Research to the performance and adequacy of

Fire compartmentation

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Preface

This document is the thesis report for my master of Science degree in Building Engineering at the Faculty of Civil Engineering and Geosciences at Delft University Technology, with a specialisation in Structural Design. This report is intended for the members of the graduation committee and all others who are interested.

The performance of fire compartmentation has been investigated in this research, as well as the achievements and adequacy of fire compartmentation in practice. This research confirmed that many uncertainties are present in the performance of fire compartmentation and the importance of fire compartmentation. Although little information and knowledge is currently available about these aspects, it is found that compartmentation systems are in practice very vulnerable for poor implementation, and this probably affects the fire performance of compartmentation in most of the investigated buildings strongly.

I would like to thank my graduation committee members, prof. ir. R. Nijsse (TU Delft), ir. R.J.M. van Mierlo (Efectis Nederland B.V.), ir. S. Pasterkamp (TU Delft) and dr. ir. D.M. Hanea (TU Delft) for their support, guidance, critical comments on my interim reports and sharing their knowledge. Also I would like to thank the colleagues of Efectis Nederlands B.V. for providing me with a good working environment and their help during my thesis project.

Last but not least I would like to thank J. van de Ven and ing. H. van Vulpen of the Rijksgebouwendienst for providing me inspection reports of some government-owned buildings in the Netherlands, which are an important input in this research. In addition, I would like to thank the members of the European Network for Fire Investigation and Prevention (ENFIP) for sharing their information and knowledge about the performance of fire compartmentation.

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Abstract

Fire compartmentation is an important aspect in the design of buildings. Buildings need to be divided into one or more fire compartments, which are intended as the maximum extension area of the fire. The Dutch Building Decree (nl. Bouwbesluit) therefore prescribes a maximum floor area of compartments and a resistance against fire spread to other compartments, dependent on the occupancy class (nl. gebruiksfunctie) and whether it is a new or an existing building. Also collapse of the building outside the fire compartment should be prevented for sufficient period of time, therefore loadbearing elements need to have a prescribed fire endurance.

The conceptual idea behind the current fire safety legislation is evident, but the (quantified) requirements are arbitrary and it is not clear how these requirements contribute to the safety of people and property. The same holds for fire compartmentation. It is not clear what is actually achieved by the current legislation and policies for compartmentation in terms of safety of people and protection of property. Also it is currently uncertain what the performance of compartmentation systems is in actual building fires relative to its intended design performance. The objective of this research is therefore to answer the following research question:

> *What is the actual performance and reliability of compartmentation systems against fire spread and what is in practice achieved by applying fire compartmentation?*

Compartmentation systems are designed to prevent fire spread to adjacent compartments. Many different compartmentation systems are available, ranging from concrete and masonry structures to light weight stud walls and glazed partitions. Moreover, it is in many buildings necessary to have passages between different fire compartments for functional reasons, for example doors, ducting and piping between compartments are often essential. The implementation of these systems in compartmentation makes compartmentation vulnerable for mistakes and weaknesses and its performance difficult to predict.

The performance of compartmentation systems depends on many different factors, such as size effects, decrease of system quality during the life time of the building, interaction between elements, construction quality, systems which do not operate during fire and the fire conditions. All these factors are characterized by uncertainty and unpredictability.

Little research has been carried out on the performance of compartmentation systems in actual building fires. In the Netherlands, some research was carried out on the performance of compartmentation during a research on high-damage fires (damage > 1 million euros) in 2001 by Nibra and NCP. It was found that compartmentation was in approximately 35% of the high-damage fires was not sufficient to prevent fire spread to other compartments in the building.

Whereas it is often difficult to determine the causes of fire spread to adjacent compartments and to determine the quality of the compartmentation before the fire started, shortcomings are often mentioned as main reasons in case of premature failure of compartmentation systems. Shortcomings are in this case defined as elements in a compartmentation system which are not built in accordance with the applicable legislation

and standards, elements which are not correctly used or elements which are not properly maintained. To get insight in the presence of shortcomings in buildings, some inspection reports provided by the Governments Buildings Agency (nl. Rijksgebouwendienst, RGD) have been analysed. These inspection reports included buildings with an industrial function, buildings with a meeting function and offices. It is presumable that these inspection reports are representative for most similar buildings in the Netherlands, also buildings which are not owned by the RGD.

It turned out that many shortcomings are present in the analysed buildings. Especially shortcomings related to doors, ducting and piping are frequently found in buildings. In fact, 92% of the analysed buildings has one or more shortcomings related to doors and 88% of the buildings has one or more shortcomings related to ducting and piping. Also the maximum compartment size is exceeded in many buildings (±60%) compared to the requirements for new buildings.

With the rough quantification of shortcomings derived from the RGD inspection reports, an estimation was made of the probability of fire spread to other compartments due to these shortcomings. This estimation is based on judgement of fire engineers, since statistics on the influence of shortcomings on the performance of compartmentation do not exist and knowledge on this topic is limited, or at least not well documented. It is estimated that shortcomings in approximately 6% of the compartments can lead to fire spread within 5 minutes when a fully developed fire occurs in the compartment. The probability of fire spread to adjacent compartments due to the presence of shortcomings is estimated to occur in approximately 36% of the compartments within 15 minutes and in 56% of the compartments within 30 minutes.

The estimated probability of failure can for example be reduced by fire brigade intervention or by a slow fire development inside the fire compartment (for example due to a subdivision of the compartment into subcompartments or rooms). Also when the fire duration is relatively small and burnout of the compartments occurs in an early stage, the probability of failure will be smaller, since the probability of fire spread to adjacent compartments via many shortcomings is estimated to become larger with an increasing fire duration. Other aspects, such as failure of compartmentation due to interaction between elements, premature failure of elements which do comply with legislation and the influence of differences in fire conditions are neglected in this analysis.

When the results of the analysis are compared to the figures about failure of compartmentation in the Nibra and NCP researches on high damage fires in 2001, the results are quite similar in order of magnitude. However, the performance of compartmentation in buildings constructed after the introduction of the national Building Decree in 1992 is much better according to the Nibra investigation, since only in 17% of the buildings the compartmentation failed to keep the fire inside the compartment where the fire originated. No clear explanation for the improvements in the performance of fire compartmentation after the introduction of the Building Decree can be found based on the limited number of inspection reports used for this analysis. The presence of shortcomings is more or less similar in the analysed buildings; no clear relation can be distinguished with the function of the building (meeting, office, industrial) or the age of the building based on the inspection reports.

Most shortcomings (±70%) in fire compartmentation occur during construction and/or maintenance/modification works in the building. Also a lack of maintenance is an important cause of shortcomings. A lack of awareness among stakeholders about the importance of proper compartmentation is probably the main source of these shortcomings. When the probability of fire spread due to shortcomings is considered, failure of compartmentation is in approximately 50% of the cases attributed to shortcomings during construction and maintenance of the building, whereas the majority of these mistakes are related to ducting and piping. This might be the crux for the better performance of newer buildings as found in the Nibra research, since less changes and modifications are to be expected in buildings which are just completed, but the analysed inspection reports do not offer solid evidence for this.

Despite the many shortcomings which are present in fire compartmentation, the consequences for the safety of people appear to be small. In building fires where fatalities occurred, (insufficient) performance of fire compartmentation was generally not appointed to be decisive. In the period 2001 - 2008, on average about 85% of the fire casualties occurred in dwellings. The relative high fatality rate in dwelling fires is mainly ascribed to the rapid fire and smoke development in dwellings due to the materials used in modern furniture (e.g. synthetic foams). People are also often not warned in time, for example because they are asleep, or they are not aware of the danger of fire and smoke and leave their house too late. When casualties occur in other building fires, there is often a strong relation with accidents such as explosions, disregarding rules for escape routes, disregarding flammability requirements for interior or decoration, too crowded buildings and/or poor evacuation policies. And in some cases it is hard to avoid casualties by taking reasonable measures.

Compartmentation is usually not mentioned as one of the key aspects in case of fire fatalities. However, cases where compartmentation was successful and essential to prevent harm to the occupants, are not reported. It is therefore difficult to determine the contribution of fire compartmentation to the life safety of people and how big the safety margin is between the actual performance of compartmentation and the required performance which is necessary for the safety of people.

The importance of fire compartmentation becomes more apparent when property losses are considered. When compartmentation functions well, it helps to limit the fire damage by limiting the maximum extension area of fire and smoke. Whereas fire compartmentation for the safety of people should function well until everyone has left the building, for damage prevention it should function as long as property outside the fire compartment is endangered by the fire. The latter seems to be more difficult, since fire spread occurred in approximately 40 – 50% of the buildings where compartmentation was relevant (constructed before 1992) according to the Nibra research. Especially when larger fire durations are considered, the presence of shortcomings makes it very likely that fire compartmentation will not succeed in keeping the fire inside the compartment where the fire originated without the help of fire brigade. For this purpose, the quality of compartmentation systems should be very high, or possible failure of the compartmentation systems should be considered in the design of the building.

The quality and performance of compartmentation is often worse than intended, but fatalities are generally not attributed to bad performance of compartmentation, especially not in office, meeting and industrial buildings. For the prevention of casualties it seems therefore generally not necessary to improve the quality of compartmentation systems in these buildings compared to the modern day standard. If significant improvements in prevention of fire damages by fire compartmentation are envisaged by building-owners and/or insurers, than the current policies and attitude regarding compartmentation should be changed in order to secure better quality of compartmentation and to reduce the number of shortcomings which lead to premature failure of compartmentation.

It is doubtful if regulatory changes for compartmentation will improve the fire performance of buildings and will lead to more efficient designs with smaller differences between the intended (design) performance level and the actual performance level and more fit to purpose designs, since knowledge is currently inadequate for an integral assessment and design mainly relies on conceptual judgement. Arbitrariness is therefore difficult to avoid. Moreover, the differences between the intended performance level and the actual performance in real building fires are in many cases caused by poor implementation and maintenance of compartmentation in practice, which is difficult to anticipate on and to foresee during design. More attention and budget for good implementation and maintenance of compartmentation subsequently or instead of investments in high quality systems which are poorly maintained during the exploitation phase of the building is more cost effective and makes compartmentation more effective.

To get more insight in the failure modes of compartmentation and to develop better design methodologies based on this information and to improve inspection plans and maintenance, it is recommended to establish a database which systematically reports the performance of compartmentation systems in real building fires. Also it should be found out what a reasonably (and practically) achievable fire resistance is for compartmentation in actual building fires, so that the risk of premature failure of compartmentation is reduced and/or can be taken into account in design, both for the purpose of human safety as for the safety of property. It will help to create more understanding about the importance and the usefulness of investments in fire compartmentation.

Contents

List of figures

List of tables

1 Introduction

The fire safety regulations in the Netherlands are based on consensus among stakeholders. Regulatory changes are mainly disaster-driven and hardly based on an integral risk assessment. Furthermore it has not been determined what goals are pursued, such as how many victims or euros damage per year are acceptable. Because of this, it is unclear how useful investments are in various buildings. In office buildings for example, there are rarely any casualties due to fire, yet the demands are for approximately 70% identical to the demands of more risky buildings like hotels. The requirements for dwellings are relatively limited, while house fires cause most fatalities (1).

Uncertainties at all levels of fire safety engineering and insufficient knowledge about many fire safety related variables are important reasons why the fire safety regulations are not based on an integral risk assessment yet. These uncertainties range from human behaviour to the adequacy and performance of fire prevention measures. Reducing these uncertainties will allow more sophisticated design approaches and more knowledge about the adequacy and reliability of different fire safety measures will lead to more substantiated design choices and opportunities. With more knowledge about the performance, the achievements and importance of different fire safety measures, the fire safety system in buildings can be designed more effective.

1.1 The scope of this thesis

This research will focus on the current fire safety regulations in the Dutch building codes. To limit the scope of the study, it is not possible to consider all the fire safety. The emphasis of this research will therefore be on fire compartmentation.

Compartmentation is a widely applied and accepted fire safety measure. The purpose of compartmentation is to limit fire spread in a build environment. A building is therefore divided into one or more fire compartments with the aim of limiting the maximum extension area of the fire within the building, or from the burning building to other buildings. To limit the maximum extension area of the fire, the maximum compartment size is limited. Also the perimeter of the fire compartment should have sufficient fire resistance to prevent fire spread from the burning compartment to other compartments. In this thesis the emphasis is on compartmentation, the focus will in particular be on the spread of fire within buildings.

Compartmentation is, when the equivalence principle (see section 3.2) is disregarded, a fairly defined area within the Dutch building legislation. Also the loadbearing structure will be considered in this study, since it has a strong correlation with compartmentation. Compartmentation and the loadbearing structure often act together as a fire separating system between compartments. Floors are an example of this. Furthermore, the (partial) failure of the loadbearing structure has in general a direct influence on the integrity of compartmentation systems. Another common property of compartmentation and the loadbearing structure is that fire performance of these two aspects are primarily of interest in a fully developed compartment fire (after flashover) and not, or at least to a much smaller extent, in the development stage of a fire.

The fire resistance of compartmentation systems and loadbearing structures is expressed as a time until failure in minutes (20, 30, 60, 90 or 120 minute rating, nl. WBDBO, weerstand tegen branddoorslag and brandoverslag). For compartmentation systems, failure occurs when the system has lost its separating function between the compartments and fire propagation outside the fire compartment is no longer stopped. For loadbearing structures failure is defined as the time after which the structure has lost its load carrying capacity in fire conditions.

For compartmentation and loadbearing structures, the minimum time until failure is prescribed in the building legislation dependent on the building type (nl. gebouwtype) and its use function (nl. gebruiksfunctie). Also the maximum size of compartments depends on the building type and its use function.

The use functions are in the Dutch building codes categorized in different occupancy classes. The necessary fire performance rating, expressed as fire resistance in minutes, depends on the occupancy class of the building. Not all occupancy classes are considered in this research. The focus will be on buildings with a meeting function, offices and industrial buildings.

The performance of compartmentation systems in real fires will be a main part of this research. Nowadays the performance of compartmentation systems is an important uncertainty in fire safety design and little research has been carried out on this topic.

1.2 The importance of this research

The lack of knowledge which is present in the area of fire compartmentation is hindering the development of advanced fire safety assessment methods. Moreover it is not clear why the regulations for compartmentation are as they are now, how compartmentation performs in reality and how this contributes to the safety of people and property. This research is aiming at reducing this gap in knowledge about compartmentation.

Since failure of compartmentation has an important influence on the occurrence of fire damages, the performance of compartmentation is investigated. For example, a research of the Nibra (Institute for Fire Brigade and Disaster Prevention) on high damage fires in 2001 has shown that compartmentation was not sufficient to prevent fire spread outside the fire compartment in 27 out of 47 cases (5).

Insight should be gained in the actual behaviour of compartmentation systems in real fires and its weaknesses and points of attention. This will lead to an increased understanding of the actual fire performance of compartmentation systems and its reliability. Also the predictability of the actual fire performance can be increased with the results of this research.

The reliability of compartmentation system is an important input parameter for risk assessments on fire damages, since failure of compartmentation systems leads to fire propagation outside the fire compartment. Investigating the reliability and actual performance of compartmentation systems is therefore an important topic in this thesis.

1.3 Research questions

The main research question is defined as follows:

> *What is the actual performance and reliability of compartmentation systems against fire spread and what is in practice achieved by applying fire compartmentation?*

Several sub-questions regarding compartment size, fire performance of fire separations between compartments and fire damages should be answered to get a proper answer to the main research question:

- What requirements are set for fire compartmentation and why?
- What are the main functions of compartmentation?
- What is the performance compartmentation systems in real fire situations taking into account shortcomings in design, construction and maintenance and what are the main causes of these shortcomings?
- What are the main results of fire safety measures and compartmentation in practice?
- How does the actual performance of compartmentation systems influence the consequences of fires?

1.4 Objectives

The objectives of this research are defined as follows:

- *Identifying and summarize the properties and influence factors that determine the actual fire resistance of compartmentation systems.*
  This objective aims at the actual fire performance and reliability of compartmentation systems, influenced by shortcomings which may lead to premature fire spread, differences between standard classification conditions and real fire conditions etc. The resistance of the compartmentation systems depends on many variables and is characterized by many uncertainties. These variables and uncertainties are for example related to the temperature development inside the fire compartment, the quality of construction, failure of components in the compartmentation system, scatter in test results etc. The factors that might lead to differences in the performance of compartmentation systems in case of fire and the performance according to current design methods.

- *Determining the effect of the quality of compartmentation systems on fire spread to other compartments.*
  This objective aims at the effect of the actual performance level on the probability of fire spread to other compartments. When a compartmentation system loses its separating function against fire spread after a certain amount of time, this does not directly mean a complete burnout of the adjacent fire compartment. It should therefore be investigated to what extend fire spread does occur in the adjacent compartment, and how likely severe fire spread to adjacent compartments is.

- *Determining the probability of insufficient fire performance to prevent fire spread relative to its intended design performance.*
  The aim of this objective is getting more insight in the probability of premature failure of compartmentation systems, i.e. the probability that the system does not perform sufficiently as intended in design.

- *Drawing conclusions about the strengths and weaknesses of regulations and policies concerning compartmentation relative to its original objectives.*
  The intention of this research is to investigate the fire safety requirements and policies for compartmentation in the Dutch building legislation and to determine its effectiveness and efficiency.

1.5 Methodology

An important part of this thesis is a literature review. The literature review will be used to gain general information about the topic in order to increase the understanding of all aspects that are related to the topic of this research. This is necessary to be able to distinguish the main and side issues in this research, and to set a sharp research scope. Also a part of the literature review is necessary to make the assumptions about variables and uncertainties as realistic as possible and to find out what research results are already available about the performance of compartmentation.

The actual fire performance of compartmentation systems will be investigated partly based on a literature review, in order to determine which aspects already have been investigated or to investigate which aspects are important for the performance in real fires. Inspection reports from the Dutch Government Building Agency (nl. Rijksgebouwendienst) will be used to identify frequent shortcomings in compartmentation systems in practice and whether or not these shortcomings have an important influence on the actual performance of compartmentation. The outcome of these inspection reports will be analysed and a judgement will be made on the effect of these shortcomings on the actual fire performance in relation to their frequency of occurrence. This will help to create more insight and knowledge in realistic failure modes of compartmentation systems and the probability of the occurrence of these failure modes.

In order to investigate what is actually achieved by fire compartmentation in the modern day building practice, the available statistics about casualties and fire damages will be analysed. Casualties and property damages are in this research used as the main benchmarks to measure the achievements of fire compartmentation. Also some information about the performance of compartmentation and its consequences for the safety of people and property have already been investigated in literature, as well in the Netherlands as abroad, therefore these results will also be considered in this research.

1.6 Limitations

Fire safety has a wide and complex field of application and therefore it is impossible to cover the entire field of fire safety in a proper way. Hence, this research has its limitations, also for the topics within the scope of the research.

In the previous section it was already mentioned that the fire resistance of compartmentation against fire spread to other compartments depends on many variables and uncertainties. Due to the limited amount of available time, it will not be possible to investigate all these aspects in depth. Assumptions have to be made to limit the number of variables and uncertainties. The aim is to take these assumptions as realistic as possible and to properly substantiate the assumptions. Also the effect of the assumptions should be considered throughout the research and where necessary, further research will be recommended.

Very little research has been carried out on the actual fire performance of compartmentation, also not by legislators. Many requirements are quite arbitrary which makes them difficult to fathom. Moreover, the regulations have to be practicable and applicable, which implies that a lot of optimisation is perhaps not possible, or at least not practicable. This does not necessarily limit the research, but it should be taken into account.

Data about the performance of buildings in actual fires are limited. Therefore only very little information is available about the failure modes of building constructions in case of fire, fire development in real building fires and the relation with the performance of compartmentation. A limited number of inspection reports has been used to get insight in the presence of shortcomings (i.e. elements which do not comply with the applicable legislation and standards) and the causes of these shortcomings. The influence of these shortcomings on the fire performance of compartmentation systems has been estimated based on expert judgement.

Also very little information is available about the required performance of compartmentation for the safety of people and property is very limited, i.e. what should the performance of compartmentation be to prevent casualties or fire damages? Currently this is mainly based on assumptions. Also what actually is achieved by applying compartmentation is uncertain. Although compartmentation has multiple functions (increase the time available for escape, protect escape routes, facilitate fire fighter access during rescue operations, limit the area of possible loss, reduce the impact of the fire on the structure, separate different occupancies, isolate hazards and contain releases of hazardous materials, see section 3.3), fire casualties and fire damages are taken as reference measures for the achievements of compartmentation in practice, since these are the only aspects of which data are available.

1.7 Overview of the structure and contents of this report

Following the introduction, chapter 2 provides background information about building fires. The general characteristics of building fires are discussed and the different stages in the development stage of building fires, as well as the influence factors determining the speed of fire development, the temperature development and the fire duration, such as the fire load and ventilation. Heat and smoke are important products of fire. Heat affects the structure of the building and smoke is also an important design aspect in buildings, since the smoke is dangerous for human life safety. People should be able to leave the building in time before dangerous conditions are reached. Building egress is therefore also discussed in chapter 2.

The fire safety regulations in the Netherlands are described in chapter 3. First the general background and structure of the fire safety regulations in the Netherlands is discussed as well as its objectives. Then the specific objectives of structural facilities such as fire compartmentation are discussed, how these specific objectives relate to the general objectives of fire safety legislation and how the building structure is intended to reduce the fire risks for humans and property. The requirements for structures are then discussed, such as the required fire resistance and compartment size as well as the performance criteria for these systems.

In chapter 4 it is discussed what actually is achieved by the current fire safety measures in practice. The fire risk is a function of the probability of fire occurrence and the consequences of the fire. The consequences can be expressed in terms of property damage and casualties. The acceptability of fire risks, the probability of fire occurrence and the consequences of fires in practice are discussed, as well as the importance of compartmentation for the reduction of these risks.

The performance of structures and compartmentation in fire conditions is discussed in chapter 5. It is discussed what failure modes can occur when different construction materials/compartmentation elements are exposed to heat and how failure can be prevented. In the next chapter it is then discussed what the actual performance of building constructions is real building fires and what factors are in actual fires important for the failure of compartmentation, such as the actual fire conditions, interaction between elements, shortcomings in construction and assembly etc.

The presence of shortcomings in assembly and construction is further investigated in chapter 7, as well as its influence on the performance of buildings in case of fire, since the presence of shortcomings appears to have a strong influence on the fire performance and reliability of buildings. First the presence of shortcomings is investigated based on inspection reports, than it is investigated what the consequence of the presence of shortcomings is on the performance of compartmentation and what the main causes are for the presence of shortcomings.

Finally, the conclusions, recommendations and recommendations for future research are presented in chapter 8. The conclusions are followed by a reference list and appendices I and II, which are complementary to the analysis of the inspection reports.

2 Building fires and building egress

In this section some general information is presented in order to explain the basic fire and smoke behaviour in buildings and its effects on human life safety. Different stages can be distinguished during a fire, each having specific possibilities for fire safety measures. The development of heat is an important design aspect for compartmentation and loadbearing structures in buildings, since the material properties are affected by heat.

