall.

7 Case study: Combustible façade materials in an apartment building

This chapter contains a case study where fire sprinklers are used as compensatory measure to allow for combustible façade materials in an apartment building. This design alternative is allowed in the Swedish building regulations and is therefore not in need of a verification. However, the design alternative could be of interest to other countries and is therefore included in the report. The case study could be applied to other buildings as well, but the data and the results presented in this chapter are specific to apartment buildings.

7.1 Qualitative design review

7.1.1 Architectural design and occupant characteristics

The building in the case study is an ordinary apartment building with four storeys. It is constructed of wood and has three apartments on each floor. The occupants in the building (app. 30-40 people) are expected to be familiar with it and be able to escape by themselves. They are, however, not assumed to be awake at all times. People are able to escape from the building through the main stairwell (placed in its own fire compartment). If the stairwell is blocked by smoke, occupants should remain in their apartments and wait for assistance of the fire service. The fire service has an intervention time that is less than 10 minutes and the shortest distance to neighbouring buildings is app. 15 m.

7.1.2 Fire hazards and other factors

The fire load in dwellings is well established and consistent. It is unlikely that the fire will spread to adjacent fire compartments and those injured by the fire are most commonly in the apartment where the fire started.

All apartments have windows in two directions making a wind-aided projection of flames possible in the event of a fully developed fire. The fire safety features are not sensitive to snow, rain or extreme temperatures.

7.1.3 Trial fire safety design

The trial fire safety design of the building complies mainly with the prescriptive requirements of apartment buildings found in the building code. A residential fire sprinkler system will be installed in the building as a complementary fire safety measure and the design team proposes a deviation from the prescriptive requirements on façade materials and allow for a combustible product in Euroclass D. The code requirement on façade material is normally that the material should be incombustible (e.g. Euroclass A).

Table 7.1 outlines the main fire safety features of the building.

Table 7.1 Trial design solution for the apartment building.

Barrier	Measure	Requirements
Prevent ignition	Insulation of kitchen extract ducts	Prescriptive design
Control fire growth	Combustible surface finishes (Euroclass C)	Prescriptive design
Control smoke spread	Fire dampers	Prescriptive design
Limit fire spread within building	Fire separating structures (EI 60)	Prescriptive design
	Façade materials in Euroclass D[11].	Analytical design
	Residential fire sprinkler system[12]	Relevant standard
Prevent fire spread to other buildings	Safety distance to neighbouring building	Prescriptive design
Means of escape	Smoke alarm	Prescriptive design
	Main stairwell	Prescriptive design
	Assistance by fire service from windows	Prescriptive design
Facilitate rescue service operations	Access to building	Prescriptive design
	Smoke vent in stairwell	Prescriptive design
Prevent structural collapse	Structural elements protected by fibre boards (R 60)	Prescriptive design

7.1.4 Selection of design method

Since the design team proposes a deviation from prescriptive design, there is a need to verify that the trial design offers sufficient safety in case of fire. Analytical design will be used to perform the verification.

7.1.5 Verification prerequisites

The verification requirements are identified by the use of the tools provided by Lundin (2005), see Figure 7.1 and Figure 7.2.

[11] The prescriptive code requirement is Euroclass A.
[12] The residential fire sprinkler system is a complementary fire safety measures.

Purpose of the fire safety measure (linked to the major barrier groups)	Trade-off					
	Added measure			Removed measure		
	A_1	A_2	...	R_1	R_2	...
Measures to prevent ignition						
Measures to control fire growht	+					
Measures to control smoke spread	+					
Measures to limit fire spread within a building	+			-		
Measures to prevent fire spread to other building	+					
Allow rapid egress						
Facilitate rescue service operations						
Prevent structural collapse	+					

Figure 7.1 Identification of the effects of the trial design in comparison with the prescriptive code requirements. Note that A_1 is the fire sprinkler system and R_1 is façade material in Euroclass D.

A short evaluation of Figure 7.1 states that there is imbalance in "added" and "removed" measures and the positive side as fire sprinklers is a multifunctional measure that influences several barrier groups in a positive way. There is a balance in the number of measures "added" and "removed", which makes the task of verification easier.

Functional requirements in NKB (1994)	Trade-off					
	Added measure			Removed measure		
	A_1	A_2	...	R_1	R_2	...
The load-bearing capacity of the construction can be assumed for a specific period of time	+					
The generation and spread of fire and smoke within the construction is limited	+			-		
The spread of fire to neighbouring construction works is limited	+					
People in the construction on fire can leave it or be rescued by other means	+					
The safety of fire and rescue service personnel is taken into consideration	+					

Figure 7.2 Investigation on the effect of the added and removed fire safety measures on the functional requirements. Note that A_1 is the fire sprinkler system and R_1 is façade material in Euroclass D.

Figure 7.2 indicates that there is a balance among the added and removed safety features. No safety features has been removed that hasn't been compensated for. To conclude, a check list on different attributes of the fire safety system is presented

Table 7.2 Evaluation of attributes of the fire safety system.

Attribute	Answer
Is the effectiveness of the added protection system dependent on human action?	No
Is the design alternative characterized by the reduction or elimination of several independent safety measures and replaced by a single measure?	No
Is the added safety measure dependent on several sub-systems functioning correctly?	No
Does the design alternative have the necessary degree of flexibility to cope with possible fires in the building?	Yes
How will the function of the protection system be affected by time and to what extent are service and maintenance necessary?	Fire sprinklers need maintenance according as outlined in the relevant standard
How vulnerable is the added protection system on power failure, weather conditions, software failure, etc?	Not vulnerable

The design alternative is considered to be properly verified by the use of a quantitative assessment with probabilistic analysis as:

- It must be ensured that the combination of fire sprinklers and increased combustibility of the façade has a sufficient safety in terms of limit fire spread within the building.
- The potential unavailability of the fire sprinkler system must be considered when the risk of fire spread is evaluated.

The verification of the trial design will thus be done quantitatively assess the risk of fire spread in the building and compare this risk with the performance of a reference building designed in accordance with the prescriptive requirements. The key task is to assess the risk of fire spread between fire compartments (via façade) in the building and compare this value to the risk of fire spread via façade in an ordinary non-sprinklered apartment building that has incombustible façade material. Some key analysis tasks to be answered are:

- What influence does the façade material have on the fire spread via outer walls?
- What is the expected performance of the residential fire sprinkler system in the apartment building?
- What is the probability of fire spread via the façade in an apartment building with incombustible façade material?
- What is the expected probability of fire spread in an apartment building with sprinklers and façade material in Euroclass D?
- Are there other limitations to be considered when using façade material in Euroclass D?

7.2 Verification by quantitative assessment with probabilistic analysis

7.2.1 Characterisation of fire spread via façade and windows

The spread of fire via façade and windows is one of the more likely routes of fire spread as the prescriptive regulation on vertical safety distance between windows do not fully protected the apartment above the room of fire origin. Swedish prescriptive regulations enforce the use of a 1.2 m vertical distance between windows, as well as the use of non-combustible façade material. A fully developed fire in an apartment results in flames coming out from the windows, and the characteristics of such flames are described in EN 1991-1-2:

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

L_L is the flame height, Q is the heat release rate of the fire, w is the width of the window and h is the height of the window. A typical building with a window height of 1.8 m and 1.2 m vertical distance between windows will result in a flame height of 6.0 m for a 10 MW fire, see Figure 7.3.

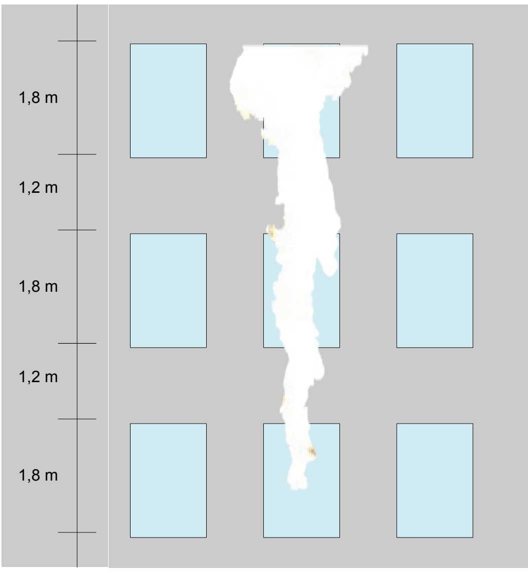

Figure 7.3 Illustration of flame engulfing from apartment window in a fully developed fire.