The evacuation of buildings is an important design aspect in fire safety engineering, since the building occupants should leave the building before dangerous conditions are reached inside the staying areas of people. The behaviour of people has a strong influence on the evacuation of the building. People's behaviours can cause or prevent fires, affect fires or increase or reduce the harm from fires (8).

2.1 Building fires

The fire development in buildings depends on several variables, such as the amount and characteristics of combustibles and the availability of oxygen. If a fire is enclosed by a closed envelope, like a building, this strongly influences the behaviour of the fire, since heat and smoke cannot be released freely. Also the spread of smoke within a building is an important design aspect, since smoke is in practice often decisive for the success of a building evacuation.

2.1.1 General fire behaviour

Fire is a chemical reaction between fuel and oxygen in which energy (heat) is released. The reaction starts when the fuel is exposed to a particular ignition energy. This can be the heat of an external ignition source, but it can also be the heat of the fire itself. When the fuel is sufficiently heated, the fuel is decomposed into combustible gasses (pyrolysis gasses). Solids and liquids are not directly combustible, but need to be decomposed into combustible gasses first. For the pyrolysis, some energy is needed. After that, the pyrolysis gasses are combusted in a reaction with oxygen. A lot of energy is released in this reaction (9) (10).

The reaction depends on the presence of fuel, oxygen and heat, see the 'fire triangle' in Figure 1. The fire reaction will not take place if one of these three aspects is not available.

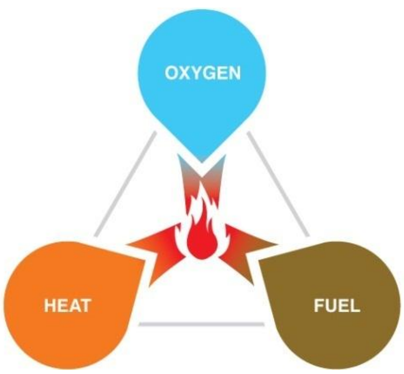

Figure 1 The fire triangle (11)

- Fuel can be present in different compositions, different dimensions, in direct contact with oxygen or in a dense packing. These aspects influence the required ignition temperature and the speed of the fire development. The quantity of fuel in a room is expressed in MJ/m^2, but the temperature development is strongly dependent on many other characteristics, like the rate of heat release in certain conditions. The difference between large wooden blocks and fine sawdust is for example apparent; the combustion can only take place around the perimeter of the block, whereas the exposed surface of sawdust is much larger. This results in a higher ignition temperature and the rate of heat release will be lower.

- Oxygen is required for the combustion of a fuel. The amount of available oxygen strongly influences the chemical reaction. In general, the required ignition energy decreases with an increasing concentration of oxygen in the surrounding air. Vice versa, the fire will extinguish when the oxygen level gets too low.
- Heat is necessary to start a fire and for the continuation of the fire. The required energy which is needed for ignition depends on the fuel type and the oxygen level in the surrounding air. There are many heat sources possible which can initiate or propagate a fire, like an open fire, a spark, hot objects etc. After ignition, the fire will only continue if sufficient energy is released during the reaction to continue the combustion, i.e. a part of the released energy is necessary to continue the reaction (thermal feedback) (9).

During a fire, heat is released. The heat spreads into the surroundings by convection, radiation and conduction. Heat (and therewith fire) can therefore be propagated via one of these means (9):

- Convection: diffusion of heat due to a moving substance. This can be a gas (air circulation) or a liquid.
- Radiation: heat transfer without the interference of a substance. The heat travels through a space by energetic waves.
- Conduction: diffusion of heat through a material due to a temperature gradient within the material.

2.1.2 Fire development in buildings

After ignition, the fire starts growing when sufficient fuel, heat and oxygen are available. In open space, the produced heat and smoke can spread to the atmosphere. This is different in a building. The fire is in an enclosed area and cannot release its heat and smoke freely. The smoke plume spreads along the ceiling and the room temperature increases. The smoke typically contains unburned pyrolysis gasses and increases in temperature due to the heat release of the fire. At a certain moment in time, when the radiation level becomes about $20kW/m^2$ and the temperature of the smoke layer becomes about 400 – 600°C, all combustible gasses in the room start to burn within a short period of time. This moment is called flashover. The temperature rises quickly and after flashover, all present combustible materials in the room start burning, see Figure 2 (12).

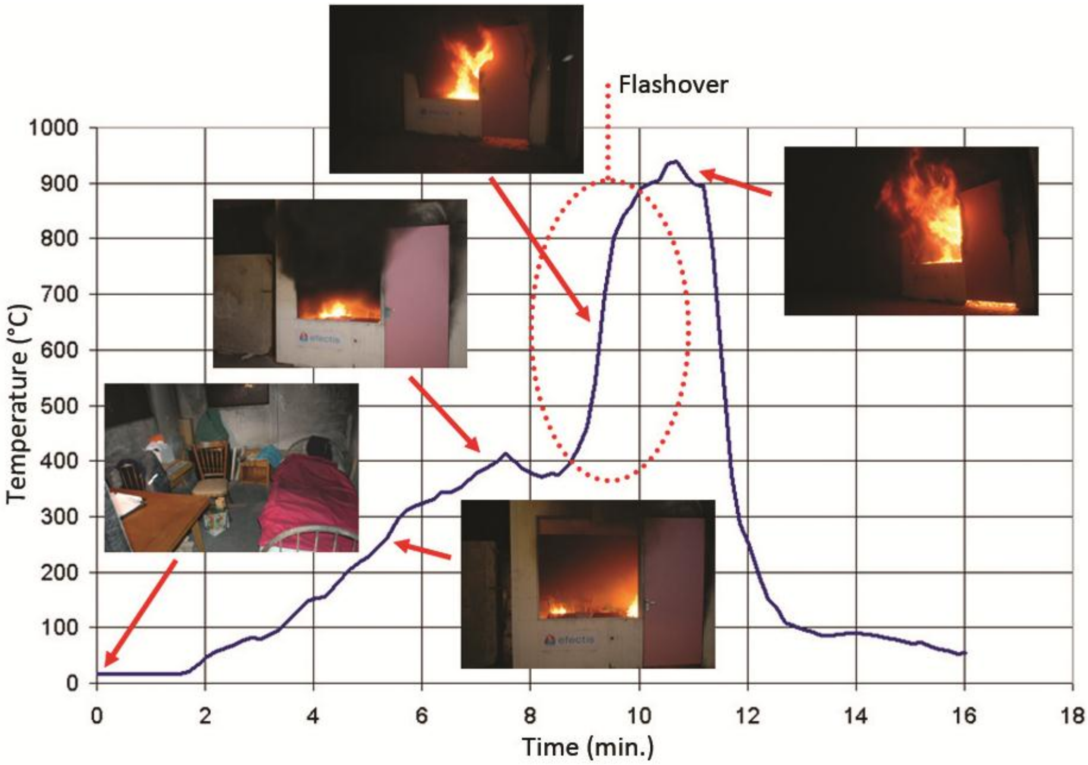

Figure 2 Fire development and flashover in a room (13)

In a compartment fire, three fire development phases can be distinguished: the development stage, the post-flashover stage and a decay or cooling stage, see Figure 3. The development stage is the period between ignition and flashover. The fire grows gradually until the moment of flashover. During flashover the fire spreads quickly through the compartment and the temperature increases rapidly. In the post-flashover stage, all combustibles in the compartment are burning. The fire is fully developed now. When most combustibles have been burned, the fire starts cooling down. This is called the decay stage.

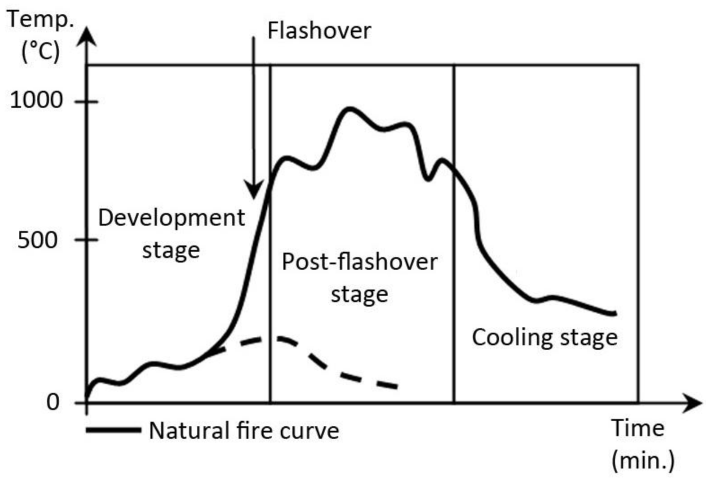

Figure 3 Typical temperature-time curve for a compartment fire (13)

Before flashover, the fire can be suppressed using active fire suppression measures like sprinklers and hand extinguishers. After flashover, these active suppression measures are not very helpful anymore. The amount of released heat is simply too big to suppress the fire effectively. This is where passive fire measures such as compartmentation and structural fire protection become important to prevent or limit structural collapse or fire spread (14).

The fire development in a compartment depends on many parameters, such as the dimensions of the compartment, availability of oxygen, presence of combustibles etc. The fire load density (the amount of available fuel in an area, expressed in MJ/m^2)[1] is one of the factors determining the fire development. Since the fire load density varies during the life time of a building, the fire load is often treated as a statistical value (15). Some typical values for the fire load in different building types are given in Table 1.

Table 1 Some typical fire loads densities in different buildings according to NEN-EN 1991-1-2 (15)

Use function	Fire load [MJ/m^2] Mean	Fire load [MJ/m^2] 80% fractile
Dwelling	780	948
Hospital	230	280
Hotel	310	377
Library	1500	1824
Office	420	511
School	285	347
Shopping center	600	730
Theatre, cinema	300	365
Transport function	100	122

Very important is also the speed in which these fuels release their energy. This is called the Rate of Heat Release (RHR), expressed in MW. When a certain amount of fuel with a high rate of heat release is combusted, the room temperature will increase fast and reach a high level within a short period. When the same amount of fuel with a low rate of heat release is combusted, the temperature will increase more slowly, but the fire will last longer; it takes longer before all combustibles have been burned. Besides the type and characteristics of the fuel, the RHR is also dependent on some other factors, such as the amount of available oxygen. If a compartment is well ventilated, more oxygen is available and the RHR increases (12) (13).

Fires can be ventilation controlled and fuel bed controlled. In case of a ventilation controlled fire, the heat release of the fire depends on the availability of oxygen. Fuel bed controlled fires are dependent on the availability and type of fuel, i.e. there is a surplus of oxygen for the fire reaction. In general, the duration of ventilation controlled fires is longer, and fuel bed controlled fire show higher maximum temperatures (14). The latter is not always true, since more ventilation also results in more heat discharge in some cases which leads to lower maximum temperatures, see Figure 4 (16).

[1] The fire load is in practice also often expressed in kg pinewood (1 kg pinewood ≈ 19 MJ). A general rule of thumb is that the fire duration in minutes is equal to the fire load density in kg pinewood per m^2 (31).

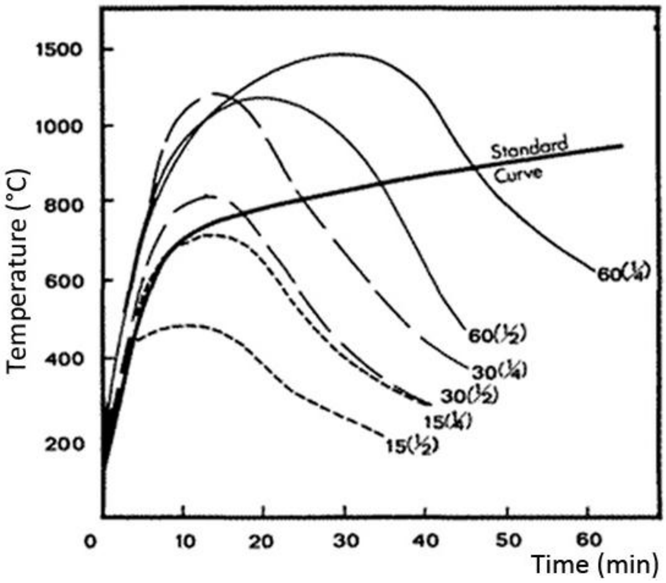

Figure 4 Temperature - time curves with different fire load densities (15, 30 or 60 kg pinewood per m^2) and the ventilation area as a proportion of the facade area (¼ or ½) (16)

Building fires are typically ventilation controlled, i.e. there is a lack of oxygen inside the fire compartment and the smoke contains unburned pyrolysis gasses. As soon as the smoke exits the building, the smoke is mixed with oxygen and the temperature of the smoke is usually high enough to ignite the gasses. Typically for such a fire are flames burning outside the ventilation openings (16).

2.1.3 Smoke

Smoke is produced during the combusting of materials. Smoke is a mix of hot gases, unburned particles and vapour. The volume of smoke is further enlarged by entrained air, which is mixed into to smoke by the turbulence of the smoke plume.

When a fire develops, the temperature increases and the air expands. As a consequence, the air pressure in the fire compartment increases and a pressure difference between the fire compartment and the adjacent compartments is created. The air is pushed out of the compartments through openings and gabs. In addition, the temperature gradient causes thermal draught. Under the neutral line, where no pressure difference is compared to the original situation, the air flow is towards the fire. Above this neutral line, the air flow is away from the fire. This means that fresh air (and oxygen) is supplied to fire by the air flow under the neutral line, and the smoke and hot gasses are discharged above the neutral line, see Figure 5 (12).

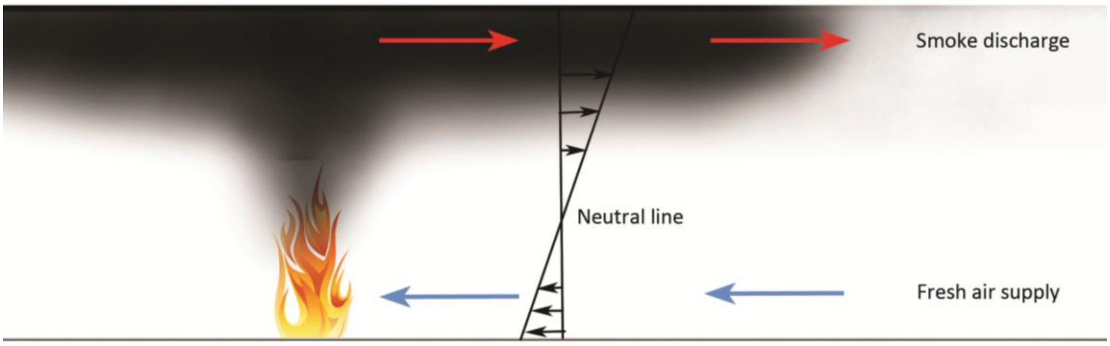

Figure 5 Differences in air pressure due to temperature gradient over the height of the fire compartment

The smoke spreads through a building under influence of differences in air pressure. The cause of these pressure differences are wind pressure on the facades, temperature differences inside the building (stack effect) and, when applied, the air handling system. The amount of smoke escaping out of the compartment depends on the fire development itself, but is also strongly influenced by the effect of the fire on the compartment's envelope and the condition and performance level of the compartmentation.

In principle, there are two possible ways in which the smoke can spread in the compartments. In case the smoke has a higher temperature then the adjacent air, the density of the smoke is lower than the density of the surrounding air and the smoke spreads like a layer along the ceiling. This is called stratified smoke. When the temperature differences are small or the turbulence is high, the smoke mixes with the air and spreads more or less uniformly through the space, see Figure 6 (12).

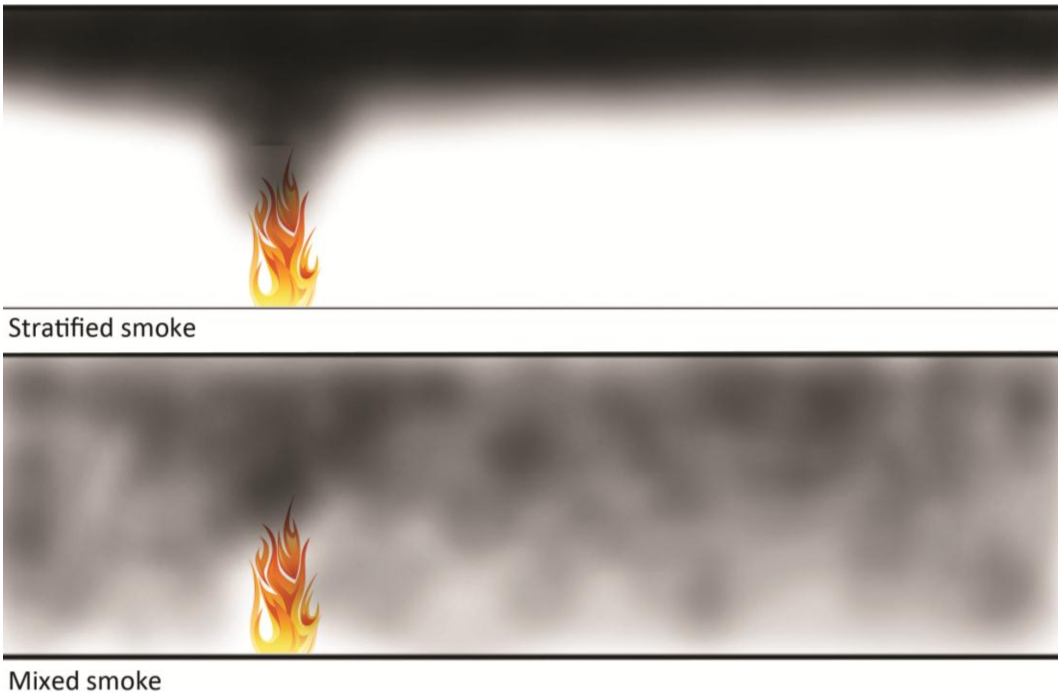

Figure 6 Stratified smoke and uniformly mixed smoke

Smoke generally spreads faster than the fire itself and is dangerous for people. Smoke endangers people's safety in two ways: due to its bad effects on the physical state of people, and its effect on the mental state of people. In case of a situation with stratified smoke, people might be able to walk underneath the smoke layer as long as the radiation level is low enough to prevent burning of their skin. When people have to walk in smoke, their vision is reduced, which slows down their movement. In addition, the smoke contains toxic gasses and heat, which affects people's health condition. Therefore the spread of smoke is one of the key aspects in fire safety engineering. Sufficient means should be provided in a building to slow down the spread of smoke and to buffer or extract the smoke in order to give people sufficient time to escape without travelling in smoke.

2.2 Building egress

It is important for human life safety to consider the evacuation time of a building. After fire detection, it depends on the availability and quality of escape routes how long it will take before all occupants have left the building. Also human behaviour is an important aspect.

To prevent any fire casualties, the evacuation time of the endangered zone under fire conditions is important. Detection time, pre-movement time and travel time determine the total evacuation time (17). The available evacuation time is mainly dependent on the heat development, the smoke spread, the amount of toxic gasses in the smoke and the amount of available oxygen. People's safety gets threatened when they are still in the building while the conditions become hazardous.

2.2.1 Detection time

After ignition it will take some time before the fire is discovered. This is defined as the detection time. The fire can be discovered by the users of the building, by an automatic detection system or by bystanders.

Legislation concerning automatic detection and alarm systems is included in the Dutch Building Decree. When a building has a complex lay-out and a possible fire cannot be detected soon enough, an automatic detection and alarm system is compulsory. Regulations have been established for automatic detection systems dependent on the function of a building, the building height and the use area (20).

With an automatic detection system, the fire can be detected and located quickly after ignition and the occupants can be alarmed by an automatic evacuation alarm. A detection device is able to detect one or more of the following phenomena of a fire (21):

- Smoke detection;
- Heat detection;
- Flame detection;
- Sound detection.

The speed at which the fire is detected by a detection device depends on the location of the detector relative to the fire, the fire development and the smoke spread. The time before occupants are alarmed is not only dependent on the reliability of the detection device, but also on the reliability of the alarm output device (20).

A (starting) fire can also be discovered by people. Especially in buildings with a high occupancy of alert and awake people, fires can be discovered in an early stage by sensory perceptions of the occupants (21):

- Seeing smoke and/or fire;
- Sensing a smell of burning;
- Feeling an unusual rapid increase in temperature;
- Hearing the fire (crackling of combustible materials, shattering of glass, explosions etc.).

The speed at which a fire is detected by human perception is strongly dependent on the amount of people inside a building and their alertness. If people are asleep, it is more unlikely that the fire will be detected in time. In sleeping areas it is therefore recommended to use automatic fire detection and alarm systems.

2.2.2 Pre-movement time

After the detection of a fire, either by automatic or human detection, all occupants must be warned by an evacuation alarm. After hearing an alarm, people do often not directly start with the evacuation. People do often not perceive the situation as dangerous, and often undertake other actions before they leave the building, like checking if it concerns a real alarm (they first need to be convinced of the danger), securing their personal belongings, finishing their current activities, getting their car keys etc. This behaviour may take some significant time, and should therefore be considered in the evacuation process.

A combination of time pressure and stress makes that people take their decisions quickly and often unwise, which causes an inefficient evacuation process. Often people exit the building via the same route as the route they used to go inside the building. People also tend to follow other people in case of an emergency. Therefore it is important to organize regular fire drills and to inform people about what to do in case of fire (21).

In practice it has been found out that, in case of fire, people take the following actions (12):

- Trying to fight the fire;
- Leaving the building;
- Warning others or the fire brigade;
- Continuing their normal activities as if nothing is wrong.

There is a difference in people’s behaviour between private homes and public occupancies. Most people are supposed to be awake in public occupancies such as offices and meeting buildings, and people are less inclined to rescue their belongings, therefore the evacuation proceeds more efficient (22).

2.2.3 Travel time

The travel time is the time which is needed before people reach a safe location (usually outside) after the start of an evacuation. The travel time depends on the size of the building and the walking distances, the number of escape routes, the availability and capacity of these escape routes and the number of occupants in the building and the organization of the evacuation. The health condition of the occupants is of inherent importance for the travel time, just like whether or not the people are familiar with the building. The travel time can be further increased due to smoke in the escape routes, reduced sight, fire spread and collapsed elements.

In some situations, people are not able to move themselves. Young children, bedridden patients or prisoners are for example completely depending upon the help of others. In this case it depends on the organization of the institution what the evacuation time will be.

2.3 Danger of fires for human life safety

If the fire is perceived as life threatening, the level of stress hormones will increase and people become more alert and extra energy is released in their bodies. One starts acting by instinct and learned behaviour. Useless stimuli like pain are neglected, and therefore one is better able to flee. The danger of this is that people might take wrong decisions and take dangerous actions (12).

As a result of fire, people can get the following injuries (12):

- Injuries due to contact with flames;
- Injuries due to smoke;
- Injuries due to (local) collapse of the structure;
- Other injuries (for example jumping out of a window).