A vertical distance of 1.2 m will hardly prevent fire spread from a fully developed apartment fire. An interaction, either by fire service personnel or by residents of the building, is necessary to prevent this from happening. Although, a combustible façade material will aid fire spread and as a result of this, the use of combustible material in the façade is limited. Special attention is given to the possibility that a fire will spread to an apartment two floors above the fire floor. Figure 7.3 shows that this might be the case even if the façade material is incombustible, but nevertheless, the risk will definitely increase if the fire could be fueled from the façade material as well. Babruaskas (2001) states that wood is ignited when it reaches a temperature of 300-400° C and Figure 7.4 shows a measurement of the plume temperature made by Suzuki el. al. (2001).

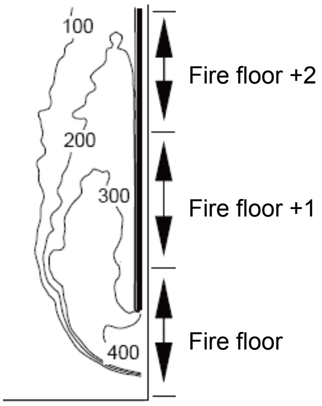

Figure 7.4 Illustration of temperature profile of the fire plume.

The experiments by Suzuki et. al. (2001) show there is a risk of igniting wood at one level above the fire floor. Such ignition could eventually cause the fire to spread to the whole façade, and oppose a serious threat to the building.

7.2.2 Expected performance of fire sprinklers in an apartment building

Nystedt (2011) shows statistics on sprinkler performance from several sources. The success rate of sprinklers in apartment buildings is high, app. 96 %. Upon on sprinkler actuation, the fire will most likely be put out. As described in section 6.2.2, a fully-developed fire is a requirement for fire spread to another fire compartment. A fire sprinkler system does prevent this from happening by a high degree of reliability as described in section 7.2.3 below.

7.2.3 Probability of fire spread

A method on estimating the probability of having a large (fully-developed) fire is presented in section 6.2.2. By applying the same method to apartment buildings with data from Nystedt (2011) results in the following probabilities of a large fire:

- The probability of a large fire an apartment without sprinklers is 51.0 %.
- The probability of a large fire an apartment with sprinklers is 2.0 %

Note that the response of the fire service is not included in the calculated probabilities. Without the response of the fire service, the large fire will most likely be able to spread to the apartment above (as shown in section 7.2.1). The same conclusion is valid for a sprinklered building, when the fire is large and the sprinkler system is unavailable. If the façade material is combustible, the presence of material that could fuel the fire will increase the risk of fire spread two floors above the fire floor. Nystedt (2011) shows that the statistics on fire spread to another fire compartment shows is app. 3 % in apartment buildings. This indicates that there are other measures (or actions) taken to prevent the large fire (51 %) from spreading (3 %). Even if we do not consider any other measures than the sprinkler system, a building with sprinklers will have lower probability of fire spread (2 %) than a building without sprinklers.

7.2.4 Other aspects and limitations

First, materials with less rating then Euroclass D should not be allowed as façade material. Such material will have a burning behaviour that makes the risk of fire spread immediate and hard to control. Fire sprinklers will limit the risk of fire spread via the façade for fires occurring in a room with sprinklers. Therefore, there are some additional aspects that need to be considered when using combustible façade material:

- The risk of fire spread within the outer wall.
- The risk of fire spread due to an outside fire.