The most dangerous aspect for people in a building fire is smoke. Smoke spreads faster through a building than the fire itself and has a major impact on the physical and mental state of humans. Therefore smoke causes most fatalities. When the smoke spreads through the building, it might block escape routes and slow down the evacuation. Smoke has the following influences on humans (23):

- Toxicity and suffocation. The oxygen level in smoke is usually lower than in clean air. When the oxygen level gets lower, the abilities of people decrease. People get dizzy and tired, and when the oxygen level gets really low, people suffocate and die within a couple of minutes. Besides the low oxygen level, smoke contains poisoning gasses like hydrogen chloride (HCl), hydrocyanic acid (HCN), hydrogen sulphides and carbon oxides. These gasses cause irritation of eyes and lungs, tiredness, intoxication or even deadly poisoning. Intoxication with carbon monoxide is a frequent cause of fatalities. Carbon monoxide is especially released during incomplete combustion, i.e. smouldering fires or sprinkler-suppressed fires.
- Heat: if the smoke has a high temperature or releases a high radiation level, people's skin gets burned.
- Visual effect: the sight distances are reduced, which worsens the coordination of people.
- Psychological effect: people get afraid of the smoke and might start to panic.

Due to these harmful properties of smoke for humans, it should be prevented that people have to walk long distances through smoke and escape routes have to be clearly indicated and free of smoke. It should be noticed that visual and physiological effects are in principle not deadly, but these aspects influence the exposure time to smoke and heat, which are endangering life safety. Obviously escape routes should have sufficient capacity to prevent queuing. These aspects have therefore a large influence on the design of buildings. For design purposes, staying in a space is possible as long as the following conditions according to a Dutch TNO Bouw report are met (26):

- The radiation flux is smaller than $1kW/m^2$;
- The temperature is lower than 45°C;
- The visibility distance should be larger than 100m.

2.4 Conclusions

Fire development in buildings mainly depends on the content of the building, reaction to fire of the building content, the dimensions of the fire compartment and the availability of oxygen. The fire duration is mainly dependent on the fire load density inside the fire compartment (expressed in MJ/m^2). The rate of heat release determines how fast a fire will develop. After flashover, when all combustibles in the compartment are burning, fire suppression with active fire suppression measures is no longer possible. Passive fire protection measures, like compartmentation and fire protection for the loadbearing structure, are the only means for limiting the consequences of a fire after flashover.

Important products of fire are heat and smoke. Passive fire protection measures are designed to resist the heat for a sufficient amount of time. Spread of heat through fire resistant elements can be caused by conduction, radiation or convection of heat. The purpose of passive fire protection systems like compartmentation and fire protection for structural elements is to limit these heat transfer mechanisms. The fire resistant elements should therefore have sufficient resistance against heat conduction, radiation and convection, in order to keep the temperature of loadbearing elements sufficiently low and to avoid fire propagation to areas outside the fire compartment to prevent fire ignition in these areas by limiting the transfer of heat to these areas.

Smoke is a product of fire which has an important influence on the safety of building occupants. Smoke generally spreads faster through a building than the fire itself. Poisoning gasses in the smoke affect the human physical state and these gasses can be lethal. People can also get wounded by the heat from the smoke. Smoke further endangers people's safety by reducing sight, causing people troubles in finding the exits, which might result in a too long stay in smoke. Smoke is therefore an important design aspect in fire safety engineering.

Regarding the bad properties of smoke for human life safety, it should be avoided that people stay for a too long period of time in smoke in case of a building fire. The provision of fire detection and alarm systems and sufficient (smoke free) means for escape are therefore important aspects in building legislation, in order to reduce the required building egress time. Human behaviour is an important aspect in the evacuation of buildings. Among others, the behaviour of people in case of a building evacuation depends on the function of the building. In dwellings people tend to stay longer, for example to rescue their belongings. If people are familiar with the building, evacuation generally also proceeds faster. Moreover it is important whether or not people are awake and able to evacuate themselves.

Also the available time for building egress should be sufficient, therefore the production and spread of smoke, structural collapse and fire spread through the building should be prevented for a sufficient amount of time to prevent people from getting trapped inside the building. People should be able to leave the building before dangerous conditions occur in their staying areas.

3 Fire safety legislation

Building regulations generally cover the total field of fire safety related aspects, from the reaction to fire of materials (e.g. smoke production), escape routes and detection systems to the fire resistance of structural elements and compartmentation. Building codes contain requirements that are typically considered to represent a minimum level of performance necessary for the health and safety of building occupants, emergency responders and public welfare. The main objectives of fire safety regulations are (25):

- Safety of people;
- Conservation of property;
- Continuity of operations;
- Protection of the environment;
- Preservation of heritage.

These objectives can be applied to all constructions, including transportation systems such as tunnels and bridges, industrial installations and buildings.

Different fire safety regulations are available in the Netherlands. The Building Decree (nl. Bouwbesluit) contains the most important requirements for buildings, among which many fire safety related regulations, such as escape routes, the maximum size of compartments and fire resistance requirements. Other laws related to fire safety are for example fire brigade laws (nl. Brandweerwet), health and safety at work regulations (nl. Arbobesluit) and environmental laws (nl. Besluiten Milieubeheer) (10).

3.1 Fire safety regulations in the Netherlands

The safety of people is the most important objective in the Netherlands, together with preventing fire spread to neighbouring premises. Property damage is of minor importance. The Dutch building codes therefore mainly aim at providing sufficient warning and egress time and at providing building occupants sufficient time for a safe evacuation (26).

3.1.1 The Dutch Building Decree

The Building Decree (nl. Bouwbesluit) contains the most important fire safety requirements for buildings. For example the maximum length of escapes routes, the maximum compartment size, fire resistance requirements, fire detection and suppression systems etc. are prescribed in this document.

The initiative for a national Building Decree was taken during the eighties. At that time, every municipality had to define its own regulations for construction and layout of houses. This resulted in large differences in building legislation in the Netherlands. After the Second World War, the need appeared for more uniform requirements in the Netherlands, since many new houses had to be built in a relatively short period. A lot of similar houses were built across the country and the differences in building legislation were hindering the construction of these houses. The Decree Uniform Requirements (1956) was the first building legislation which was valid nationwide. The building legislation between different municipalities was further uniformed with the Model-Bouwverordening (MBV) in 1965. The MBV was continuously updated until 1992, then it was replaced by the national Building

Decree. The Building Decree 1992 included technical fire safety requirements for construction and layout of dwellings, offices and lodging buildings. The fire regulations for other buildings types were further developed in the Building Decree 2003. The aim of Building Decree was to make the regulations more user-friendly, to reduce the regulatory burden and to make the regulations more practicable (28) (29).

In the current Dutch Building Decree, the fire safety objectives are achieved by regulating the following aspects (2):

- Reducing the risk of fire ignition (e.g. ban on smoking in rooms intended for the storage of flammable substances);
- Limiting fire development in a fire compartment;
- Limiting fire spread outside the fire compartment;
- Provision of escape options;
- Provision of opportunities for fire brigade intervention.

The Dutch fire safety regulations are mainly focussing on limiting the effect of a fire. In the regulations, it is assumed that fire has occurred, and the aim of the regulations is to limit the effects of the fire (26).

New insight and knowledge require the building regulations to change continuously. Accidents and disasters can reveal shortcomings in regulations, but there are also some trends in building design forcing the building regulations to adapt and to become less restrictive (14):

- Increase in building height;
- Functional need for larger compartments;
- Introduction of large covered building volumes (atria, shopping centres);
- Extended use of air handling systems;
- Use of modern synthetic materials in interior, furniture, equipment etc.

In this research the focus will be on the fire resistance requirements of structures and compartments. The rules related to these aspects are regulated in the Dutch Building Decree.

In the Dutch Building Decree, first a general objective (performance requirement) for fire safety is stated and this further specified as a set of performance based and prescriptive requirements, dependent on the use function (nl. gebruiksfunctie) and building type. The general objective is stated in the so-called *aansturingsartikel*. It is obligatory to fulfil these requirements, unless the intended safety level is achieved in another way via the equivalence principle. The authorities (mainly the municipality and fire brigade) have to check whether the requirements are met.

3.2 Different types of fire safety regulations

In order to achieve the fire safety objectives mentioned in the previous section, the building should fulfil the requirements. In the Dutch Building Decree, three types of requirements are used for fire safety: prescriptive, performance based and functional requirements (25).

Besides these requirements, the equivalent safety principle is included in the building legislation, which states that a building which does not directly comply with the fire safety performance requirements can still have a sufficient safety level if the intended level of safety is achieved in another way. This solution has to be approved by the authorities (e.g. municipality and fire brigade) (2).

Fire safety regulations for buildings have been developed based on experience of earlier fires which implies that the development has been slow. Traditionally, these regulations have been formulated in detailed requirements for buildings, expressed as specific technical solutions. Little freedom was left for innovation. Due to the development of different structural systems and the need for unusual and complex buildings, the number of detailed prescribed requirements would grew so large that it would become impossible to work with. Therefore the need appeared for a regulation system with performance based requirements. The performance approach is concerned with what a building or building product is required to do, rather than prescribing how it is to be constructed. In the Dutch legislation this approach is already incorporated in the Building Decree and the Eurocodes, however for many aspects, the acceptance criteria have not been quantified yet, so this approach is still developing in the Netherlands (17).

3.2.1 Prescriptive requirements

Prescriptive requirements in the regulations specify how a certain safety goal should be achieved, by giving a certain technical solution (e.g. the minimum width of a door). Risk control is achieved by using detailed demands on component level. The freedom of taking decisions in the design is very limited.

The advantage of the prescriptive design method is that it is relatively simple, well-known and not very time consuming. Less fire safety competences are needed from the designer and verification can be done by following a checklist, therefore prescriptive fire safety design is still widely applied many countries, including the Netherlands. Disadvantage is that the prescriptive design method is often not applicable for more complex building designs. In addition, this method does not allow opportunities for the design of new solutions (19).

3.2.2 Performance based requirements

Performance based requirements place demands on the safety output of a design. It is specified what is to be achieved, but it is left to the owner, users and designers to decide how to achieve this. A good example of a performance based requirement in the Dutch Building Decree is the fire resistance of a loadbearing structure; it is stated what the performance should be according to a certain rating method (e.g. 30, 60 or 90 minutes), but it is not stated how the required performance should be achieved.

Internationally, there is a tendency to make building codes more and more performance based instead of (or in addition to) prescriptive regulations (17). It is an attempt achieve deregulation in fire safety design, which leads to simplification of regulations, a clearer division of responsibilities, more cost-effective solutions, flexibility and freedom of choice, since more freedom is left for the designer and advanced fire safety engineering methods can be used to find more innovative solutions. This is further stimulated by EU-harmonisation (17).

Problem with the performance based design is that for many aspects no acceptance criteria have been stated yet. For many aspects it is unclear what the intended performance level and the accepted risk level is. In practice this means that a performance based design must be compared with a solution accepted in prescriptive regulations, often based on expert judgement (17).

3.2.3 Functional requirements

Functional requirements are general guidelines for the design of a fire safe building. These requirements state the function or goal of the fire safety system in case of fire. Nothing is specified in values or specific design criteria, which gives the designer a lot of freedom. 'People should have sufficient time to leave the building in case of fire' is a typical example of a functional requirement.

3.3 Objectives and functional requirements for structures and compartments

Compartments have the function of limiting the harm or damage due to fire spread outside the fire compartment. The function of a fire resistant structure is to limit the harm or damage due to the collapse of structural elements. For compartments, the three main functional requirements are outlined as follows (27):

- Prevent or limit fire spread within the building. The building is divided into fire enclosures (compartments) with barriers (walls and floors) which contain the fire in the enclosure in which it originated.
- Prevent or limit fire spread to other buildings and outside the building. The enclosure of a building should have sufficient fire performance to prevent secondary ignition and to contain an interior fire.
- Maintain the integrity of the separating function of the building. This provision aims to increase the time available for escape, protect escape routes, facilitate fire fighter access during rescue operations, limit the area of possible loss, reduce the impact of the fire on the structure, separate different occupancies, isolate hazards and contain releases of hazardous materials.

The functional requirements for structural performance in case of fire are also defined in the codes. The main functional requirement is outlined as follows (21):

- Prevent or limit structural failure. Insufficient structural fire performance of a building endangers life safety and property protection. Therefore, structural elements should have sufficient fire performance to prevent or delay structural failure, both in terms of integrity and stability. Also deformation is important, since this may cause considerable property damage and it may affect escape routes.

The fire performance of structural elements and compartments is defined as the time until failure, i.e. the loadbearing structure is no longer able to carry its loads or the compartmentation system to keep the fire inside the compartment in which the fire originated. These minimum time until failure depends on the type of building and its function (nl. gebruiksfunctie). Distinction is made between new and existing buildings, the function and occupancy of the building and the height of the building. Also an exception is made for buildings with a low permanent fire load.

3.4 Building types and occupancy classes

In the Dutch building codes, many fire safety requirements are dependent on the function of the building. Eleven occupancy classes are distinguished in the codes (20):

1. Dwellings
2. Meeting function
3. Cell function
4. Health care function
5. Industrial function
6. Office function
7. Education function
8. Sports function
9. Shopping function
10. Other occupancy classes (e.g. parking garage)
11. Structure being no building (e.g. tunnel)

Also some subdivisions are made in these classes. Care facilities are for example subdivided into sleep areas (bed area) and other health care functions. The most important aspects on which the division between different types of occupancies are based dependent on whether the majority of the occupants is familiar with the building, can be expected to be awake and/or have the ability of the occupants to evacuate on their own. This is related to the expected evacuation time, see section 2.2.

Performance requirements for the fire resistance of structures are besides the function also dependent on the building height and the age of the building. The building code is valid for buildings up to 70 meters. For heights lower than that, there are three height categories distinguished, for dwellings <7 m, 7 – 13 m and > 13 m and for other occupancy classes <5 m, 5 – 13 m and > 13 m. The requirements get stricter with increasing building height, because the potential danger for losses is higher. Higher floors are less accessible for emergency services and evacuation proceeds slower.

The fire safety requirements have become more stringent for new buildings and the Dutch Building Decree does therefore not require the same performance level for existing buildings. Increasing the performance level of existing buildings is relatively expensive compared to buildings in a design stage. In addition, the reference period in which the building should fulfil its function is generally lower than for new buildings (28).

An exception is made for buildings with a permanent fire load density lower than 500 MJ/m^2. The permanent fire load is the amount of fuel which is permanently present in the building. If the structure is for example made of combustible materials, these materials contribute to the permanent fire load. The fire resistance in these buildings can be lowered under certain conditions.

For all building functions in the Dutch legislation, the fire severity for the classification of fire resistant systems is similar, independently from the fire characteristics to be expected in the compartment. The fire severity used for classification methods, assumes a fully developed fire in the compartment. Even though the fire severity which can be expected in different buildings is variable (e.g. concrete factory with low fire load vs. sawmill with high fire load), still the same fire severity is assumed for classification purposes in the building regulations.

3.5 Performance criteria for loadbearing function

The functional requirement for the performance of a loadbearing structure is that the building in case of fire can be evacuated and searched for a reasonable period of time, without any risk of collapse. The basic principle is that the structure within the fire compartment may collapse as long as this does not lead to the collapse of any loadbearing structures outside this fire compartment for a certain period of time, to prevent progressive collapse of the loadbearing structure. Buildings with only one fire compartment have therefore, strictly spoken, officially no main loadbearing structure. In addition, it should be avoided that collapse of the structure results in the unavailability of smoke free escape routes (26).

The loadbearing structure of buildings should fulfil its function for a minimum time duration of 30, 60, 90 or 120 minutes in standardized fire conditions. The required fire resistance rating (30, 60, 90 or 120 minutes based on standard conditions) of the loadbearing structure depends on the height of a building and the occupancy class of the building. The requirements are stricter for buildings where people sleep (indicated as 'sleep buildings') or where disabled people live. In Table 2 an example is given of the requirements for housing and offices. The difference between 'sleep' buildings and 'non-sleep' buildings is shown in Figure 7.

Table 2 Example of fire resistance requirements for housing and offices

Function	**Highest floor of staying area**	**Fire resistance regarding structural collapse (minutes)**		**Reduced fire resistance when fire load density ≤500MJ/m^2**	
		New buildings	Existing buildings	New buildings	Existing buildings
Housing	< 7 m	60	0	30	0
	7 - 13 m	90	30	90	30
	> 13 m	120	60	120	60
Office	< 5 m	0	0	0	0
	5 - 13 m	90	30	60	30
	> 13 m	90	30	60	30

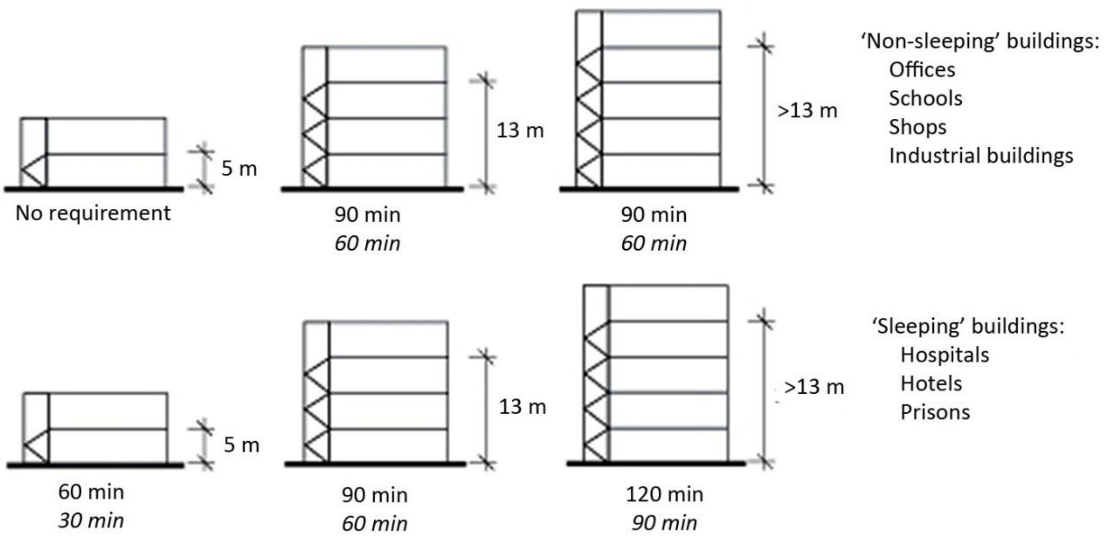

Figure 7 Fire resistance requirements for the main loadbearing structure of new buildings. For building with a permanent fire load density less than 500MJ/m^2 a reduction of 30 minutes is possible.

According to these codes, the fire resistance of loadbearing elements can be determined based on calculations, design charts and graphs or tests.

3.6 Performance requirements for fire separating function

The main objective of compartments is to reduce the risk of a fast fire spread in the building and to keep the fire controllable, i.e. to prevent fire spread to adjacent premises. The partitions in the building should provide the occupants sufficient time to escape from the building before fire spread occurs. If the fire remains within the fire compartment, this contributes to the safety of persons in the other parts of the building.

The Dutch Building Decree includes requirements for the maximum compartment size and the fire performance of internal partitioning systems and external partitioning systems. Two means of fire spread are distinguished: fire propagation through an internal separation (nl. branddoorslag) and fire spread to another compartment via the exterior of a building (nl. brandoverslag), see Figure 8.

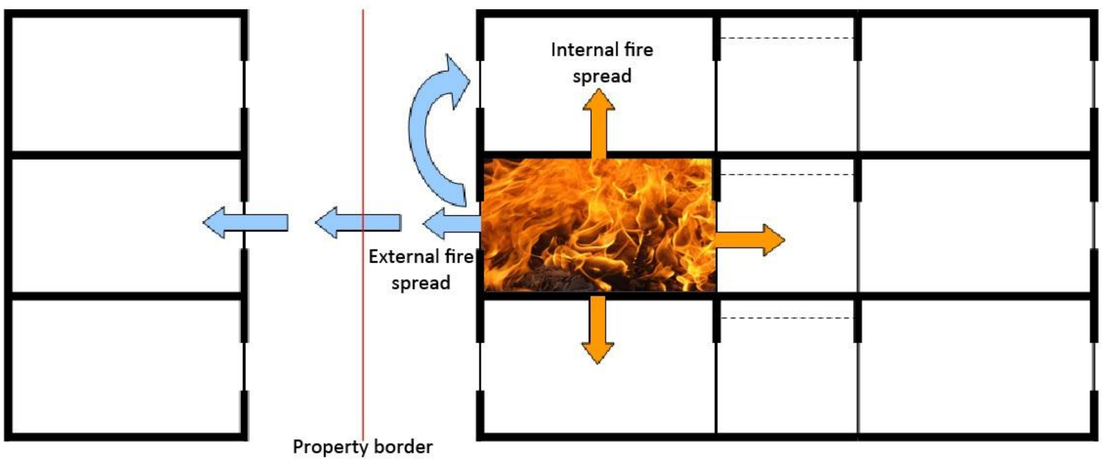

Figure 8 Different ways of fire spread between spaces (13)

Fire spread between compartments can be prevented in three ways (29):

- By providing sufficient distance between compartments;
- By providing a distance between compartments in combination with a fire separating structure;
- By providing a fire resistant separating structure.

Fire spread through outside air can be the fire spread to an adjacent compartment within the same building or to a compartment in an opposite building. In order to limit this fire spread mechanism for a sufficient time period, the distances between openings in the façade and the fire resistance of the façade have to be considered. The fire resistance for fire spread to an opposite compartment is determined based on a symmetrical situation, in which the resistance against fire spread is determined based on an identical building at the same distance to the property border as the considered building.

In order to prevent or limit the fire spread through internal separating elements, fire resistance requirements are set for walls, floors, facades, doors and door frames, ducting, joint seals etc. The fire resistance is typically determined in terms of resistance against collapse, resistance against fire penetration and the resistance against the transfer of excessive heat.

There are protocols in Europe for the classification of fire resistant elements. Elements get a certain classification based on standardized fire conditions, expressed as a time duration in which the structure meets particular performance criteria. In case of elements with a separating function, this classification rating is known as the resistance against fire spread (nl. Weerstand tegen Branddoorslag en Brandoverslag, WBDBO). A certain performance rating is needed for a partition system, dependent on its application, the building type and the function of the building.

Dependent on the application of the elements, the elements should fulfil one or more criteria for a certain amount of time. The following six criteria are defined (30):

- R – loadbearing capacity: the ability of the element to withstand fire exposure under specified mechanical action without loss of structural stability. Also limits are set for deformations to avoid damage to adjacent elements or the test furnace, see Table 3.

Table 3 Deformation limits for test pieces

Deformation limits for loadbearing criterion R	
Horizontal elements	
Maximum deflection [mm]	$\delta_{fire} \leq \frac{L^2}{400\,d} \leq \frac{1}{30}\,L$
Maximum rate of delection [mm/min]	$\frac{\delta_{fire}}{\partial t} \leq \frac{L^2}{900\,d}$
Vertical elements	
Maximum deflection [mm]	$\delta_{fire} \leq \frac{h}{100}$
Maximum rate of delection [mm/min]	$\frac{\delta_{fire}}{\partial t} \leq \frac{3\,h}{1000}$

- E – integrity: the ability to prevent the propagation of fire as a result of the passage of significant quantities of flames or hot gasses;
- I – thermal insulation: the ability to prevent the transmission of fire as a result of significant heat transfer (maximum allowable increase of surface temperature on average ≤140°K on average and maximum allowable temperature rise ≤180°K);
- W – heat radiation: the ability of an element or a construction to reduce the probability of the transmission of fire as a result of significant heat radiation (radiation level at 1 meter distance ≤ 15 kW/m^2);
- S – smoke leakage;
- M - mechanical action.