The risk of fire spread within the outer wall must be controlled despite the presence of fire sprinklers. A fire, with flames engulfing from the window, must not cause fire spread within concealed inside the outer wall as such fire spread is hard to control and could have an unpredictable behaviour. There are several measures available to control the risk of fire spread via the façade (Trätek, 2002) and if there is an air gap behind the wooden façade "fire stops" must be used, see Figure 7.5.

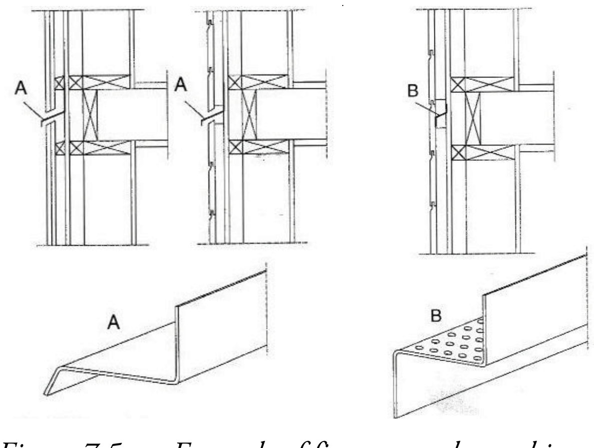

Figure 7.5 Example of fire stops to be used in a vented outer wall with wooden façade (Trätek, 2002).

An outside fire could cause fire spread to the façade and statistics on apartment fires shows that app. 400 of 44,000 apartment fires (i.e. 1 %) has its origin in the outside. Such low probability of fires starting in the outside will not have any significant influence of the probability of fire spread, even if sprinklers are considered to have 0 % effectiveness on these scenarios. However, there are a few measures that could be applied to limit the risk of outside fires causing fire spread to the combustible façade.

- Paved surface close to the façade without trees or large bushes.
- Cars should not be allowed to park closer than 2.0 m to the façade.
- Use of fire rated products or incombustible material on the first floor.

7.3 Conclusions

Fire sprinklers are effective in keeping a fire small. This effectiveness will result in far less probability of fire spread to another apartment, compared to a building without fire sprinklers, despite the prescience of combustible façade material. The use of combustible material (at least Euroclass D) will not result in any significant risk of fire spread as long as the sprinkler system is available, or the fire being kept small by other means.

If the sprinkler system is unavailable and the fire becomes large, the use of combustible material could result in fire spread via the façade. It is necessary that the behaviour of such fire is predictable and therefor any air gaps in the façade must be equipped with fire stops. It is also important to take some action in order to prevent a fire in the outside to involve the combustible façade.

8 Case study: Combining trade-offs in an office building

This chapter contains a case study where fire sprinklers are used as compensatory measure to allow for several design alternative and should be used to illustrate how to evaluate the effects of combining trade-offs. The case study could be applied to other buildings as well, but the data and the results presented in this chapter are specific to office buildings.

8.1 Qualitative design review

8.1.1 Architectural design and occupant characteristics

The building in the case study is an office building with four storeys. It is built of concrete and has different tenants on each floor and a centrally placed atrium. The occupants in the building (app. 400 people) are expected to be familiar with it and be able to escape by themselves. No plan sketch is available, but the design of the building is similar to the one used in chapter 6.

8.1.2 Fire hazards and other factors

The fire load in offices is well established and consistent. However, there is often a need for maximum design flexibility in order to adapt the building to the requirements of the tenants. The fire safety features are not sensitive to snow, rain or extreme temperatures.

8.1.3 Trial fire safety design

The trial fire safety design of the building has large deviation from the prescriptive requirements of office buildings found in the building code. A fire sprinkler system will be installed in the building as a complementary fire safety measure and the design team proposes several reductions in the traditional safety features:

- Surface finishes in Euroclass D.
- Extended travel distance to fire exits.
- Windows in E 30
- Façade materials in Euroclass D.

Table 8.1 outlines the main fire safety features of the building.

Table 8.1 Trial design solution for the office building.

Barrier	Measure	Requirements
Prevent ignition	Furniture clothing	Relevant standard
Control fire growth	Surface finishes in Euroclass D[13]	Analytical design
Control smoke spread	Fire dampers	Prescriptive design
Limit fire spread within building	Fire separating structures (EI 60)	Prescriptive design
	Windows in E 30[14]	Analytical design
	Façade material in Euroclass D[15]	Analytical design
	Fire sprinkler system[16]	Relevant standard
Prevent fire spread to other buildings	-	-
Means of escape	Two stairwells [17]	Analytical design
Facilitate rescue service operations	Access to building	Prescriptive design
Prevent structural collapse	Structural elements made of concrete (R 60)	Prescriptive design

It is assumed that all deviations from prescriptive design have been verified individually by adopting the methods documented in chapter 4 to 7. The focus in this chapter is to analyse the combination of trade-offs and verify that these could be applied all together.

8.1.4 Selection of design method

Since the design team proposes several deviations from prescriptive design, there is a need to verify that the trial design offers sufficient safety in case of fire. Analytical design will be used to perform the verification.

8.1.5 Verification prerequisites

The verification requirements are identified by the use of the tools provided by Lundin (2005), see Figure 8.1 and Figure 8.2.

[13] The prescriptive code requirement on surface finishes is Euroclass B.
[14] Windows in E 30 is a deviation from the prescriptive code requirement on EI 60.
[15] The prescriptive code requirement is Euroclass A.
[16] The fire sprinkler system is a complementary fire safety measures.
[17].The maximum travel distance is 50 m. which deviates from a maximum distance of 30 m (escape in one direction only) found in the prescriptive code.

Purpose of the fire safety measure (linked to the major barrier groups)	Trade-off						
	Added measure			Removed measure			
	A_1	A_2	...	R_1	R_2	R_3	R_4
Measures to prevent ignition							
Measures to control fire growht	+			-			
Measures to control smoke spread	+						
Measures to limit fire spread within a building	+					-	-
Measures to prevent fire spread to other building	+						
Allow rapid egress					-		
Facilitate rescue service operations							
Prevent structural collapse	+						

Figure 8.1 Identification of the effects of the trial design in comparison with the prescriptive code requirements. Note that A_1 is the fire sprinkler system. R_1 is linings in Euroclass D, R_2 is the extended travel distance to exits, R_3 is the reduced fire ratings on windows and R_4 is façade material in Euroclass D

The vertical distribution of measures in Figure 8.1 indicates that a there are added measures to meet up with those removed. However, as Figure 8.1 indicates there is only one added measure and four removed. The barrier group on "limit fire spread within a building" has two removed features that the fire sprinkler system must cope with. This imbalance must be addressed in the verification. As in Figure 8.1, Figure 8.2 indicates that there is an imbalance among the added and removed safety features. Removed safety features have been compensated for but it must be analysed if the total fire safety in the building is sufficient as only one measure is added.

Functional requirements in NKB (1994)	Trade-off						
	Added measure			Removed measure			
	A_1	A_2	...	R_1	R_2	R_3	R_4
The load-bearing capacity of the construction can be assumed for a specific period of time	+						
The generation and spread of fire and smoke within the construction is limited	+			-		-	-
The spread of fire to neighbouring construction works is limited	+						
People in the construction on fire can leave it or be rescued by other means	+				-		
The safety of fire and rescue service personnel is taken into consideration	+						

Figure 8.2 Investigation on the effect of the added and removed fire safety measures on the functional requirements. Note that A_1 is the fire sprinkler system. R_1 is linings in Euroclass D, R_2 is the extended travel distance to exits, R_3 is the reduced fire ratings on windows and R_4 is façade material in Euroclass D.

To conclude, a check list on different attributes of the fire safety system is presented.

Table 8.2 Evaluation of attributes of the fire safety system.