It depends on the application of the element which of the above mentioned criteria are governing, see Table 4. The time period in which the elements must meet these governing criteria depends on the building type and the occupancy class, and are expressed in time periods of 20, 30 or 60 minutes. For some exceptional cases 90, 120, 240 or even 360 minutes fire resistance may be required (30). The required fire resistance times of partition systems are shown in Table 5.

Table 4 Test criteria for different building constructions

Walls	Interior wall	E and I
	Loadbearing interior wall	R, E and I
	External wall, heated from inside	E and W
	External wall, heated from outside	E and I
Windows, doors, hatches		E and W
Floors		R, E and I
Walls with glazing		E and I or E and W

3.7 Size requirements for compartments and subcompartments

In order to fulfil its main function – reducing the risk of a rapid fire spread in the building and keeping the fire controllable[2] – the maximum size of compartments is restricted. In the Dutch Building Decree this is prescribed as the maximum floor area within one compartment. For some functions, the fire compartment has to be divided into one or more smaller subcompartments.

3.7.1 Subcompartmentation

The purpose of subcompartments is to reduce the spread of fire and smoke within a fire compartment. Occupants of a subcompartment are protected from a fire somewhere else in the fire compartment for a certain period of time. By applying subcompartmentation, the available escape time in a compartment increases. This is particularly important for people who are sleeping or who cannot escape, like young children, bedridden patients or prisoners.

There are two types of subcompartments: the ‘normal’ subcompartment and a protected subcompartment. The difference between these two is that a protected subcompartment

[2] Preventing the fire development and spread outside the fire compartment from getting out of hand.

provides additional resistance against fire spread to other areas within the fire compartment than a subcompartment. The fire resistance against fire spread of a subcompartment is at least 20 minutes, where the fire resistance is determined based on NEN 6068, where only the integrity (E) criteria is taken into account. For protected subcompartments, the resistance against fire spread is at least 30 minutes according to NEN 6068. In case of a resistance against fire spread of 20 or 30 minutes, the resistance against smoke spread is assumed to be respectively 30 and 45 minutes (1,5 times the fire resistance) (26).

The maximum size of a subcompartment depends on the function of the building. For some functions, a maximum floor area is prescribed. Every prison cell and lodging room is in a separate protected subcompartment. Also bed areas in health care functions and childcare functions are in separated protected subcompartments. In health care buildings, the maximum subcompartment size depends on the level of surveillance. If permanent surveillance is present, than the maximum size is limited to 500m^2, if not, than the maximum size is restricted to 50m^2. For housing functions, every staying area[3] is in a protected subcompartment.

An overview of the main regulations for fire compartments and subcompartments is presented in Table 5. For some functions the required fire resistance of compartments against fire spread can be reduced with 30 minutes under certain conditions (e.g. permanent fire load density in the fire compartment is smaller than 500 MJ/m^2).

Table 5 Overview of the main requirements for fire compartments and subcompartments according to the Dutch Building Decree

	Fire compartments				Subcompartments				
	Maximum size fire compartment [m^2]		Fire resistance against fire and smoke spread [min]		Maximum size protected subcompartments [m^2]			Fire resistance against fire and smoke spread [min]	
					Limit		Enclosed areas		
	New	Existing	New	Existing	New	Existing		New	Existing
Housing function	1000	2000	60	20					
a. for care with use area >500 m2					100	200	Every staying area	30	20
b. other housing functions					500	1000	Every staying area	30	20
Meeting function	1000	2000	60	20					
a. for childcare with bed area					200	-	Every bed area	30	20
b. other meeting function					-	-		20	20
Cell function	1000	2000	60	20	500	-	Every cell	30	20
Health care function	1000	2000	60	20					
a. with bed area					50 - 500	-	Depending on level of surveillance	30	20
b. other health care functions					-	-		20	20
Industrial function	2500	3000	60	20	-	-		20	20
Office function	1000	2000	60	20	-	-		20	20
Lodging function	500	1000	60	20	500	1000	Every lodging room	30	20
Education function	1000	3000	60	20	-	-		20	20
Sports function	1000	3000	60	20	-	-		20	20
Shopping function	1000	2000	60	20	-	-		20	20

The maximum size of a fire compartment with one or more cells is restricted to 500 m^2 or to 77% of the total use area (nl. gebruiksgebied) on one building floor. Also the maximum compartment size of a bed area with bedridden patients is not larger than 77% of the total floor area on one building level. This creates the possibility of evacuating the people to an area outside the fire compartment at the same floor level (26).

[3] A *staying area* is a use area intended for the staying of persons and a *staying room* is defined as a room in a staying area which is intended for the staying of persons.

In principle, every openable component in a partition system with a fire resistance requirement needs to be self-closing. For example doors between fire compartments or subcompartments should close automatically during fire, to prevent fire spread through the doors, making a fire resistant system useless. This requirement does not hold for openings between a (sub)compartment and the outside air or doors inside a subcompartment. Also doors in dwelling functions which are only for non-shared use (e.g. entrance to an apartment) and doors of prison cells do not need to be self-closing (26).

3.7.2 Larger compartments based on the equivalence principle

If compartments need to be bigger than allowed according to the requirements in the Building Decree (Table 5), than an equivalent level of safety should be achieved based on the equivalence principle. A frequently used method in practice is the 'Method Controllability of Fire 2007' (nl. Methode Beheersbaarheid van Brand 2007, BvB). This method provides general guidelines to determine an equivalent solution for larger compartments, but the BvB 2007 is no official legislation. According to these guidelines it is possible to have larger compartments, but the quantity of combustible materials in the fire compartment is restricted and the fire resistance of the boundary of the fire compartment should be larger than the expected fire duration (with a maximum of 240 minutes), so the fire resistance is related to the fire load[4]. Also the effect of installations such as sprinkler suppression systems are taken into account.

The idea of BvB 2007 is that compartments can be larger, as long as damage to compartments on adjacent plots is prevented. Also probability of the occurrence of casualties should be limited to an acceptable level. This method is not meant for buildings where people sleep or for buildings with bedridden patients. The BvB method is also not meant for extension of the requirements from the Building Decree without applying compensation measures. This method is therefore in practice mainly used for industrial (storage) buildings (31).

3.8 Conclusions

The Dutch building legislation contains many fire safety related requirements to limit the consequences of a fire. Fire damages can be expressed in terms of casualties and property losses. The emphasis of the government is on the prevention of casualties, the building legislation therefore mainly aims at the safety of people. A secondary objective of the Dutch fire safety legislation is to prevent damage to property of third parties.

Most important legislation regarding the fire safety of buildings is stated in the Dutch Building Decree (nl. Bouwbesluit). The requirements are related to possible ignition sources, fire development, fire detection and building evacuation, structural collapse in case of fire, spread of fire and smoke and fire extension to adjacent premises and to facilitate fire fighter access during rescue operations.

The fire development is regulated by setting requirements for the burning behaviour and smoke production of materials and other interior items. It is important for the safety of

[4] It is assumed that a fire load of 1kg pinewood/m^2 corresponds with 1 minute fire duration (1kg pinewood ≈ 19MJ)

people to provide escape routes which are clearly indicated, have sufficient capacity and are available for sufficient period of time. People should be able to leave the building before they are surrounded with smoke, since smoke intoxication is in practice the main danger for humans in case of building fires and causes most fatalities.

The primary objective of compartmentation in buildings is to limit the maximum extension area of fires. The underlying idea is to prevent casualties and damage to property-owners outside the parcel where the fire started. To achieve these objectives, buildings have to be divided into one or more fire compartments. The perimeter of the compartment should have sufficient fire resistance to prevent fire spread to other compartments and should not collapse within a specific fire duration period. The legislator therefore prescribes the maximum size of compartments and a resistance against fire spread to other compartments, dependent on the age (existing or new buildings) and the occupancy class (nl. gebruiksklasse) of the building.

These fire compartments are in principle intended as the maximum extension area of the fire and smoke. For some occupancy classes it is necessary to divide the fire compartments into smaller subcompartments, to protect occupants from the smoke and fire in other parts of the fire compartment and to give the occupants extra time to leave the fire compartment. This requirement for subcompartmentation holds for buildings where people sleep (so-called ‘sleep buildings’) and buildings where people are not able to evacuate themselves, such as bed areas in care institutions, lodging buildings and prisons.

The requirements for the maximum floor size of fire compartments are based on the common building practice and there is no extensive reasoning behind these prescriptive requirements. These requirements are quite arbitrary and based on consensus among stakeholders, experience from the past without an integral risk assessment. Integral risk assessment is also complicated due to many variables. This can also partly be attributed to the uncertainties in actual fire performance and the lack of knowledge about the effect of the measures on the fire safety level for both human safety and safety of property. The same holds for the fire resistance against fire spread between compartments.

The fire resistance against fire spread is determined based on standardized fire conditions and failure criteria. The failure criteria are set for different ways in which fire spread through the compartmentation system can occur. The most important criteria relate to heat radiation (W), heat conduction (I), integrity (E) and collapse (R). As long as the compartmentation system does not exceed the limits for a specified number of these criteria in standardized fire (testing) conditions, it is assumed that the structure retains its separating function against fire spread. It depends on the type of structure and the application which of the test criteria are governing. The time duration after which the separating structure fails to fulfil the governing criteria in standard fire conditions, is rounded down to 20, 30, 60, 90 or 120 minutes. This value is referred to as the fire resistance against fire spread (nl. Weerstand tegen Branddoorslag en Brandoverslag, WBDBO).

The required fired resistance is lower for existing buildings since the requirements for buildings have been gradually increased for new buildings, and it would be very expensive to adjust all existing buildings to the required performance level for new buildings.

Both the standardized fire conditions and the failure criteria for compartmentation systems are an approximation of fire conditions and fire spread in reality and are supposed to be on the conservative (safe) side. However, it is uncertain how these conditions relate to fire conditions and fire spread in reality and how this affects the performance of compartmentation.

The Dutch fire safety regulations are mainly focussing on the effect of a fire. It is assumed that a fire has occurred, and the legislation mainly aims at limiting the effect the fire to an acceptable level. The effect can be expressed in fire casualties, property damage and/or financial losses. Casualties are the main concern of the government. To get an idea of how passive fire protection measures contribute to the safety of people and property, these aspects should be further investigated.

4 Fire risk: acceptability, probability and consequences

The government has set requirements for buildings to keep the fire risk sufficiently low. The fire risk is defined as a function of the probability of fire occurrence and the consequences of a fire. Building legislation in the Netherlands mainly aims at keeping the consequences low by providing requirements which are intended to limit the potential for casualties, property losses and environmental damage to an acceptable level. This acceptable level is not defined in the Netherlands, only the means that should lead to an acceptable level of safety are prescribed.

The general definition of risk in a particular scenario is defined as follows (68):

$$Risk = probability * consequence \qquad (4.1)$$

According to this definition, it is possible to reduce the fire risk by reducing the probability of fire ignition and/or by reducing the consequences of a fire. When multiple scenarios are considered, the total risk is a summation of the separate risks of the different scenarios.

Before any decisions can be based on risk assessments, it should first be defined what risk level is acceptable. This is not only a pure technical problem, but it is more about the safety perception in our society. The consequences of fires can be expressed in financial and/or property damages and casualties. When financial damages are considered, distinction can be made in direct and indirect financial losses. The direct losses refer to the losses which have occurred immediately after the fire, such as damage to the building and the content of the building. Indirect losses occur in the wake of the fire due to the disruption of economic activities. The owner/users of a building are responsible for carrying these losses. The government is mainly concerned with public safety, and therefore the government has interest in the fire safe construction and use of buildings in order to limit the risk of fire casualties.

4.1 Acceptance of risks

An acceptable level for fire risks is hard to quantify, especially when the physical safety of people is considered. There are many factors that influence the acceptance level for fire risks (17). No acceptance level has been defined for fire risks in the Netherlands, nor for people’s physical safety as for the safety of property.

4.1.1 Risk perception and acceptance

According to the above stated definition, the risk of a scenario with a small accident with a large probability is equal to a scenario with a big disaster with a small probability of occurrence. In society it is not perceived and accepted like this. There are several criteria determining the acceptance level (69):

- Public acceptance level: safety level is related to an accepted probability of casualties or damage at a certain location due to a particular event;
- Economical optimisation: achieving a safety level at which the total costs are as low as possible;
- Psychological acceptance level: safety level is related to the public opinion about the consequences of a certain event;

- Political acceptance level: safety level is closely related to the psychological acceptance level, since the decision-making is often dependent on the public opinion.

Society generally draws much attention to low frequency, high consequence events. These events are causing much public concerns and society attempts to prevent them (psychological acceptance level). One should realize that measures to reduce the risk of these events are not necessarily taken to reduce a factual risk, but primarily to reduce a feeling of unsafety, also known as ‘management of public confidence’ (70).

Given that there can be no guarantee that a severe fire occurs in a particular building, these high consequence events need a more sophisticated approach. Only reducing the probability of a certain event is therefore not sufficient in fire safety engineering, and compartmentation and loadbearing structures need to be assessed in order to reduce the consequence the a fire (46). In addition, fire is an event which involves many uncertainties, therefore the building should contain sufficient robustness (i.e. should be able to deal with unanticipated events) in its fire safety system.

Most fires affect one or a few people. More disastrous fires occur less often, but involve many casualties or considerable material, environmental or financial damage. These large disasters need special attention compared to the more frequent fires with small consequences. The reason behind this is that many people are involved in these disasters and these events catches the attention of media and politics. It creates a feeling of insecurity in society and, especially for the huge disasters, society may be unable to deal with the consequences of the event. The accepted risk level therefore varies between different buildings (high rise vs. low rise), different industries etc., because of the differences in the potential consequences of a fire (17) (69).

When the event is uncontrollable and it is not possible to deal with its consequences or the impact cannot be reduced sufficiently, people perceive the risk as high. Also when the danger is feared and people are exposed to the event unwillingly, people’s perception of the risk is high. This especially holds for fire risks. People are always unwillingly exposed to fire and have much fear for fire. As a result of the differences in risk perception, the accepted risk level for single-family houses is higher than for example the accepted risk level in buildings like hospitals, nightclubs etc. (17).

Many fire safety regulations are disaster-driven, and are therefore mainly aiming at the negative effects of a fire, not at prevention of fire. As a consequence, measures which aim at limiting the negative effects of a fire have the advantage of having a better gratitude. Measures to prevent the occurrence of fire are therefore underappreciated in practice, while these measures are very effective for the reduction of risks.

Stakeholders often have different interests in fire safety. For example, an insurance company usually has different interests (limiting material damage) than the fire brigade (mainly casualties). Therefore, also the acceptance of these risks will be different.

Different methods for defining an accepted risk level are available (13):

- A fixed acceptance limit, e.g. risk of casualties <0,1%;
- Comparative to other accepted solutions: e.g. equivalent to the performance requirements of the Building Decree (equivalence principle);
- A reasonable risk level: taking measures in order to reduce the risk as long as it is reasonable compared to the investment costs, the gain in safety or in relation to practical considerations; i.e. the ALARA-principle (As Low As Reasonably Achievable).

A quantification of the acceptance limit is not defined in the Dutch legislation for fire safety yet. The equivalence principle is part of the Dutch building legislation, but it is up to the designer to prove the equivalent safety level. The ALARA-principle is mainly applied in complex and special projects which are not within the scope of the building codes or in projects with special demands from the owner/user. The lack of a defined accepted risk level makes this area vague and difficult to comprehend.

4.1.2 Required reliability during fire according to the Eurocode

Some guidelines are provided in the Eurocodes for probabilistic design in fire safety engineering. These guidelines focus on structural performance in fire conditions, and the approach is similar to the approach used in structural engineering. The reliability of the structure in fire conditions should be similar to the reliability of the structure during normal service conditions.

The reliability of the structure should be sufficient to fulfil the following condition (52):

$$p_f \leq p_t \tag{4.2}$$

With:

p_f the probability of failure;

p_t the accepted probability of failure. In the Eurocode EN 1990 this accepted probability is defined as $7{,}23 * 10^{-5}$ for a reference lifetime of the structure of 50 years (reliability class 2).

For fire safety engineering purposes, the probability of failure is defined as:

$$p_f = p_{f,fi} \cdot p_{fi} \tag{4.3}$$

With:

$p_{f,fi}$ the probability of structural failure in fire conditions;

p_{fi} the probability of fire occurrence.

The accepted probability of structural failure in fire conditions is somewhat different from normal service conditions, since fire is a rare event. The proposed acceptable probability of failure depends on the possibilities for evacuation (72):

- $p_t = 1{,}3 * 10^{-4}$ in normal circumstances [1/year];
- $p_t = 1{,}3 * 10^{-5}$ in difficult circumstances (e.g. hospitals);
- $p_t = 1{,}3 * 10^{-6}$ when no evacuation is possible (e.g. very high buildings).

The acceptable probability of structural failure in fire conditions depends on the probability of fire occurrence and can therefore be calculated via:

$$p_{f,fi} \leq \frac{p_t}{p_{fi}} \quad (4.4)$$

4.2 Probability of fire occurrence

The probability of fire occurrence depends on the occupancy type of the building, e.g. the probability of fire occurrence in a waste recycling plant is different from an office building. Some international statistical research has been carried out to estimate a realistic probability for the occurrence of fire in a certain building type (6) (7). For the fire resistance of compartmentation and loadbearing structures, the occurrence of a fully developed compartment fire is important. It depends on several aspects whether a full compartment fire will occur (52):

- Probability of fire occurrence;
- Detection of fire in due time;
- Extinguishment of the fire in due time, automatic or by fire brigade;

The probability of a fire in a compartment, severe enough to endanger the loadbearing structure and the compartmentation, is defined as (71):

$$p_{fi} = p_1 \cdot p_2 \cdot p_3 \cdot p_4 \cdot A_{fi} \cdot n \quad (4.5)$$

With:

p_{fi} the probability of a severe compartment fire within the reference period;
p_1 the probability of a severe fire, which includes the effect of the actions of attendees and the public fire brigade (in $1/(m^2 \cdot year)$);
p_2 reduction factor dependent on the type of fire brigade (professional or voluntary fire brigade), the time between detection and intervention and whether or not the fire brigade intervention is successful;
p_3 reduction factor which takes the effect of automatic fire detection and fire alarm into account;
p_4 reduction factor which takes the effect of automatic fire suppression into account;
A_{fi} the floor area in the fire compartment (m^2);
n the reference period (years).

In Switzerland, France, Finland, Sweden and the UK, research has been carried out to the frequency of fire occurrence per building area (7). The data include figures about dwellings, industrial buildings, offices and public buildings. The probability of a fully developed fire is based on the frequency of fire occurrence, minus the frequency of successful extinguishment before fire growth occurs. These figures are used to determine the probability of a severe fire p_1[5], see Table 6 (7).

Table 6 Frequency of fire occurrence for different occupancy classes (72)

[5] $p_1 = p_{occ} * (1-p_{occup}) * (1-p_{FB})$

		Dwellings	Offices/Public	Industrial
Frequency of fire occurence per building area $[10^{-7}/(m^2 * year)]$	p_{occ}	3	1	1
Fire extinguished by occupants	p_{occup}	0,75	0,6	0,45
Fire extinguished by public fire brigade	p_{FB}	0,90 - 0,95	0,90 - 0,95	0,80 - 0,90
Frequency of occurrence severe fire per building area $[10^{-7}/(m^2 * year)]$	p_1	2 - 4	4 - 9	5 - 10

UK-data about the frequency of fire occurrence, show a relation between the compartment size, the occupancy class and the probability of fire occurrence per m^2 (6). In general, the probability of fire occurrence is decreasing with an increasing floor area, see Figure 9. The fire probability in buildings with a small compartment size appears to be larger than the fire probability in large compartments. So, the probability of a severe fire per m^2 is a function of the compartment size. However, this interdependency between the compartment size and the frequency of fire occurrence per m^2 could not be confirmed with the data from other countries (6) (7).

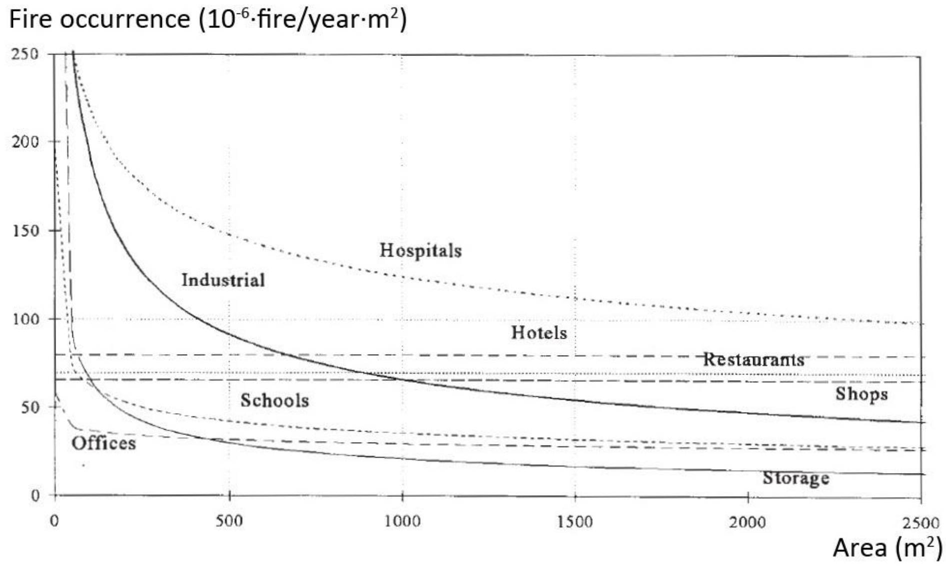

Figure 9 The relation between compartment size and the probability of fire occurrence according to UK research (6)

The reduction factor p_2, dependent on the type of fire brigade (voluntary or professional) and the time between fire detection and intervention of the fire brigade. This reduction factor is derived from data from Switzerland, see Table 7 (7).

Table 7 The reduction factor p_2, dependent on type of firemen and time from alarm to action of firemen (7)

	Time from alarm to action of the firemen		
Type of firemen	**0-10 min**	**10 - 20 min**	**20 - 30 min**
Professional	0,05	0,1	0,2
Non-professional	0,1	0,2	1

The reliability of sprinkler systems has been studied in Australia, USA, Germany, Finland and France. From these data, the reduction factor p_4 has been derived (7). These reduction factors are given for three standards of sprinkler systems: normal, high standard and low standard. Normal standard is referring to sprinkler systems which are according to the regulations. High standard sprinklers are systems with for example two independent water sources or electronically checked valves. Sprinklers systems which are not according to the regulations, are referred to as low standard sprinklers (7).

Table 8 Values for reduction factors p_3 and p_4 (7) (52)

Detection	**Reduction factor p_3**
Smoke detection	0,0625
Heat detection	0,25
Automatic reporting to fire brigade	0,25
Sprinkler	**Reduction factor p_4**
Normal	0,02
High standard	0,01 - 0,005
Low standard	≥ 0,05

In case a fully developed fires occurs, it depends on the compartment size, the performance of the compartment's envelope and the capability of the fire brigade to control the fire within the fire compartment if fire spread to adjacent compartments will occur. The performance of the compartmentation depends on the fire severity itself and the quality of the compartmentation. The size of the fire affected area determines the effect of the fire.

4.3 Fire damages

Fires can cause huge economic losses. Most casualties are due to smoke intoxication, economic damages are due to the destruction of property, like damage to buildings and inventory (direct or immediate losses), and due to the disruption of economic activities after a fire (indirect losses). As an indication: approximately 40% of all companies which are affected by a serious fire cannot deal with the impact of the fire and go bankrupt, even if they had insurance (59). Users and owners (and their insurers) are in practice the party with most interest in these economic fire damages. However, these parties are usually not involved in the design process of a building and are only involved during the exploitation of the building. Financial fire damages are not the main priority for the government (5).

Compartmentation is important for damage prevention, since the aim of compartmentation is to limit the maximum extension area of fires. The size of compartments is therefore limited and the compartment's enclosure should have sufficient fire resistance to prevent spread of fire and smoke between compartments. Destruction of property can be caused by fire, but also by smoke, for example by making the content of the building unusable by covering it with soot. The spread of smoke through a building is therefore also an important cause of property damages (43) (44).

4.3.1 Research to damages in large fires

The Dutch National Centre for Prevention (nl. Nationaal Centrum voor Preventie, NCP) investigated the damage of large building fires in the Netherlands, commissioned by the Dutch Association for Insurers (nl. Verbond voor Verzekeraars) (5). The investigated fires include all building fires in the period 1995 – 2001 with a damage of more than 1 million euros. These damages include direct material and property losses. The aim of this research is to investigate how the damages caused by large fires can be reduced. This study shows that compartmentation has an important role for the prevention of fire damages.

The government and insurers have different interests in fire safety issues. The main objectives of the government are preventing casualties and reducing the fire risk for third parties. Insurance companies' objective is to reduce the financial damage of fires. Improving the fire safety level from government's point of view, will therefore not directly lead to less fire damages for insurers. However, more government involvement in fire safety will lead to more attention of users and owners for fire safety and for fire safe use of buildings. This will indirectly result in less fires, and thus in less premium payment for insurance companies. In addition, more control and inspections on compliance with the regulations, will lead to better fulfilment of these regulations, which will also result in less damages (5).

4.3.1.1 Damage statistics

The statistics about fire damages are collected by Statistics Netherlands (Centraal Bureau voor de Statistiek, CBS). The CBS receives these data from the fire brigade and insurance companies. Among data about damages, these statistics include also information about fire causes, casualties and more detailed information about the actions of the fire brigade.

In Table 9 the total annual damage due to building fires in the period 1995 – 2010 are shown.

Table 9 Total annual damage in building fires 1995 – 2010 (statistics by CBS)

Year	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010*
Total annual damage (in million euros)	400	485	493	492	501	656	800	878	1093	830	634	627	778	907	791	449

The total damages show an increasing trend. According to the research, the total damage is mainly caused by a relatively small amount of high-damage fires, which become more frequent and are showing higher damages (5).

High-damage fires seem to occur notably often in the following four categories (25):

- Industry, as well production as storage buildings;
- Shops and shopping malls;
- Schools;
- Catering industry.

Many of these fires (±70%) are caused by human activities, like arson, playing with fire, smoking or fire hazardous works. The other fires are caused by technical defects, like electrical short circuits or overheating. The fire causes are strongly dependent on the building function/type. In schools for example 60% of the fires are caused by arson, while arson also occurs relatively often in storage buildings (5).

In the Netherlands, there are in total about 14 000 building fires per year (64). About one out of ten of these fires is classified as a high-damage fire. This implies that about four large fires occur per day.

In many fires the compartmentation failed and fire spread occurred (obviously this is also one of the causes of the large damages). In the buildings where fire compartmentation was relevant, it failed in about 50% of the cases. When failure of compartmentation occurred, it was in 50% of the cases due to the failure of self-closing doors (5).

4.3.1.2 The importance of compartmentation

One of the best measures to limit fire damages is proper compartmentation. For insurers it is therefore important to have proper fire compartments in a building. In practice the insurance companies are often not involved in the compartmentation design, first because they lack expertise, and secondly because they are not interested in it, which is mainly caused by competition in the insurance sector (insurers are not focussing on technical issues) (5).

The researchers of NCP emphasize the importance of compartmentation and promote more involvement of insurers into the design of fire compartments. In principle, the maximum area of a fire compartment is not important for insurance companies, but the content of a compartment is of importance. For example, the potential fire damage in a small compartment with very valuable content can exceed the damage in a large compartment with low-value content. It should be noticed that the value content of a compartment can vary over the time (e.g. full storage building vs. empty storage building).

When the compartmentation has been decided and thus the maximum fire extension area, the fire resistance of the compartmentation system becomes important. The partition should have sufficient fire resistance to prevent fire spread to another compartment. Also the spread of smoke should be reduced to prevent damages due to smoke in the adjacent compartments. It depends on the fire development and the quality of the compartmentation if the fire can be kept inside the compartment. If the fire duration is longer than the fire resistance of the compartmentation, the change of fire spread is large. The fire resistance of the compartmentation is also strongly influenced by the fire development itself. Extreme high temperatures have for example an unfavourable influence on the fire resistance.

Other aspects which help controlling the fire are for example (automatic) fire suppression systems and fire brigade deployment. A well-trained and well-equipped fire brigade can for example help to prevent fire spread to other compartments, which is an effective way to limit damages.

A well-balanced compartmentation system in agreement with owners/users, engineering consultant, fire brigade and insurance company can result in an optimal system for damage reduction. For optimisation (e.g. economical optimisation, see section 4.1.1) it is necessary to have knowledge on performance of compartmentation, costs and benefits.

4.3.1.3 More high-damage fires

The researchers appoint several developments which lead to the increase in high-damage fires (5):

- Insurance technical changes: due to more competition in the insurance sector, the insurance coverage has increased and excess decreased, therefore the damages to be compensated by the insurers have increased;

- Economic developments: the economy is growing and changing from an industrial into a service economy. Fire damages can be very high for service providing companies;
- Upscaling, concentration and centralisation of particular industries: some products are increasingly produced by specialized companies which leads to higher damages in case of fire.

Other reasons for the damage-increase according to the NCP research are:

- Increased value concentration: increased financial value under one roof, more value per m^3 (high-tech products) and more value per m^2 (higher buildings, more high-tech equipment);
- Higher fire load: the fire load of modern materials is higher (increased use of plastics and other synthetic materials) and these materials are used more often in buildings (e.g. insulation materials).
- Insufficient prevention measures;
- Expensive and vulnerable equipment: equipment becomes more expensive and due to the centralisations in certain industries, the loss of certain machinery can lead to very high damages. In addition, high-tech equipment is more vulnerable to fire (electronic operating systems are affected by smoke, aggressive gasses and soot which are in particular released during combustion of synthetic materials, while these materials are applied more often);
- Taller and more complex buildings: higher building density and concentration of different functions into one building;
- Lack of knowledge among insurance companies and fire brigade about compartmentation and fire prevention. Risk reducing measures are therefore not valued properly and there is no incentive for building owners with good fire prevention measures.

4.3.1.4 Other conclusions and recommendations NCP-research

The potential fire damage can be predicted based on the following aspects:

- The fire development to be expected: the available fire load and speed of fire development;
- The fire extent to be expected: the maximum extent of the fire in the most unfavourable situation (no extinguishment possible in due time, one or more compartments in fire);
- The value content: the financial value of the building and its content.

The fire damage can be reduced by considering these three aspects. The fire load, together with the other fire characteristics of the combustibles, are of importance for the functioning of compartmentation and the effectiveness of fire brigade deployment. For fire extinguishment in due time, the detection time is important, just like automatic suppression systems such as sprinklers.

In addition, also the probability of fire occurrence should be considered (less fires result in less damages). Since there appears to be a strong relation between fire causes (arson, defects etc.) and the building function, the damage can be reduced by taking measures for these particular fire causes, for example extra surveillance at school buildings.

4.3.2 Recent figures about fire damages

More recent figures about fire damages underline the conclusions of the NCP-research. In the CBS dataset about damages, the following building functions/types are distinguished:

- Dwellings, subdivided into single-family dwellings, other dwellings and other residential buildings;
- Prisons;
- Lodging buildings;
- Offices;
- Education buildings (schools);
- Health care institutions;
- Industrial buildings including agricultural and livestock buildings;
- Stations;
- Meeting functions (shops, theatres, restaurants, event buildings etc.);
- Other buildings.

The largest total damage occurs in industrial buildings, followed by buildings with a meeting function. The damage due to fires in schools do not have a significant stake in the total damage, see Figure 10.

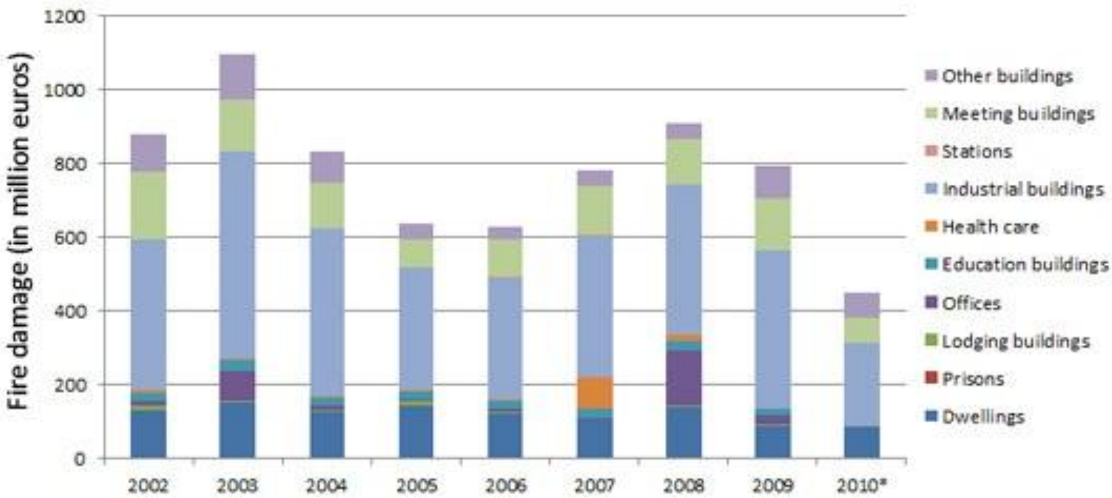

Figure 10 Annual damages 2002 – 2010 (statistics by CBS)

Also dwelling fires cause a relatively large part of the total the damage. These fires occur very frequently, but usually no big damages occur in these fires (on average about €25 000 per fire). The same holds for buildings with a lodging function, see Figure 11 and Figure 12.

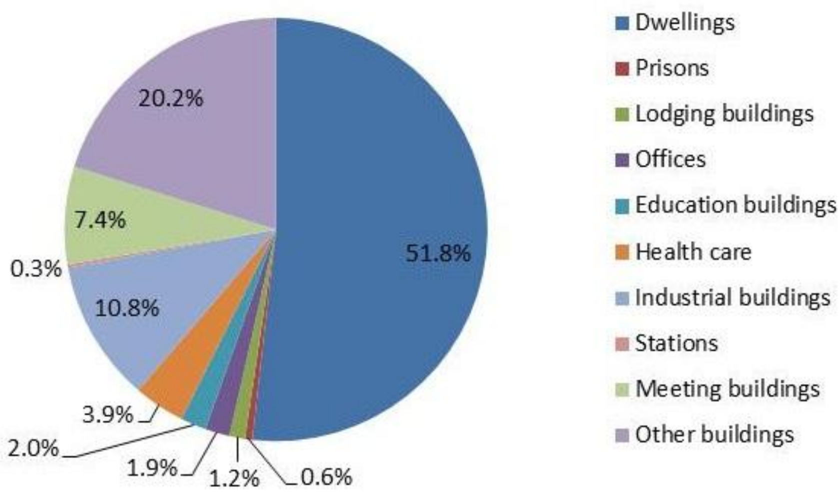

Figure 11 Number of fires with damage in the period 2002 – 2010 per function (total number of fires with damage is on average ±10 000 per year) (statistics by CBS)

In Figure 12 it becomes also apparent that a few very destructive fires have a big influence on the statistics. For example, in 2008 a high rise office building of Delft University of Technology burned down causing a damage of 140 million euros This fire caused approximately 90% of the total annual fire damage in office buildings in 2008. Also in general, the major part of damage is caused by a limited number of very big fires. According to (59), about 80% of the total fire damage is caused by only 6% of the fires.

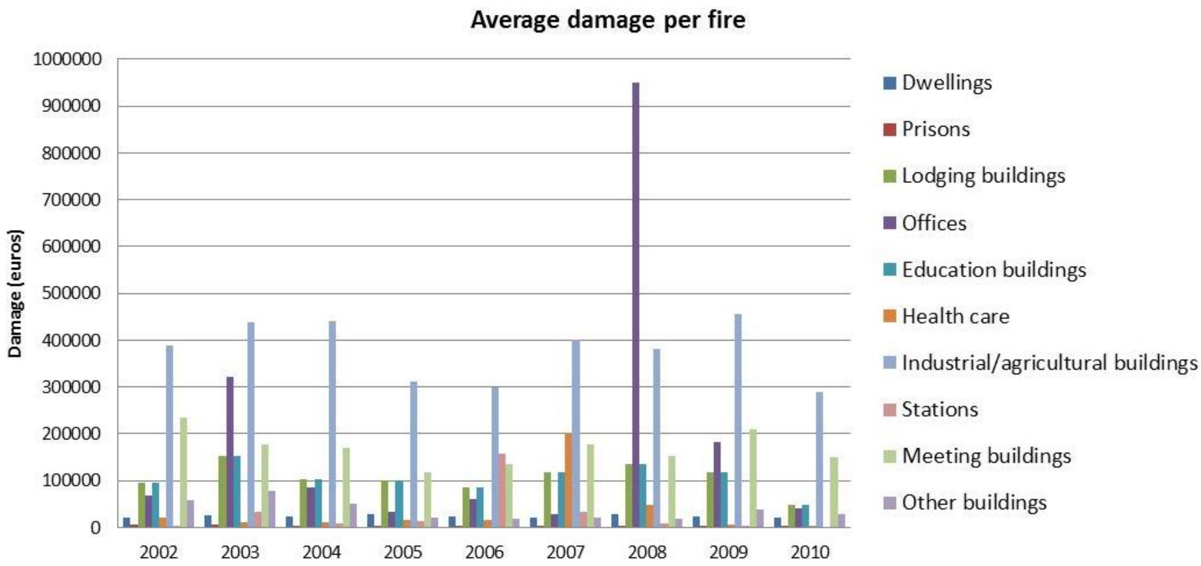

Figure 12 Average damage per fire per year (statistics by CBS)

In Figure 13 the main fire causes are shown. In accordance with the NCP-research, about 70% of the cases have a ‘human cause’, i.e. arson, playing with fire, smoking, fire hazardous works, fireworks etc.

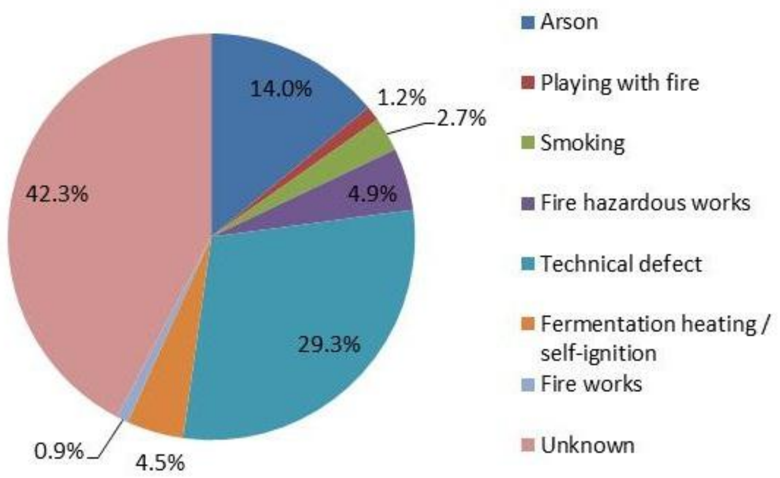

Figure 13 Main fire causes in the period 2002-2010 (statistics by CBS)

4.3.3 UK research on financial fire damages

A research on financial damages carried out in the UK during the eighties, shows the relation between the compartment size and the average fire damaged area, as well as the average amount of financial damage, see Figure 14. The relative damage decreases with increasing floor space of the building. This relation also holds for the probability of fire occurrence: with increasing floor area, the probability of fire occurrence per m^2 decreases (6).

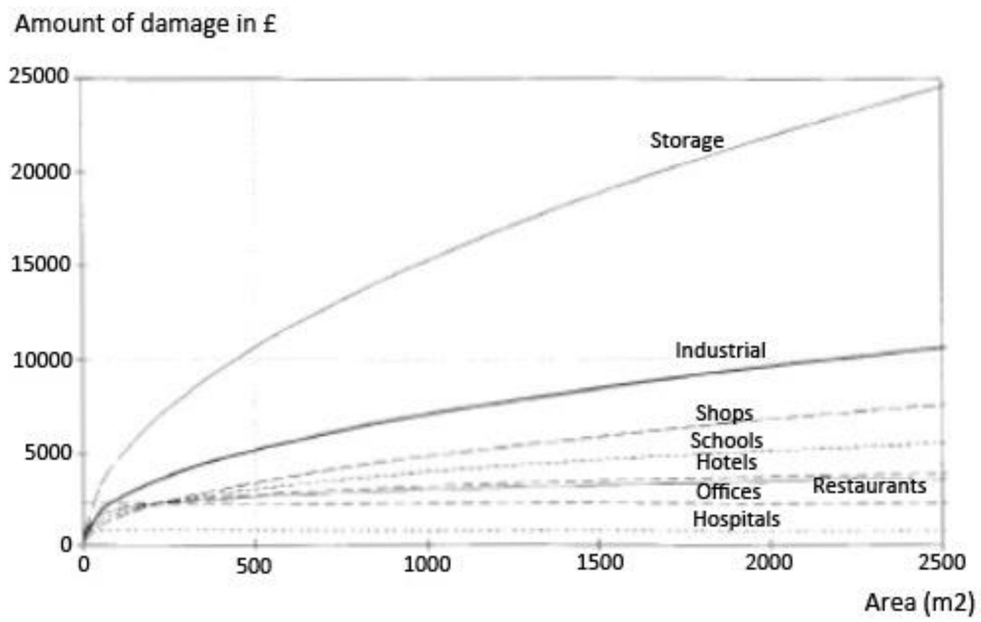

Figure 14 Average amount of financial fire damage as a function of total floor space of the building (6)

The relative damaged area can be expressed as a function of the total compartment size according to this research. The relative damaged floor area is defined as the damaged area divided by the total floor area in the compartment. Apparently there is a tendency of decreasing loss with increasing value at risk (6). This is in contradiction with the recommendations of the NCP-research, where smaller compartments are recommended to reduce the damage, whereas the UK research shows that the average fire damage per m^2 floor area decreases with increasing compartment size. Smaller compartments therefore do not necessarily reduce the total damage. It should be noticed that the UK research was carried out in the eighties. With modern materials and building content this relation might have changed.

4.4 Fire casualties

People's life safety is endangered when they are exposed to smoke and heat produced by the fire, or by collapse. The government set building and construction regulations to prevent fire casualties. These regulations focus on building evacuation and preventing the occurrence of dangerous situations, for example by limiting the smoke spread and smoke production in a building.

For an adequate fire safety system it is important to analyse where and why casualties occur in building fires, and what the main influence factors are. Reviewing the figures about casualties can also give an idea of the effect of compartmentation on the occurrence of casualties, because it shows in which buildings casualties occur and why the people were not able to get out of the building in time.

In the Netherlands there are two organizations which collect the data about fire casualties, Dutch Statistics (nl. Centraal Bureau voor de Statistiek, CBS) and the National Fire Service Documentation Centre (nl. Nationaal Brandweer Documentatie Centrum, NBDC). The collected data of these institutes show significant differences. These differences are a result of different collecting methods, definitions and interpretations.

The NBDC uses press publications from the national Dutch news agency (nl. Algemeen Nederlands Persbureau, ANP), local news sources and P2000-messages[6] for the collection of data about casualties. Not every fatal fire gets attention in the news, and therefore the NBDC will not report every fatal fire. For further information, the NBDC contacts the local agencies for details about the fatal fires. Casualties who die some time after the fire, are also registered by the NBDC. The NBCD pays special attention to dwelling fires, and collects therefore more detailed data about these fires, like age of victims, fire cause etc. The CBS cannot provide this information.

The CBS uses questionnaires which are to be filled out by the fire brigade after a fire. Officially, the commander of the fire brigade has to fill out these forms after the fire. The results are often not very reliable or are sometimes not even received at all. Therefore the CBS developed some techniques to estimate the missing data (61).

Table 10 Fatalities and wounded due to building fires in the Netherlands (statistics by CBS)

	2002	2003	2004	2005	2006	2007	2008	2009	2010
Fatalities	70	85	74	67	80	68	97	57	65
Wounded	1195	1139	1085	1013	1073	843	874	1018	947

People who need to be taken to a hospital after a fire or fire fighters who cannot continue their work due to the effects of a fire are reported as 'wounded'. Fatalities are people who

[6] P2000 is the communication network for all Dutch emergency services (police, ambulance, fire brigade, coast guard) (77)

are killed in a fire or as a result of fire. There is a vague boundary between fatalities and wounded, since in some cases it is hard to prove that someone died as a result of the fire (e.g. what if someone is wounded and dies one week after the event due to a medical complication).

4.4.1 Dwelling fires

About 85% of all fatalities occurred in dwelling fires in the period 2001 - 2008, see Table 11. This figure also includes fires in caravans, chalets, house boats etc. according to the definitions of the NBDC. If these dwelling types are excluded, still about 70% of all fire fatalities occur in houses. The number of deaths in other functions is relatively low. Exceptions are the Volendam New Year's fire in 2001 which killed fourteen people and the fire in the Schiphol detention centre in 2005 which killed eleven people, in Table 11 it is clearly visible that these incidents have a large influence on the total fatality count.

Table 11 Fatalities due to dwelling fires 2001-2008 (figures NBDC)[7] (62)

Year	Total	Dwelling fires	Other	% dwelling/total
2001	50	32	18	64%
2002	64	58	6	91%
2003	63	56	7	89%
2004	47	45	2	96%
2005	74	56	18	76%
2006	48	45	3	94%
2007	36	35	1	97%
2008	69	61	8	88%
Totaal	**451**	**386**	**65**	86%

Due to the high fatality rate in dwelling fires, the Dutch Institute for Safety (nl. Nederlands Instituut voor Fysieke Veiligheid, NIFV) carried out research on fatal dwelling fires. The distribution of fatalities over different dwelling types is shown in Figure 15 (63).