Attribute	Answer
Is the effectiveness of the added protection system dependent on human action?	No
Is the design alternative characterized by the reduction or elimination of several independent safety measures and replaced by a single measure?	Yes
Is the added safety measure dependent on several sub-systems functioning correctly?	No
Does the design alternative have the necessary degree of flexibility to cope with possible fires in the building?	Yes
How will the function of the protection system be affected by time and to what extent are service and maintenance necessary?	Fire sprinklers need maintenance according as outlined in the relevant standard
How vulnerable is the added protection system on power failure, weather conditions, software failure, etc?	Not vulnerable

The design alternative is considered to be properly verified by the use of a qualitative assessment as:

- It must be ensured that the combination of fire sprinklers and proposed design alternatives results in sufficient safety.
- The potential unavailability of the fire sprinkler system must be considered when assessing the possible outcomes of fires.

The verification of the trial design will thus be done qualitatively by balancing the benefits of a fire sprinkler system and the reductions on other safety features. The key task is to address the combination of trade-offs in order to assess the overall safety level and compare it to the safety level in an appropriate reference building. Some key analysis tasks to be answered are:

- What is the expected outcome (in qualitative terms) when the sprinkler system is unavailable?
- What other safety barriers are available to limit the consequences of a fire?
- What is the expected performance (in qualitative terms) of a reference building?
- Which time-scale is appropriate to use when illustrating failures?

The verification is documented in section 8.2.

8.2 Verification by qualitative assessment

8.2.1 Expected outcome when sprinkler system is available

The fire safety of building has a strong dependence on the sprinkler system. When the fire is not kept small (2 of 100 fires), either by the sprinkler system or by other measures/actions, the design alternatives will not perform as good as a building design according to the prescriptive requirements.

The use of combustible linings will result in a more rapid fire development, but escape is most likely to occur before the onset of untenable conditions if the building is equipped with smoke alarms. An analysis[18] of the robustness scenario states that escape is possible in the building prior the onset of untenable conditions, even if the robustness scenario is altered due to the presence of combustible linings. Reducing the fire rating on windows will result in possible fire spread when the sprinkler system is unavailable. A fully developed fire will most likely spread to the opposite fire compartment. Thus, there is a need for intervention by the fire service within 30 min from fire start[19] in order to prevent fire spread. A combustible façade material will aid fire spread via the outer wall. If the façade is involved in the fire, there is an increased possibility that fire will spread to floors above the fire floor. The risk of fire spread to the floor above the fire is eminent, even if the façade would be made of incombustible material. Thus, there is a need for fire service intervention to control this fire risk. If the outer walls of the building are accessible to the fire service, they will have an opportunity to limit fire spread if fires are prevented to spread within the wall (by the use of fire stops).

8.2.2 Performance of a reference building

A reference office building without fire sprinklers will have probability of a large fire of app. 47 %. An office building is most likely to be successfully evacuated in the event of fire, even without the presence of a fire alarm. Fire separating structures with an EI 60 rating will withstand the duration of the fire by a likelihood of app. 89 %. Although, there are some concerns that need to be addressed related to this issue. If there is a door between the fire compartments, the likelihood of the door being open is app. 20-50 % (BSI, 2001). Accordingly, the probability that fire-resisting glazing will achieve at least 75 % of the designated fire resistance standard is as low as 40 % (BSI, 2001). If such faults are considered, the probability of fire spread to another fire compartment is quite likely and the fire service must intervene to prevent this from happening. The fire service must also intervene to prevent fire spread via the façade as a vertical distance of 1.2 m does not result in appropriate protection.

[18] No quantitative analyses of fire development and escape have been conducted within the scope of this report. The statement is therefore only to be used as an example in this case study.

[19] Note that a fire rating of 30 min do not state that a real fire will spread after 30 min. Fire spread could occur either prior or after this time. However, the standardised fire and the parametric fire have similar time-temperature curve during the first 60 min, resulting in approximately the same stress to the fire rated structure.

8.3 Conclusions

A fire in a sprinklered building is kept small in app. 98 of 100 fires. This could be compared to a building without sprinklers where the fire is kept small in app. 50 of 100 fires. Buildings without fire sprinklers must rely on other measures/action in order to prevent fire spread. The fire service has a very important role in the safety of non-sprinklered buildings. If the response of the fire service is not considered, sprinklered buildings will generally have up to 25 times less risk of fire become large and threatening occupants as well as the building.