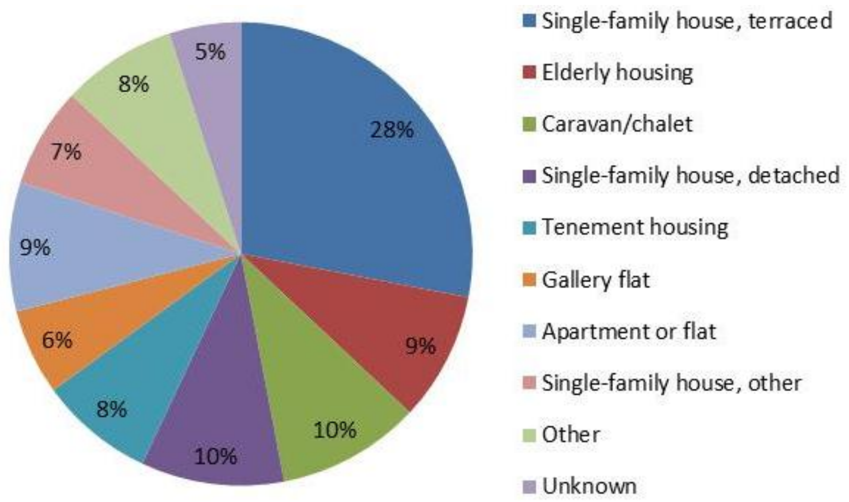

Figure 15 Fatalities per dwelling type

[7] These figures include fatal fires where possible murder or suicide are suspected, but in these cases this could not be proven.

Modern materials used in furniture speed up the fire development in houses. Flashover can occur within three minutes with modern furniture, especially synthetic foams integrated into for example seats, sofas and matrasses contribute to a rapid fire development with a high rate of heat release and much smoke production. The result is a very short survival time for occupants, which is indicated to be one of the main reasons of many casualties in dwelling fires (4).

In about 60% of all fatal dwelling fires, the victims were asleep. In case of fatal fires where the victims were not asleep, immobility is an important aspect. Especially elderly people seem to be a risk group. With the current demographic developments in society, i.e. an ageing population, this risk group is growing. Also it happens often that people stay too long in their home, trying to secure valuables or trying to rescue relatives inside the building (63).

Smoking is the most frequent fire cause in fatal dwelling fires (25%), together with defective electrical equipment (9%) and cooking (11%). Ignition due to smoking very often occurred in furniture and matrasses with synthetic foams (63).

As the researchers of the NIFV conclude that dwelling fires cause the majority of all fire fatalities in the Netherlands, but also in other countries. They also conclude that these fires have little priority in society. Most of these fatal dwelling fires cause only one or two deaths. Although it is very unpleasant for the affected people, dwelling fires do not have a big impact on society and as a consequence, it does not have much political priority yet. This in contrast to less frequent fires with more casualties, like the Volendam New Year’s fire and the fire in the Schiphol detention centre (3).

Regarding the figures it is remarkable that dwelling fires have little attention. According to the figures, it would be very effective to reduce the number of deaths in dwelling fires in order to get a significant reduction in the overall number of fire-deaths. NIFV-researchers address privacy and individual responsibility (i.e. only the owners and users of the house itself are at risk) as main reasons for not taking action and striving for a higher safety level by the government (3).

Measures to improve the fire safety level in dwellings and consequently reducing the death rate in dwelling fires are (4):

- Fire detection in staying areas. Due to the short survival time in dwellings during a fire, it is important to detect the fire as soon as possible and to warn the occupants.
- Reducing the flammability of furniture. Modern materials used in furniture (especially synthetic foams in seats and matrasses) are very flammable and show a very high rate of heat release. The effect is a very short survival time. There are several impregnation agencies available which can reduce the flammability of furniture. This will slow down the fire development, and gives the occupant more time to escape. The problem with these fire retardant agencies is that is uncertain what influence these chemicals have on human health.
- The use of sprinklers. Sprinklers reduce the fire spread and control the fire, which creates more time for the occupants to escape. However, the costs of installing these sprinkler systems are a problem (64).

In addition, it is very important to make people aware of the fire risks in their houses and to inform people about what to do (and what not) in case of fire in their house (64). Compartmentation and structural fire resistance do not seem to have any significant influence on the fatality rate in dwellings. The information of NBDC shows that most casualties in dwellings occur in the compartment where the fire started (50).

4.4.2 Other fatal fires

Fatal fires other than dwelling fires occur less frequent (about five people on annual basis), with some exceptions due to larger incidents with more fatalities, see also Table 11. These figures include for example fatal fires in hotels and lodging buildings, but also firemen who are killed in action.

Firemen get accidently killed during their fire fighting actions, often because they are surprised by a sudden collapse or an explosion. Examples of this are the fire in a shipyard in De Punt in 2008, were three fire fighters were killed after a smoke gas explosion, and collapsing façade elements killed three firemen in 2003 in Haarlem and one fire fighter in 2010 in Veendam. In the last decade, seven fire fighters were killed in action (65).

Other fatalities mainly occur in industrial buildings, often after accidents, like explosions. Also in nursing homes and psychiatric institutions some fatal fires are reported every year. Fatal fires occur only incidentally in other building types.

Incidental fatal fires which cause several deaths get usually much media attention. Large accidents like the Volendam fire or Schiphol fire with many fatalities get also much political attention, as well as environmentally harmful fires, like for example a recent fire at Chemie-Pack in Moerdijk in 2011. These disastrous fires are almost always an accumulation of mistakes and errors. For the fires in Volendam, Schiphol and Moerdijk an extensive research was carried out to reveal these errors.

4.4.2.1 The Volendam New Year's fire

At January 1st 2001, a fire killed fourteen young people and many others got wounded in a cafeteria in Volendam. The decoration on the ceiling was ignited by fireworks which resulted in a very fast fire development. There were more occupants in the building than officially allowed and the escape routes were not sufficient. In combination with the rapid fire development, this lead to the tragic ending (66).

According to the investigation board the main causes for this disaster are (66):

- Escape routes were insufficient;
- At the moment of the fire, there are more people inside the building than allowed;
- The decoration on the ceiling of pine branches was not treated with a fire retardant agency.

The owner of the building can be blamed for carelessness and not following the regulations. Maintaining the rules has failed and the municipality can be blamed for this. Withdrawing the use permit could have been a means to enforce the regulations. The effect of this tragedy is that regulations for catering industry has become more stringent and maintaining of these regulations has been intensified.

4.4.2.2 Fire at the Schiphol detention centre

At midnight, 26th October 2005, fire broke out in a detention centre at Schiphol airport. Eleven people died in their cells due to carbon monoxide intoxication, and fifteen people got wounded. The fire started in one of the cells by ignition of one of the matrasses. The fire and smoke developed rapidly in the building wing via the hallway after the door of the cell remained open when the prisoner was evacuated (67).

Investigators of the Dutch Safety Board draw the following conclusions (67):

- The cells contained a lot of combustible materials (matrasses, sheets, wall covering) and the door of the cell was not closed after the evacuation of the inmate, therefore rapid fire and smoke spread was possible via the hallway;
- Employees of the prison were not trained for a fire situation and could therefore not act properly;
- The fire brigade was late for several reasons: the automatic fire alarm system did not report the fire directly to the fire brigade, the complex was not easily accessible for the fire brigade and the fire brigade was not prepared for a fire in this detention centre;
- The building did not meet the requirements from the Dutch Building Decree, the Governmental Buildings Agency (Rijksgebouwendienst, RGD) and the local municipality (Gemeente Haarlemmermeer) should have checked this. As owner of the building, the RGD is responsible for the construction of a fire-safe building. The municipality has to check the design on compliance with the Building Decree, so they should not have given permission for this building. The main deviations from the Building Decree are:
    - Maximum walking distances: the escape routes in the building are too long. The designers were aware of this, and therefore provided the building with a

heat and smoke extraction system, based on the equivalence principle. However, the heat and smoke extraction system did not function during the fire and was not tested.

- The cell-doors were not self-closing, therefore the compartmentation did not function and fire and smoke could spread via an open door (self-closing doors are actually not obliged for cells).
- The fire resistance of ventilation ducts and hatches was insufficient.
- The compartments were bigger than allowed (850m^2 instead of 500m^2).

4.4.3 Frequency of fires in buildings

Another aspect which might explain the relative high number of fatalities in dwelling fires, is the high total number of fires in these buildings. In Figure 16 it is clearly visible that the majority of building fires occur in dwellings (48%). Other building functions which are often hit by fire are industrial buildings (10%), meeting buildings (7%) and buildings with a health care function (7%).

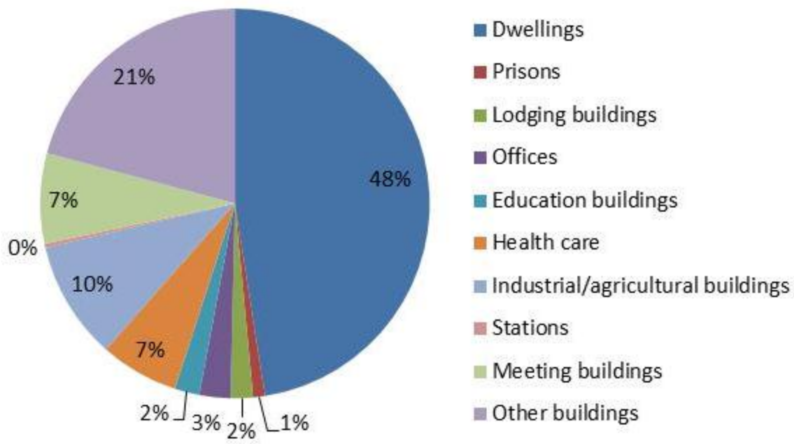

Figure 16 Proportion of the fires that occur in the different building functions (statistics by CBS)

The large number of fires might be an explanation for the high number fatalities in dwellings, but according to the figures in Table 12, dwelling fires are also on average much more lethal than fires in other buildings.

Table 12 Overview of the fires in the period 2002 - 2008 and the average number of fatalities per fire (statistics by CBS)

	Number of fires				Average number of fatalities per fire	
Year	Total	In dwellings	In other buildings	% dwelling/total	In dwellings	In other buildings
2002	14192	7744	6448	55%	0.0075	0.0009
2003	13928	7264	6664	52%	0.0077	0.0011
2004	13040	6837	6203	52%	0.0066	0.0003
2005	13147	6383	6764	49%	0.0088	0.0027
2006	14272	6928	7344	49%	0.0065	0.0004
2007	14801	6312	8489	43%	0.0055	0.0001
2008	14423	6662	7761	46%	0.0092	0.0010
Average	**13972**	**6876**	**7096**	**49%**	**0.0074**	**0.0009**

Approximately 14 000 fires occur the Netherland per year. On average, about 6 900 of these fires occur in dwellings. When this is compared to the number of fatalities in dwelling fires, the average number of casualties per dwelling fire is 0.0074. This figure is approximately eight times higher than the average number of casualties per fire in all other buildings. There is approximately one fatality per 130 dwelling fires, while there is in other building fires approximately one human fatality per 1 100 fires. It can therefore be concluded that fires in dwellings are by far the most lethal fires.

4.5 Conclusions

The acceptability of risks depends not directly on the probability and consequence of a certain event, but more on how people perceive the risk. Low frequency events, with high consequences are generally more feared by society and are therefore in practice less acceptable than high frequency events with minor damage. This also holds for fire risks, where larger events appear to have more priority and the acceptability is less. The risk acceptance level is also lower when a certain risk is taken involuntary.

The acceptable fire risk in the Netherlands is not quantified per building or occupancy type. Only the means to achieve an acceptable fire risk level are prescribed, but it is not defined what objectives these regulations are exactly aiming for.

The probability of the occurrence of a severe fire depends on many factors, like the occupancy type, the number of occupants and active fire protection measures. Also there appears to be a relation between the compartment size and the probability of fire occurrence per square meter floor area. This phenomenon is currently not incorporated in determination methods for the probability of fire occurrence.

Fire can result in casualties, financial and/or property damages. The government's interest is mainly related to casualties (protecting citizens) and damage to adjacent premises (protecting citizens from other citizens). The fire (both direct and indirect) damage in buildings is mainly the burden for owners and users and of the building, together with their insurers.

In most buildings it is difficult to determine the importance of compartmentation for life safety. An appropriate size of compartments can be determined by assessing hypothetical boundaries of the fire and to determine if the fire and/or smoke will cut off escape routes for occupants of other parts of the building.

When property damages are considered, the importance of compartmentation becomes more obvious, since property is confined by the compartment. In an ideal situation, the choice for compartmentation will the depend on the possibility of an fire outbreak and the extent to which a fire can be allowed to develop. When total destruction of the building and its content is tolerable, the evacuation of the building will be governing for the design. For this approach the knowledge about fire compartmentation and human behaviour and evacuation is still too limited for a wide application and therefore simplifications are necessary in the building legislation.

4.5.1 Fire damages

About 14 000 fires occur in the Netherlands per year. The total damage due to these fires is increasing and this increase is mainly dependent on the increase of high-damage fires, since high-damage fires determine the majority of the total damage. High-damage fires are increasing in number and severity.

Several reasons can be appointed for the increase in high damage fires. Important are market developments in both the insurance business as in the insured parties' businesses. The insurance market is currently characterized by severe competition. As a result, insurers lost their expertise and interest in technical fire safety issues. As a consequence, insurance companies make less demands on these fire safety issues.

Buildings became also more complex with a higher value content. For example the upscaling of companies and the increase of service providing companies is resulting in higher potential fire damages. Moreover machinery, equipment and stock items are increasingly high-tech, which also results in higher potential fire damages.

The majority of the total fire damages occurs in industrial buildings, followed by buildings with a meeting function (shops, shopping malls, restaurants etc.). Also the damage per fire in school buildings is relatively high, but the number of fires in school buildings is relatively small, and therefore the total annual damage in school buildings is relatively low. Most fires occur in dwellings, but the average damage per fire is small in dwelling fires.

For the reduction of high-damage fires, it is important to take the right prevention measures. First of all, it is important to reduce the probability of getting a fully developed fire, by eliminating possible ignition sources and taking active fire suppression measures. There are many different fire causes possible, but there appears to be a relation between the function and ignition source, so many fires can be prevented with a proper function-specific fire prevention policy.

The damage is further determined by the extension area of the fire and smoke and the value content of this area. A proper balance between compartment size and compartment content should therefore be found. British research has shown that the relation between compartment size and potential fire damage is not as straight forward as one would expect, since the amount of fire damage increases under-proportional to the increase of total floor area in a compartment. Also the fire resistance of compartmentation systems against fire spread should be sufficient and in balance with the content of the fire compartment (and potential fire severity) and also with the capacity of the fire brigade to limit fire spread.

The compartmentation systems failed in many of the high damage fires investigated by the NCP and Nibra. In approximately 50% of the fires where compartmentation was relevant, the adequacy of compartmentation systems was insufficient to prevent fire prevent fire spread to other compartments. In 50% of the cases where the compartmentation failed, this was due to the failure of self-closing doors, so self-closing doors did not function in approximately 25% of the high damage fires.

4.5.2 Fire casualties

The majority of all fatalities in building fires occur in dwellings in the period 2001 - 2008. Only a very small part (±10%) of the fatal fires occurs in other buildings, whereas the larger incidents with multiple deaths happen accidentally. In the last decade the Volendam New Year's fire (2001) and the fire at the Schiphol detention centre (2005) are examples of this.

The total number of fires in dwellings is approximately equal to the total number of fires in all other building types. This implies that dwelling fires are in relative terms more lethal than fires in other buildings. The risk of fatalities in dwelling fires is eight times higher than the risk of getting killed in another building fire.

The main factor in causing fatalities in dwelling fires is the rapid fire development, where the developed heat and smoke create deadly conditions before people are able to escape. The rapid development is mainly caused by the materials used in modern furniture, especially synthetic foams used for matrasses and sofas are highly flammable.

Since most fatalities occur in dwelling fires, focussing on fire safety measures in dwellings would be the most effective way for achieving a significant reduction of the total fatality rate. Compartmentation and fire resistance of loadbearing structures are not crucial aspects in dwelling fires.

Disastrous fires with many fatalities like the fire in Volendam and Schiphol are not the consequence of shortcomings in building legislation, but important factors which contributed to these disasters are carelessness, lack of control and inspection, ignorant or not well trained staff and (deliberately or not) disregarding the rules or unawareness about the importance of the rules.

In contrary to fire damages, passive fire protection such as compartmentation does not seem to be essential for the prevention of casualties. The current legislation regarding these passive fire protection systems seems to be adequate for the protection of people's life safety. In case of fatalities, the suffering has generally already been done before collapse occurs and fatalities in dwelling fires generally occur in the compartment where the fire started. When property damages are considered, passive fire protection does often appear to be not sufficient: when applied and where relevant, fire compartmentation is often not sufficient to prevent fire spread to other compartments. The actual performance of compartmentation will therefore be further investigated.

5 Structural behaviour during fire

Heat affects construction materials during fire. Materials generally decrease in strength, burn, elongate or bow due to thermal expansion. The behaviour is important for the performance of buildings during fire, as well for the loadbearing function as for the separating function of compartmentation systems. The resistance to fire is defined as the time period during which a building element or system can fulfil its anticipated functions under end-use conditions when exposed to fire.

Different methods have been developed to determine the fire resistance of building elements, ranging from simple (component level) calculation methods to advanced calculation methods. Testing is a widely applied classification method for more complex systems, such as doors, glazed partitions etc.

The reduction of mechanical strength at elevated temperatures of elements with a loadbearing function is typically material specific and depends on the interaction between different elements. In case of structures with a separating function, the interaction between elements is of eminent importance. Moreover, compartmentation systems with a separating function are often composed of many different elements and materials and passages between compartments are necessary in normal use conditions.

5.1 Structural behaviour with regard to loadbearing function

Due to the change of material properties during fire, the strength and stability of the loadbearing structure is reduced which may lead to significant damage or even collapse. To prevent casualties due to collapse, requirements have been set for the fire resistance of loadbearing structures. These requirements hold for all structural elements which can cause the collapse of other structural elements outside the fire compartment when structural failure of this particular member occurs. In the Dutch Building Decree this is expressed as the time to failure, to be determined in standardized fire conditions.

There are different methods possible to assess a loadbearing function (criterion R) in fire conditions (32) (33):

- Approved design solutions using semi-empirical design tables and charts for specific structural elements (e.g. tables with minimum concrete cover, critical section temperature, reduced cross-section based on 500°C isotherm etc.). This method is generally only applicable for normal forces and bending moments, not for shear, torsion, thermal-cracking, pre-stressing bond etc. (14);
- Simple calculation models for specific structural elements;
- Advanced calculation methods for simulating the behaviour of an entire structure, parts of a structure or an element (e.g. finite element analyses, CFD).

Simple calculation methods are for example based on the utilization factor or the reduction factor of a certain element. Since fire is an accidental load situation, partial safety factors (material factors and load factors) are taken as γ=1,0 and also the load factors for transient loads are lower. Therefore the design load on the structure is lower than its design capacity at room temperature. This implies that the theoretical loadbearing capacity is not fully utilized and has some overcapacity. This overcapacity is expressed with the utilization factor. The loss of strength in fire conditions should be less than the overcapacity of the loadbearing structure. The loss of strength is expressed with the reduction factor. The reduction factor depends the temperature of the element and/or the fire duration (32).

In practice, the strength reduction is not only dependent on the temperature of the section and the fire duration, but also on many other factors which influence the loadbearing capacity, such as thermal expansion, non-uniform temperature distribution etc. Dependent on the material type, the Eurocodes therefore provide correction factors for simplified calculations methods to take into account non-uniform temperature distribution in the cross-section or along the length of the section, dependent on whether the element is statically determinate or indeterminate and to what extent the section is engulfed by the fire (14).

The reduction of the mechanical resistance in fire conditions is mainly dependent on the construction material. Steel, concrete and timber are the most commonly applied materials in building structures. The behaviour of these construction materials is discussed in the next sections.

5.1.1 Behaviour of steel structures during fire

Steel has a high thermal conductivity, and therefore the temperature distribution is quite uniform over the cross-section during heating, as well for fully engulfed sections as for sections heated from one side. The steel expands with increasing temperature. This thermal expansion will cause elongation of steel members during heating. In case of non-uniform heating of the cross-section, thermal bowing will occur: the member will curve under influences of differences in elongation. Typical for steel structures (also doors and window frames) is that the members bow towards the fire. When the deformation of the member is obstructed, stresses will develop in the structure (13).

The mechanical properties of steel will decrease with increasing temperature. Both the stiffness (Young's modulus) and the strength of the material will decrease, see Figure 17. Due to a decreasing stiffness, an element will deflect more under constant loading. Also stresses induced by thermal expansion will decrease due to the decreasing stiffness.

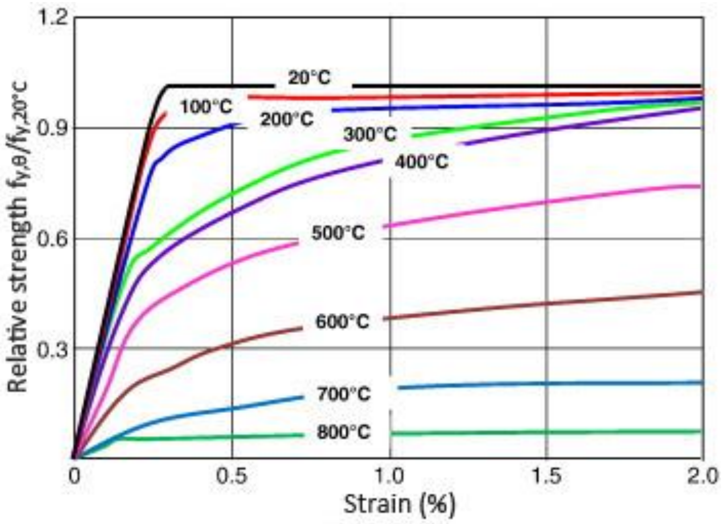

Figure 17 Stress-strain relation of steel at elevated temperatures (34)

The yield strength of normal structural steel will start decreasing from about 400°C. After that, the strength reduces rapidly. The material has almost completely lost its original strength at about 800 - 1000°C, see Figure 18.