The proposed design alternatives asks for the fire service to initiate an intervention before 30 min in order to prevent fire spread within the building and app. 10-15 min to prevent extensive fire spread via the façade. Most, importantly the dependence on the fire service to fulfil important technical requirement on fire safety is far less in a building with sprinklers compared to a non-sprinklered building.

Thus, fire sprinkler would allow for a combination of trade-offs. However, a minimum set of fire safety measures are needed to ensure the successful escape of occupants as well as assuring appropriate means of fire service response.

9 Discussion

9.1 Available methods

Section 2.3 describes three suitable methods to be used when verifying the trial fire safety design solution. These methods are presented more thoroughly in Nystedt (2011) but some notes on their application could be discussed in this section. As stated by Nystedt (2011), the selection of a suitable method is mostly dependent on the degree of deviation from the prescriptive design. If there is a limited deviation from those requirements and if the added safety feature (e.g. a fire sprinkler system) has well-known performance in the application of interest, the designer could verify compliance with the building regulations by using a qualitative assessment. A qualitative assessment must rely upon existing proofs that the trial design solution will perform better than the prescriptive design solution. The demand of sensitivity analysis is considered to be low by applying a sufficient safety margin to the design in order to treat relevant uncertainties.

Quantitative analyses, either deterministic or probabilistic, should be applied when a qualitative assessment is inappropriate. Practically, there is little difference between a deterministic and probabilistic analysis. The modeling of consequences is practically the same and the difference relates mostly to how the result is evaluated. In a deterministic analysis the performance of the trial design solution is explicitly evaluated for a number of design scenarios and design criteria. The building must meet the design criteria for each individual scenario. A probabilistic analysis requires that additional scenarios are studied in order to express the building fire risk. The building could does not necessarily have to meet the design criteria of each individual scenario as long as the total fire risk is lower than the one in a reference building designed according to prescriptive requirements. The selection of type of quantitative method is decided by the design team, and any of the methods could be appropriate to a given design situation. However a probabilistic method is the only suitable method to use when there is a need to consider the minimum performance that a building must have when sprinklers are unavailable.

9.2 The fire safety design process

The fire safety design process presented by Nystedt (2011) is described in chapter 2 and Figure 2.1 and a part of the figure is reprinted below for clarity.

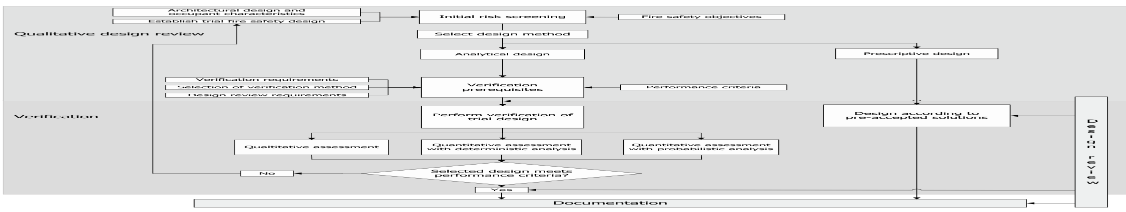

Figure 9.1 Part of Figure 2.1 on the fire safety design process.

One could argue that the design process has some inconsistencies that need to be addressed. First, the purpose of performing an initial risk screening prior to the selection of design method seems a little bit odd. The intention of the initial risk screening in this stage of the design is to decide if prescriptive design is possible to apply to the specific building. But, as the stated in the limitations in section 1.4, the case studies (and the framework provided by Nystedt (2011)) are only valid in buildings where prescriptive solutions could be applied. As a result, some alteration to Figure 2.1 could be considered. Please note that the selection of design method is done prior to applying the work flow in Figure 9.2.

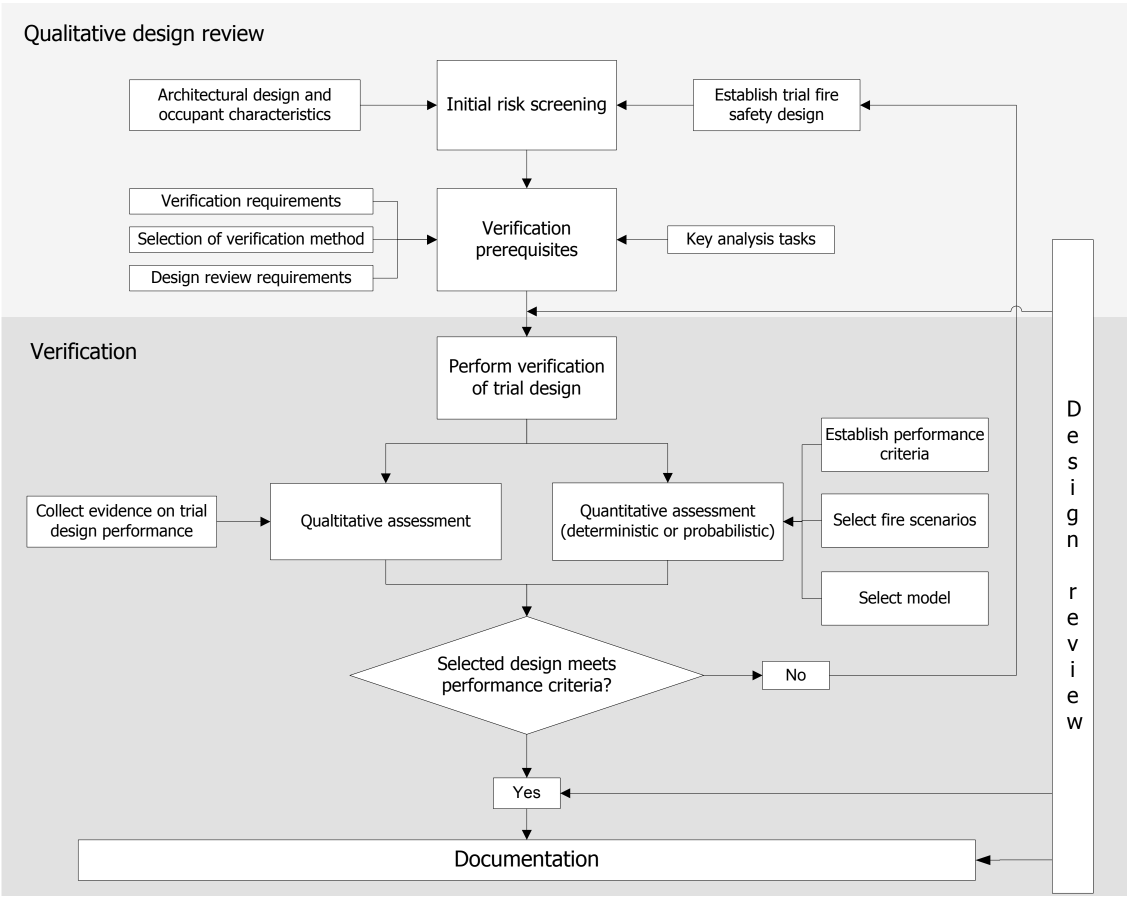

Figure 9.2 Alterations to Figure 2.1 to better suit practical application.

9.3 Key analysis tasks

Key analysis tasks should cover all essential aspects that the verification should provide answers to. Every QDR is finalised by the establishing these tasks and it is of utterly importance that all necessary aspects are covered in the formulation of them. Each case study lists some key analysis tasks to be addressed (see the end of section 4.1.5, 5.1.5, etc.), but there is no guarantee that these tasks cover all necessary aspects. Quality assurance in terms of design review is very important at this stage in order to reach consensus on the aim and the objective of the verification.

Design review should be carried out throughout the design process and the demands for review should be established at an early stage. The sooner the review is incorporated in the process, the more effective is the fire safety design. The degree of design review depends on the complexity of the proposed solutions and ranges from a simple self-check to the use of an independent third party peer-review. The use of an independent review is a great opportunity for the developer to ensure quality in complicated buildings.

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