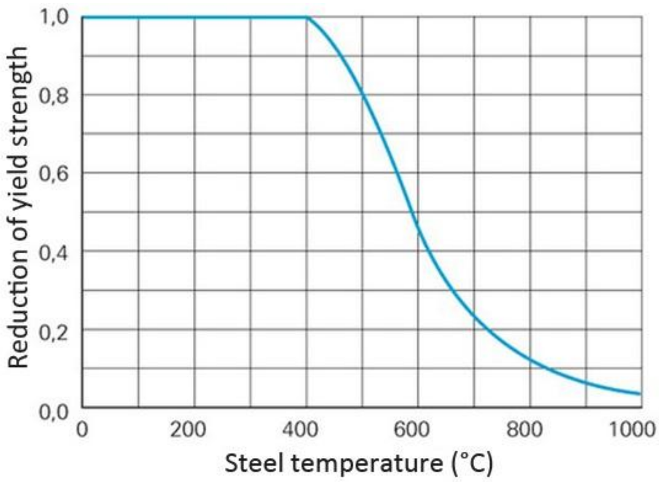

Figure 18 Relation between temperature and yield strength of steel (35)

Due to the degradation of mechanical properties, steel structures need special attention in fire safety design. The temperature of the exposed members will increase rapidly and quite uniformly, and therefore the mechanical properties will decrease fast. Without any protection, the structure will lose its strength and stability rapidly. Columns become very sensitive for buckling and beams will start sagging. The ductility of the material is relatively high, also at elevated temperatures, and therefore an alternative load path may develop based on cable action or tensile membrane action in a floor slab, but the structure should be designed properly to accommodate these forces.

Dependent on the severity of the fire, the steel structure is damaged by the fire. It depends on the type of steel (hot rolled, cold formed) and the maximum temperature of the fire to what extent the mechanical properties have changed. For hot rolled sections, the mechanical properties after cooling down have generally not changed if the maximum steel temperature during the fire was not higher than 600°C. For higher temperatures, the strength reduction after cooling can be up to 10%. Replacing the steel structure is therefore usually not necessary for strength considerations. However, during fires often big (irreversible) deformations occur. Therefore, steel members often have to be replaced because of these deformations. Cold formed sections, like bolts and anchors reduce much more in strength after being heated. These components need to be replaced (36).

5.1.2 Behaviour of concrete structures during fire

Concrete has a relatively low thermal conductivity, certainly compared to steel. The temperature distribution in the cross-section is highly non-linear. The surface temperature of an exposed concrete element becomes approaches the local fire temperature, but the core will remain cool for a long time. The advantage is that it takes a long time before the core temperature of a concrete element has reached a critical temperature, see Figure 19 (13).

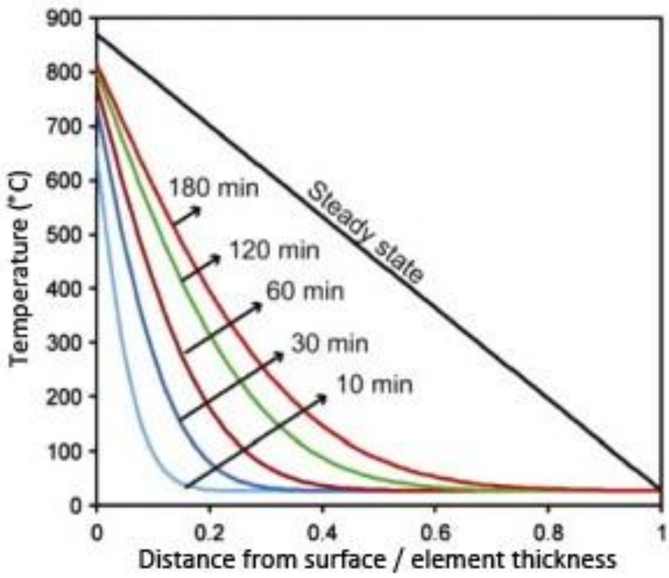

Figure 19 Heat development in a concrete section (exposed on one side) (37)

At elevated temperatures, the mechanical properties of concrete will decrease due to chemical transitions and internal cracking in the material. Chemical transitions are mainly caused by dehydration of the cement paste. The result is that the cement paste reduces in strength and therefore the connection between the aggregates becomes weaker (38).

Internal (micro) cracking is mainly caused by differences in thermal expansion between different components in the concrete mix. The differences in thermal expansion between the mineral aggregates cause cracks in the interface layer between the aggregate grains and the cement paste. The cement paste itself will also shrink due to water losses. Due to these cracks and the chemical transitions in the cement paste, the compressive and tensile strength of the concrete will decrease, as well as the stiffness of the material, see Figure 20. Of course, the exact course of the curves depends on the concrete mixture (38).

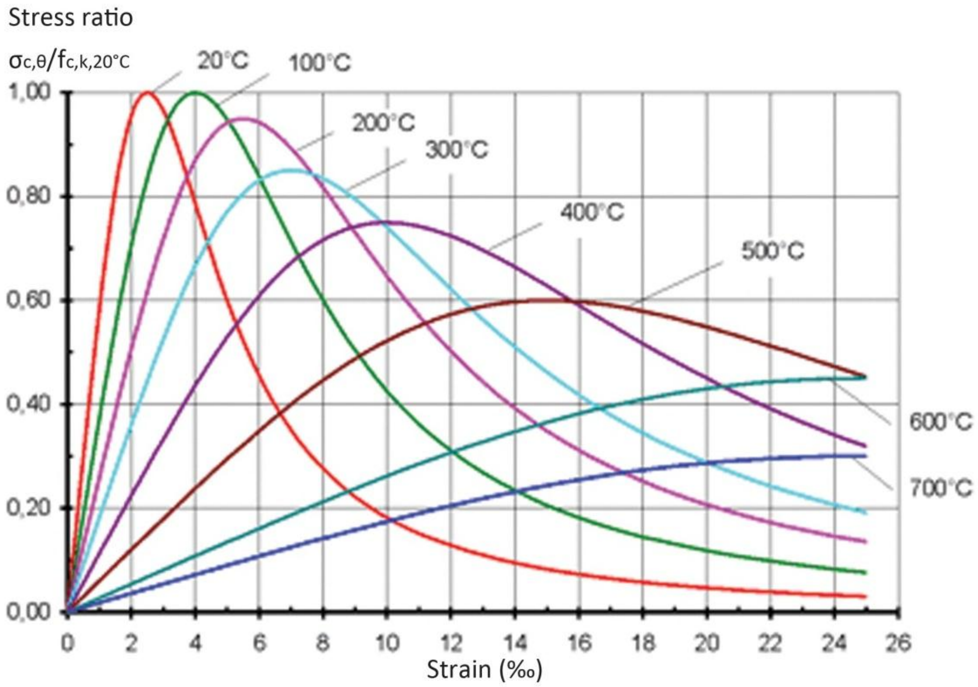

Figure 20 Stress-strain relation of concrete at elevated temperatures (39)

Thermal bowing of concrete members is usually constricted due to the large stiffness of concrete members, therefore the deformations are small. Non-linear temperature differences and thermal strains between the exposed surface and the core therefore induce thermal stresses in the cross-section. Compressive stresses will occur in the heated perimeter and for equilibrium reasons, tensile stresses may occur in the core of the concrete section, dependent on the actual load level on the member. If the tensile stresses are larger than the tensile strength of the material, cracks occur in the concrete section, affecting its strength and stiffness, see Figure 21.

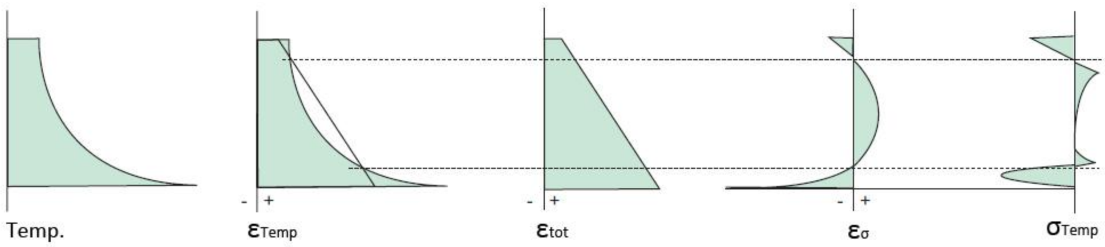

Figure 21 Stresses induced by non-linear temperature distribution in cross-section (40)

Spalling is another import phenomenon of concrete during fire. Concrete contains moisture and chemically bound water. At elevated temperatures, water starts to evaporate (which dissipates some heat) and the water vapour induces pressure in the concrete pores. If this vapour cannot escape from the pores, the internal pressure can reach a critical level. Together with the compressive stresses in the surface layer due to restrained thermal expansion (buckling), the pore pressure can cause splitting off of the surface layer of the concrete, see Figure 22. This spalling-process can be very gradual, but it can also be more violent, when pieces spall off in an explosive way. Spalling can be a progressive process and may therefore destruct a thick layer of concrete (38).

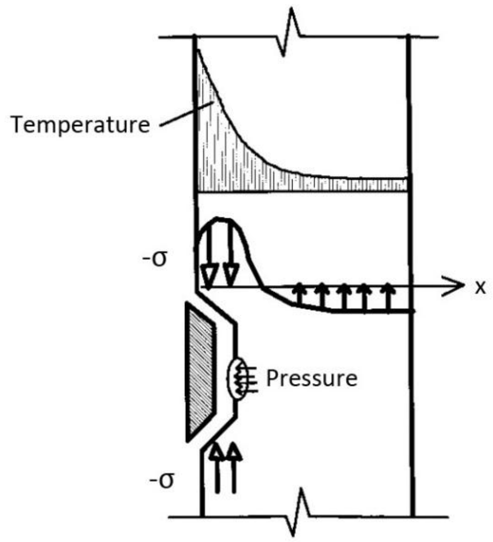

Figure 22 Principle of spalling (41)

The sensitivity for spalling depends on the porosity of the concrete, the moisture content, the aggregate type, the aggregate size and the heating rate (42). In a highly permeable concrete, only small pore pressure build up will occur, since the water vapour can easily escape from the material. High-strength concrete is in general more sensitive for spalling due to its higher density, but there is not a direct relation between the strength class of concrete and its sensitivity for spalling. The permeability of concrete is for example influenced by the cement type (blast furnace vs. Portland cement), the water-cement ratio and additives like silica fume. Also when the concrete is heated rapidly, the pressure builds up more rapidly since the vapour needs some time to escape from the pores. Spalling can therefore already occur at relatively low temperatures (43). The spalling properties of concrete can be influenced with some additives, like steel or polypropylene fibres (13).

In buildings, concrete is always applied as reinforced concrete, i.e. the concrete contains steel bars for structural reasons. In a composite structure of steel and concrete, the materials complement each other. Concrete has very good compression properties, but the material is much weaker in tension. The concrete also has a more brittle character. The use of steel bars becomes apparent here. Steel has a high tensile strength and is very ductile. In a combination of these two materials, these properties are fully utilized. In addition, the concrete will protect the steel bars from corrosion when sufficient cover is applied.

The concrete cover will not only improve the durability of the material by protecting the reinforcement from corrosion, but it will also protect the steel bars from fire. It will take some time before the steel bars reach a critical temperature level due to the low thermal conductivity of the concrete cover. For a fire resistant structure, the reinforcement needs to have sufficient cover to prevent yielding or rupture of the reinforcement bars. Also the possibility of spalling should be considered as well as the reduction of bond between the concrete and the reinforcement (14).

5.1.3 Behaviour of timber structures during fire

Timber is a combustible organic material. The material will therefore contribute to fire. In principle, the heat does not affect the mechanical properties of timber. Due to the combustion of timber, the cross-section will reduce with an almost constant speed. The char layer around the perimeter of the section slows down the combustion. The char rate for most timber species is typically around 0.5 – 1 mm/minute. The development of pyrolysis gasses takes place underneath the char layer. The core material of the timber element is hardly affected by the fire. At a certain moment in time, the cross-section of a timber member becomes too small to carry its loads and collapses, usually in a brittle manner.

In contradiction to steel and concrete elements, timber does not bend toward the fire. Due to the charring and drying, shrinkage occurs on the exposed side. Timber elements therefore typically curve away from the fire in an unloaded situation (13).

5.2 Measures to improve the behaviour of loadbearing structures

To ensure the loadbearing function of structures, it is important to protect the elements sufficiently from fire exposure. There are several ways to protect the structure, the structure can for example be protected by insulating it from the fire, by taking into account the strength losses or by providing an alternative load path. Maintaining the capacity of steel and concrete elements means keeping the temperature of critical cross-section sufficiently low.

5.2.1 Fire protection measures for steel structures.

For steel structures it is essential to keep the steel temperature sufficiently low. Insulating the members from the heat is the most commonly applied means of fire protection. Other possibilities are for example cooling with water, but this very rarely applied in the building industry.

Different commonly applied methods for protecting steel members are (44):

- Protection with mineral wools. Mineral wools are supplied by different producers. These materials are non-combustible and have a very low thermal conductivity. The fire resistance of an insulated steel member depends on the thickness of the insulating layer, the fixing and finishing of the mineral wool. Fire protection with mineral wool is in general highly reliable.
- Protection with fire resistant boards. Fire resistant boards have the same effect as mineral wools: the board provides insulation to the steel member. Advantage of these boards is that they can be finished easily, which makes these boards very suitable for in-sight applications.
- Protection with intumescent coatings. An intumescent coating can be sprayed onto steel members in a very thin layer (0.2 – 4 mm) and can be applied in many colours (49). This type of fire protection is therefore very often used in applications with high aesthetic demands. The functioning of these coating is based on the swelling of the coating when exposed to heat. The heated coating expands into a char based foam with a low conductivity, which retards the heating of the steel elements.

- Providing a concrete cover. Concrete has a low conductivity and hence it protects the steel from heating. The concrete can be applied to the steel by means of spray mortar or the steel element can be casted into a concrete composite. For proper protection, spalling of the concrete should be prevented.

It depends on the application of the members and also on the aesthetic and functional demands which of these protection measures are used.

5.2.2 Fire protection measures for concrete structures

The main purpose of fire protection in concrete structures is providing sufficient insulation for the reinforcement. The reinforcement should therefore have sufficient cover. Spalling of the concrete should be prevented by applying a concrete mix with sufficient permeability or by applying fibre reinforcement. Also the aggregate type is important.

If the cover is not sufficient, or the concrete shows substantial spalling, the fire resistance can be improved by applying spray mortar. The spray mortar basically provides extra cover. In special applications additional protection is applied with fire protection boards. Also some intumescent coatings are available, but these are not widely applied yet. Fire protection with spray mortar and fire protecting boards of concrete structures is uncommon in buildings in the Netherlands. In tunnels it is more common to apply additional fire protection (14) (45).

5.3 Structural behaviour with regard to separating function

In comparison to loadbearing structures, many different materials are used in separating partitions and facades, including many synthetic materials. Also these structures have more functional requirements than a loadbearing structure. Many links between compartments are in practice essential, such as cables, piping, air ducts, windows etc. need to be integrated into these partitions. In normal use conditions there is a need for free passage between compartments via doors (43). Despite all these ‘links’, the separating function of the ‘chain’ should be guaranteed for a certain amount of time to prevent fire spread to other compartments. Due to the different elements in the partition, many different failure modes can occur, which could cause fire spread to other compartments. Due to the complex behaviour of these separating elements, the fire resistance is mainly based on tests (E, I and R criteria) and some failure-criteria can be calculated (criterion I and R) (13).

The first minutes of fire exposure are often critical for compartments. The structure still behaves stiff, the temperatures are still relatively low but the temperature gradients relatively large. These temperature gradients cause large thermal stresses and gaps and the structure can open up due to thermal bowing, while the intumescent gap fillers and coatings are not active yet. Also mechanical closing elements should close in this stage.

When the heating continues, other aspects become more critical. The structure becomes weaker due to the increasing temperature, which may lead to load-induced deformations. The temperature of the non-exposed interface is increasing and the radiation level is rising. The temperature gradients become smaller, but erosion of elements becomes important. For example the gap filling materials can burn away and the integrity function gets lost.

Some typical failure modes for different fire resistant systems can be distinguished. Below, the main failure modes of frequently applied constructions are discussed and often critical systems within firewalls are discussed. The firewalls itself often consists of concrete, masonry, metal sandwich panels, or light weight framing walls, like timber or metal stud walls covered with fire protecting gypsum boards.

5.3.1 Doors and door frames

Doors and door frames are usually constructed of timber, steel or aluminium. Every material has different (fire) properties and therefore the behaviour of the system depends on the material. As already indicated, the material behaviour of timber and steel is different in fire conditions. Timber is a combustible material, while the properties of metals are strongly depending upon the temperature.

Some typical failure modes for doors and door frames are (13):

- The occurrence of gaps between door frames and doors due to differences in deformations (criterion E);
- The occurrence of gaps between the door frame and the wall (criterion E);
- Flames on non-exposed side from combustible sealing rubbers (criterion E);
- For wooden doors and frames: burning through of the door or frame, especially in the upper corner, around the door lock or close to the hinges (criterion E);
- To high temperature on non-exposed interface due to the high conductivity of steel parts (criterion I);
- Melting of aluminium elements;
- The loss of fixation of infill panels (e.g. glass) when framing loses its strength (criterion E).

5.3.2 Windows and glazing

Float glass is very sensitive for internal stresses due to uneven heating, and breaks due to restrained elongation or restrained curvature. Temperature differences inevitably occur between the central part of the glass which is directly exposed to the fire and its fixings along the edge of the panel, which are not directly exposed to the fire. Due to the brittle behaviour of float glass, the formation of cracks is usually immediately fatal for the entire panel. In practice, the fire performance of glass panels is improved by applying reinforcement in the glass (e.g. wired glass) or by providing the glass with an intumescent insulation layer, in order to keep the glass temperature sufficiently low and, even more important, to keep the temperature difference within the glass panel sufficiently low (i.e. the temperature difference between glass and groove).

Some typical failure modes of windows and glazing are (13):

- Cracking of the glass due to uneven heating;
- Failure of the fixation of the window panel;
- Melting of the glass;
- Burning of foils or sealing on non-exposed side;
- Too late foaming of intumescent layer.

5.3.3 Penetrations for ducting and piping

Where ducts and pipes penetrate a fire resistant compartmentation wall or floor, these ducts and the seals around the ducts should have sufficient fire resistance.

Critical issues for these ducts and pipes are (13):

- Failure of sealing around and inside the ducts;
- Failure of supports;
- Deformations of walls and floors which cause gaps around the ducts and pipes.

5.4 Conclusions

Heat is affecting the strength and stiffness of all construction materials. Especially steel structures can lose their loadbearing function relatively rapidly due to the high thermal conductivity of the material. Concrete and timber are less conductive, but concrete can be sensitive for spalling and timber is a combustible material, and therefore the cross section will decrease. Also the effect of fire-induced deformations can be significant.

The loadbearing function of structural elements can be secured by giving the structure sufficient overcapacity and taking into account the losses, or by providing additional insulation to protect the material from the heat. It is up to the designer to guarantee sufficient fire resistance of the structure, dependent on the building height and occupancy class of the building as specified in the Building Decree.

Compartmentation systems with a separating function are often more complex than the loadbearing structure, since there are many different elements and systems incorporated into compartment walls. Many services need to penetrate the partitions with cables, ducts and pipes, and there is often a need for a free passage between compartments with doors. There are many different materials used in these constructions, varying from glass, different sealing materials to aluminium. In addition, fire separating systems should operate as anticipated (fire dampers and doors should close) and when these systems operate, they should also provide sufficient resistance against fire spread. This results in many different possible failure modes, which makes predicting the fire performance of these systems very complex. Testing is usually the only way to show the fire resistance of these compartmentation systems.

The performance of compartmentation systems is usually determined by assessing single elements or test pieces. The standardized assessment conditions are an approximation of reality, as well as the failure criteria which are defined as arbitrary values. When these failure criteria are exceeded, failure is assumed to occur in practice (e.g. propagation of the fire to the non-exposed side). Since it concerns an approximation of reality, the actual performance of structures in real fires is different.

6 Fire performance of building constructions in real fires

The fire safety performance of buildings depends on many different factors, such as building lay-out, fire detection and evacuation, occupancy type etc. Factors like fire duration, fire conditions, applied construction materials and interaction between elements influence the fire performance of compartmentation and loadbearing structures. For compartmentation and mechanical fire resistance, the performance is expressed as the time until failure, i.e. the time until fire spread occurs or the loadbearing function is lost.

The fire resistance of the components is generally determined based on standardized fire conditions. Test results can be used, as well as calculation methods or more advanced fire safety engineering methods for the determination of the fire resistance. Tests (and test results) are generally used to determine the performance in standard fire conditions (e.g. standard dimensions, fire load) and for the verification of computer models. Nonstandard conditions (e.g. large compartments, high buildings) often require a more sophisticated approach. However for many systems, especially systems with a separating function, testing is the only possible and approved classification method. Test conditions should be transparent, efficient (cost and time) and not too ambiguous. Still there is scatter in test results due to poorly defined supporting conditions, poorly defined heating conditions (margins in temperature curve, heat escaping via supports etc.) and scatter in material properties. In practice, there are many more sources of scatter in performance of fire resistant systems, as well with regard to separating function as with regard to the loadbearing function (14).

6.1 Classification based on tests and calculations

The fire resistance of many building components is based on standardized determination methods, like tests or calculations. The tests are performed under standardized conditions (air pressure, ambient air temperature) and the failure criteria for the specimen are prescribed in the codes. The classification is based on the time until failure occurs (30, 60, 90, 120 minutes). The classification obtained during the tests is just an indication of the performance during a real fire, since both the fire conditions and the failure criteria only represent an approximation of reality. Not only differences in fire severity determine this deviation, the deviation is also determined by the following aspects (47):

- Standard of construction: typically better for tests than in reality and generally only the successful tests are reported (e.g. if a system fails during 4 out of 5 identical tests, and passes the fifth, the system gets its classification only based on the fifth test);
- Applied loads: the applied loads on the test specimen are often not similar to the situation in practice;
- Restraints and continuity: the support conditions are often different to those in actual buildings;
- Size effects: test furnaces are limited in size;
- Connections and critical failure modes: connection details are often overlooked but do often govern in reality. The reasons for failure are often different from what is expected.

These aspects contribute to the enormous complexity and uncertainty at all levels of the fire resistance of structures. Although fire resistance tests have some serious shortcomings, the standard fire test is the only universally recognized method for determining the fire resistance of construction elements (54).

6.2 Standard fire curves vs. real fires

The fire resistance of elements is classified according to standard fire curves, based on a semi-empirical approach. Different temperature - time curves are available for different applications. The shape of these curves is based on international consensus. International harmonisation eliminates the need for verifying the fire resistance in every country separately according to the local requirements. The standardized conditions are also necessary for the reproducibility between testing laboratories (13).

6.2.1 Standard fire curves

A natural fire curve, a pre-flashover curve and a post-flashover curve are depicted in Figure 23. The post-flashover fire curve represents the fire temperature of a fully developed fire after flashover (see section 2.1.2), and is modelled as a continuous function with a logarithmic temperature development.

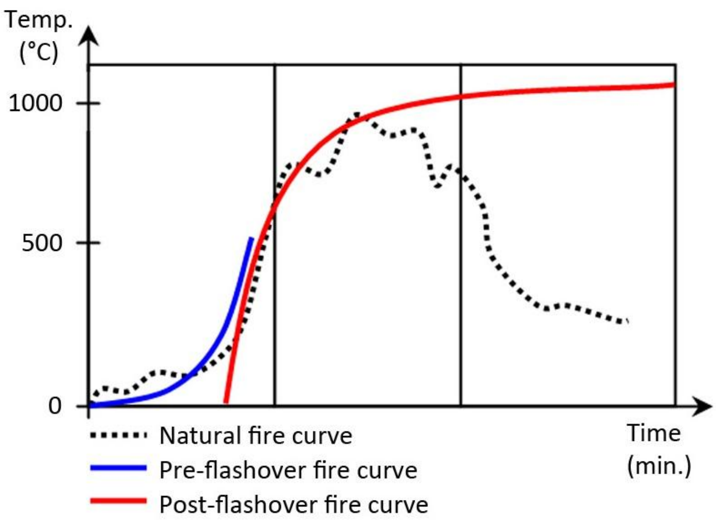

Figure 23 Natural fire compared to standardized fire curves (13)

The standard fire curve is used for the classification of construction products in the building industry. This standard ISO[8] fire curve, as defined in Eurocode EN 1363-1 and the international norm ISO 834-1 is widely used for building constructions and materials in many countries, including the Netherlands and other European Union countries. In other parts of the world, different curves are used for this purpose, but these curves are in essence all similar. In North America for example the ASTM[9] E119 or NFPA[10] 251 fire curves are very common (46).

[8] ISO: International Organization for Standardization
[9] ASTM: American Society for Testing and Materials
[10] NFPA: National Fire Protection Association

The ISO design fire is based on the most severe fire possible, and its shape is based on the following assumptions (47):

- No real fire can heat up faster;
- No real fire can last longer (burnout);
- No real fire can reach the maximum temperature of the fire curve.

A reduced fire curve is used for external fires (i.e. fire in the outside air or fire spread via outside air). The maximum temperature in this curve is lower, since hot gasses and smoke can be discharged more easily. This fire curve is for example used for façade elements which are exposed to an external fire (48).

The hydrocarbon pool fire curve is mainly used for petrochemical plants. The severity of these fires is higher, the heat development is faster and the maximum temperature is higher.

The Rijkswaterstaat (RWS) fire curve is used for tunnel fires. With a maximum temperature of 1350°C, this is the most severe fire curve. This fire curve is not used for modelling building fires, but only for tunnels.

The RWS fire curve, hydrocarbon fire curve, standard fire curve and the external fire curve are depicted in Figure 24.

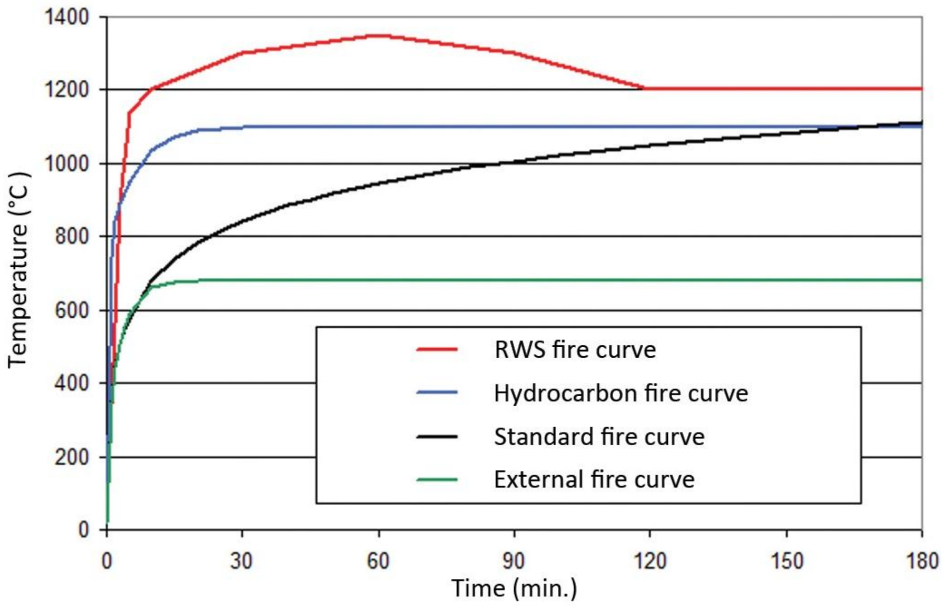

Figure 24 Some standardized fire curves from NEN-EN 1363-2 (13)

6.2.2 Parametric fire curve

In addition to these standardized continuous fire curves, the Eurocodes also provide the possibility of using a parametric curve for fire safety engineering purposes. Experience has shown that the temperature usually starts decreasing shortly after reaching its maximum value (which stands to reason). This is implemented into the parametric fire curve. The parametric fire curves represent a more realistic temperature development (49).

The natural fire curve consists of two phases, a heating phase and a cooling phase. The heating curve is comparable to the standard fire curve, and the cooling curve is a linear function. The maximum temperature is reached and the temperature starts decreasing at the intersection of these two functions, see Figure 25. The curve is parametric and its shape therefore depends on the compartment characteristics, like compartment dimensions, openings, the fire load inside the compartment and the compartment's envelope (50).

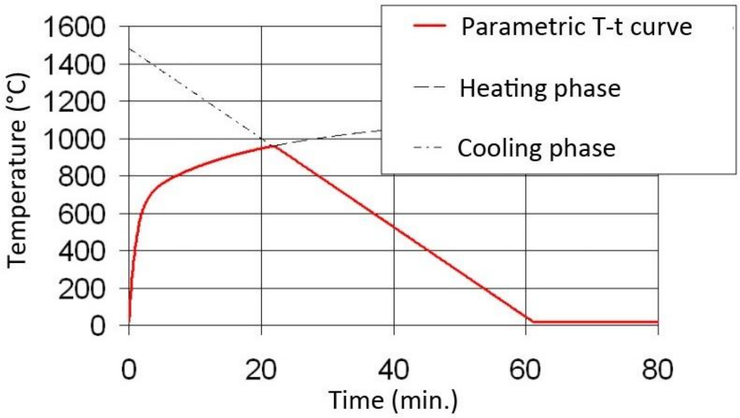

Figure 25 Example of natural fire concept according to EN 1991-1-2: annex A (50)

The parametric fire curve is primarily used for advanced fire safety engineering purposes and is therefore not often applied in the building industry yet and mainly used for uncommon and more complex projects. The standard fire curve is therefore mainly used for the classification of compartmentation systems and loadbearing structures.

6.2.3 Real compartment fires

The behaviour of real fires compared to the standard fire is much more complex. The actual fire development depends on many factors such as the fire load, the characteristics of the combustibles and the availability of oxygen and is different from compartment to compartment, see section 2.1.2. These fire load characteristics depend on the inventory of a building and the size of a compartment and vary in time (51). In some buildings it is very unlikely that a fully developed fire occurs which will reach the maximum temperature of the standard fire curve. In other building this might be different, and the fire might even be more severe than the standard fire. This implies that there is a difference in the fire performance of these buildings, even if the same fire safety demands are required for these buildings (e.g. a concrete plant with low fire load density vs. a sawmill with high fire load density).

In Figure 26 some test results of full scale compartment fires have been plotted. These fifty laboratory tests have been performed in different setups with varying fire load densities (from 200 to 900 MJ/m^2), different compartment sizes, different thermal insulation of the envelope and with different types of combustibles. It clearly shows that there is a large variability in actual natural compartment fires. The intensity of many of these fires exceeds the ISO standard fire curve (52).

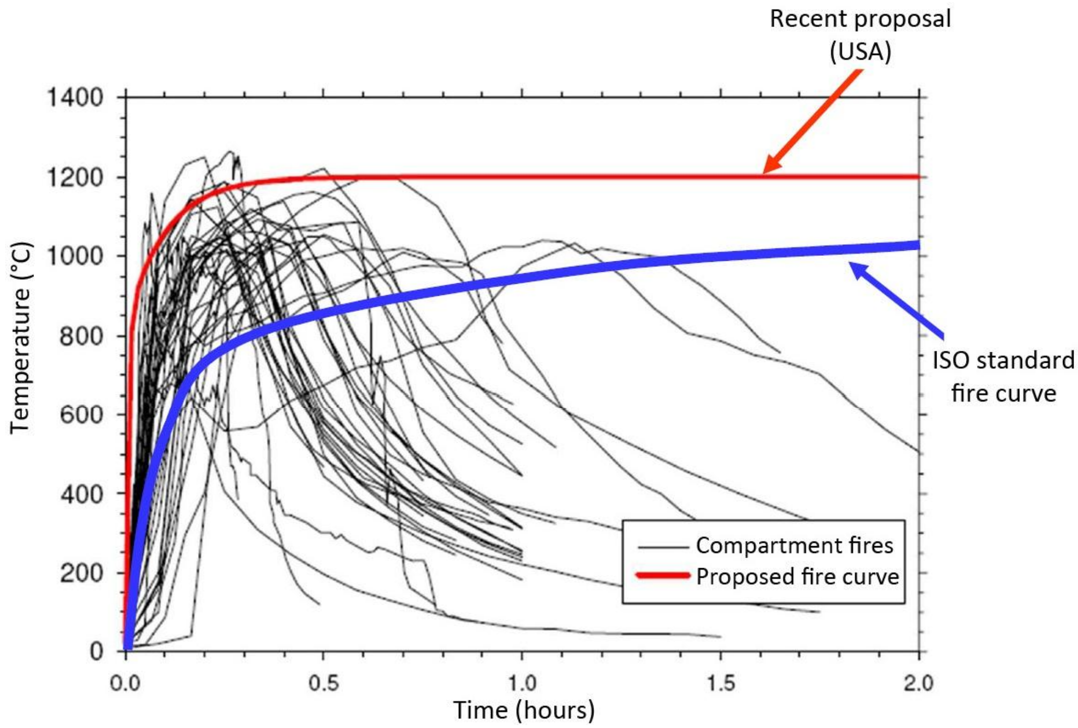

Figure 26 Comparison between real compartment fires and the standard fire curve (53)

6.3 Actual performance of buildings in fire conditions

The above mentioned aspects imply that there is a difference between the actual fire performance of structures in real fires and standardized test or calculation methods. Some international research has been carried out on the actual fire resistance of structural materials in realistic fire conditions within actual buildings. Some fire-induced building collapses have been investigated by the US National Institute for Standards and Technology (NIST). In the UK, the British Research Establishment carried out a research to the behaviour of compartment systems in actual building fires. The Dutch Institute Nibra carried out a research on the performance of compartmentation as part of a research on high damage fires in 2001.

6.3.1 NIST historical survey of multi-storey fire-induced building collapses

In the wake of the 9/11 tragedy, the NIST carried out a research on the adequacy of structural fire protection measures in multi-storey buildings[11]. Even though the collapses of the WTC towers are not representative for a normal accidental fire impact on buildings, it was decided to collect existing information about fire-induced building collapses in the period 1970 – 2002 (55).

The research involved multi-storey buildings, since these buildings are of special interest due to the potential for loss of life and economic costs (i.e. the evacuation aspects of these buildings and the accessibility of the fire by emergency services are more critical compared to low rise buildings). Both total and partial collapses were included. Since a database is lacking that systematically identifies and reports building collapses due to fire, the survey was exploratory. Building collapses due to fire appear only to be well-documented and

[11] A multi-story building is in this research defined as a building with four floors or more

reported if the event was noteworthy for other reasons, e.g. loss of life or significant property losses. Unfortunately, the adequacy and code-compliance of the original fire resistant design was not within the scope of this research (55).

The survey included 22 building fires with varying building construction materials (steel, concrete, masonry, timber), different building heights and different occupancies, among which nine office buildings, eight residential buildings, three commercial building and two combined residential/commercial buildings. Also the four WTC towers which collapsed after the 9/11 event were included in this research. These data show that all types of construction and occupancies are susceptible for fire-induced collapse. The fire risk appeared to be slightly higher during construction and renovation works (46).

The researchers address that structural building elements are currently mainly designed and tested based on a limited temperature in the cross-section. Elements are assessed for their fire resistance by verifying that the element does not exceed a predefined critical temperature. Usually single elements are considered, without verifying its connections to other elements nor the fire protection of these connections. In practice it is assumed that in case all single elements perform well, also the system as a whole performs well during fire. However, especially the connections appear to be critical in many fire induced collapses. In some steel frame buildings, the steel members did not show significant deformations, which implies that these members have not been exposed to excessive temperatures, but still (brittle) failure occurred in the connections. Failure of connections (bolts) during the cooling stage seems to be of importance here (53).

Temperature induced stresses and expansion are also influencing the load carrying capacity of surrounding members. It is not possible or feasible yet to investigate these phenomena in existing testing facilities or in newly developed fire testing methods according to real-fire conditions. Therefore it is emphasized that it is important to work on a database with systematic information on fire-induced collapses. This will lead to a better understanding of the scope and nature of the structural fire protection problem. These data will provide the basis for future analytical models for the design of structural fire protection systems (55).

Failure of the structural fire protection without the occurrence of collapse after a complete burnout was documented in some cases. Huge permanent sagging or distortion of steel members and excessive spalling of concrete elements did often not lead to immediate collapse of buildings due to unexpected alternative loadbearing paths. Sometimes the structure could be repaired, in other cases it was decided to dismantle the building from an economical point of view (55). Reporting these cases will also greatly help to improve the predictability for the performance of building elements when exposed to fire and to develop more sophisticated calculation software for assessing fire resistant components and systems (46).

6.3.2 BRE research to the integrity of compartmentation in buildings

The British Building Research Establishment (BRE) led a research to the integrity of compartmentation in buildings during a fire. The research was carried out in cooperation with experts from the engineering firm Buro Happold and the University of Ulster. The aim of the research was to provide an improved guidance to ensure the integrity of walls and floors in compartmentation systems. The need for this research had arisen because of the concern that modern methods for design and construction of compartment walls could lead to premature loss of integrity of fire resistant systems and that the assumed fire protection will not be reached (56).

In this research also the differences between testing situations and fires in actual buildings are emphasized. The fire resistance of loadbearing and non-loadbearing components that form compartment walls and floors is typically assessed in terms of insulation using the standard test procedures. In practice the failure mode often turns out to be different from that experienced in tests. Thermal expansion of walls in combination with thermal sagging of floors can cause instability of the wall which may lead to premature failure. This thermal expansion is often not directly considered when the performance of a fire resistant system is determined. There are deformation limits in fire conditions to avoid damage to adjacent elements and the test furnace (test criterion R), but there are indications that this failure criterion is not stringent enough to achieve its intended purpose. Compartmentation systems are often not designed to accommodate or resist these deformations. When these systems are used is real buildings, this can be the cause of premature failure.

To investigate these effects, a review has been made of the current situation (regulations and results from standard tests) in relation to maintaining the integrity of compartmentation during fire. The available large-scale test data have been analysed and information has been gathered for the relevant parameters for determining the fire resistance of compartments in real building fires. These parameters include frame layout, compartment geometry, imposed loads and design fire scenarios. Connections were not included in this research, nevertheless their importance is stressed.

Especially ductile loadbearing structures (e.g. steel structures, see Figure 27) can show large fire-induced deformations up to 1/20 of the span before the ultimate loadbearing capacity of the element is reached (tensile membrane action). Fire resistant partitions are often built on the main gridlines of the structure, but there is no requirement for this. Due to commercial and architectural demands for flexibility, partition walls can therefore be placed at any location within the span. When the large deformations of walls and floors occur, it can easily cause instability of (non-loadbearing) compartmentation systems.

Figure 27 Fire-induced permanent sagging of a composite steel structure (Cardington fire test) (54)

The allowable deflections of the fire resistant elements and its supporting elements need to be considered in order to solve this issue. For example, the deformations of the fire resistant construction on the fire floor itself must be considered in relation to the deformation of the floor above and the floor below. This issue is partly dependent on the construction type, which on itself is often dependent on its function. For example in dwellings, often an advantageous arrangement is applied where floors span from loadbearing compartment wall to loadbearing compartment wall. Therefore, the imposed deformations are very small. However there is no guarantee that the compartment walls will be built on the main structural grid lines, since there are no regulations about where non-loadbearing compartmentation walls should be placed in relation to the supporting elements. The magnitude of fire-induced deformations is also dependent on the construction material, e.g. steel structures generally show much larger deflections than concrete structures. It should be useful to make a review of a likely range of deflections to be accommodated in fire conditions for different forms of construction (56).

Non-loadbearing compartment systems are usually applied with a small gaps along the edges to accommodate dimensional deviations and to allow movements due to normal live load actions. These expansion gaps typically have width of around 10 mm, and are filled with an elastic fire resistant joint filler. These tolerances are often too small to accommodate fire induced deformations. Therefore stresses will inevitably occur in fire conditions. The current methods to ensure the integrity of compartment walls during fire do therefore not create adequate allowance for deformations of the structure during a fire (56).

Figure 28 Instability failure of a compartment wall due to the deflection of the floor (56)

The behaviour of compartment walls with expansion gaps is highly complicated and depends on many different parameters. These factors include thermal expansion, thermal gradients, Young's modulus, strength, insulation and the relative dimensions of the walls and the gaps. In addition, most of these factors are dependent on the temperature. Besides sufficient gap size, the integrity of fire resistance can be further improved by limiting the deformations of surrounding loadbearing walls and floors.

Besides instability failure of compartment walls, also cracking in concrete floor or wall elements cause by thermal expansion or sagging can cause the loss of integrity, without causing collapse of the structure.

When integrity is maintained, the insulation of walls and floors is an important factor. This is one of the criteria during the test (i.e. average temperature rise ≤140°K and maximum local temperature rise ≤180°K on the unexposed side). Research has shown that the ignition of timber products by a flame can occur between 270°C and 290°C. If there is no integrity failure, so when there are no flames penetrating the compartmentation, spontaneous ignition of timber products occurs between 330°C and 500°C, dependent on the species. This suggests that the failure criteria for insulation are conservative, especially in buildings where storage of combustible materials on the unexposed side is unlikely (56).

6.3.3 Nibra research 'Miljoenenbranden in Nederland'

The Dutch Institute for Fire Brigade and Disaster Prevention (nl. Nederlands Instituut voor Brandweer en Rampenbestrijding, NIBRA) carried out an extensive research to 122 building fires with a damage of more than one million euros in the year 2001 in the Netherlands. This research aimed at the fire prevention measures involved in these fires, and the role of fire brigade, insures and building owners. Also compartmentation was part of this research (57).

Table 13 Performance of compartmentation in large fires in 2001

Construction year	Fires kept inside fire compartment	Fires that are no danger to adjacent premises
Before 1992	56%	88%
After 1992	83%	92%

The performance of compartmentation is shown in Table 13. Especially in buildings constructed after the introduction of the 1992 Building Decree, the number of fires which are kept inside the compartment improved significantly, which implies that fires became better controllable after the introduction of the Building Decree 1992. This does not mean that the risk of fire occurrence has decreased after 1992, see Figure 29. The risk of fire spread to adjacent buildings did not reduce significantly.

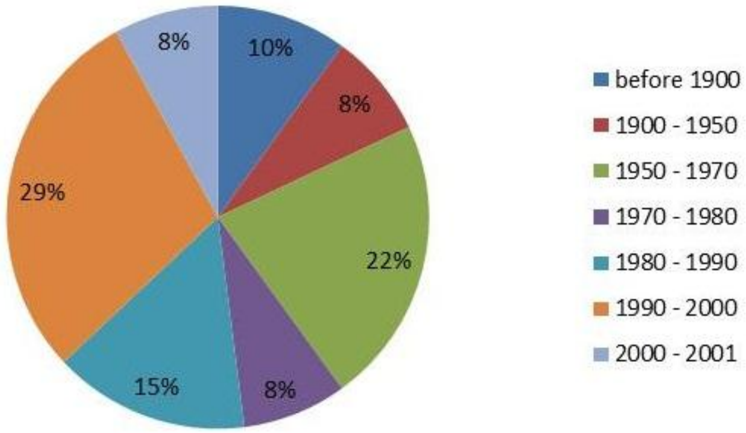

Figure 29 Construction period of the affected buildings

In about 35% of the buildings with fire compartmentation, the compartmentation did not function properly. In some cases the fire resistance was insufficient due to incorrect construction or wrong use. Fire doors were often not closed. In buildings with fire resistant self-closing doors, in 50% of the cases the doors did not close properly, see Table 14 (57). This means that in about 28% of the building where fire compartmentation was present, the self-closing doors did not function.

Table 14 Fire prevention facilities (57)

Facility	Present	Number of cases where facility played a part	Number of cases where the facility did not function
Fire compartmentation	43	32	15
Smoke compartmentation	18	9	7
Self-closing doors	25	15	12

The Nibra study shows that the performance of compartmentation is insufficient in many cases. According to this study, the failure of fire compartments is for a large part caused by non-technical issues. Knowledge about the importance of proper compartmentation among the key stakeholders (owners, users, insurers and fire brigade) is lacking. The performance level of compartmentation can be improved significantly by informing stakeholders about the importance of it. For example self-closing doors which were blocked or which were completely removed could have been prevented by creating awareness for its importance.

The users and owners are currently the main responsible parties for maintenance and the contractor during the construction of a building.

Regarding the results of the research, which showed that the failure of compartments is often caused by errors made during the exploitation of a building, it would be most effective to focus inspection and information on this phase. However, research on other failure modes of compartmentation is lacking, so it is not clear what issues are important for the performance of compartments. Also it is not reported how long it took before the compartmentation failed or what the fire duration was, since it is not certain how long the fire was burning before the fire brigade arrived (57).

6.3.4 Data on the performance of fire compartmentation from Czech Republic

The fire brigade in Prague in the Czech Republic is working on a database about the performance of fire compartmentation. In fire investigations it is often found that fire spread is caused by shortcomings related to doors, fire dampers and penetration for ducting and piping. Also the engineering construction was often indicated to be the cause of fire spread between compartments, see Table 15. The investigated fires only include fires in which compartmentation was not sufficient to prevent fire spread to other compartments.

Table 15 Causes of fire spread between compartments found in fire investigations in Czech Republic (78)

	Number of cases in 2011 (n = 74)
Inapproritate doors or firestops/fire stops were not installed	26
Fire compartment with not sealed penetrations (except electricity distribution)	12
Engineering construction as a fire crossover between fire compartments	19
Frame or fire separation frame with low fire endurance	16
Other shortcomings	1

Fire spread between compartments in Czech is in many cases ascribed to the lack of knowledge among users how to act in case of fire, for example because doors and windows which were not closed to let smoke away, but people do not know that this is opposite to the correct procedure. Moreover, many buildings in Czech are not used according to its intended purpose due to economic progress in the last decades and it is often very difficult to determine what the state of fire compartmentation was just before the fire started (78).

6.4 Reliability of fire resistant systems

Fire resistant systems with a loadbearing or a separating function are designed to fulfil a certain purpose. To accomplish this, fire doors should be closed, fire protection should function and no gaps or openings should be present. As set out above, the performance of fire protection systems shows much scatter in practice. The fire conditions can be different from the expected conditions, as well as the construction standard and condition of fire resistant systems. Also other unforeseen failure modes can occur.

For a proper design, the reliability of fire protection measures should be considered. For example, in a 60 minutes rated fire resistant wall with fire resistant ducting and piping, the efforts are negated when the self-closing doors in the wall do not function in case of fire. For safety reasons and functional efficiency, the reliability of different components should therefore be maximized. In performance based fire safety engineering, reliability is also an important input for safety analysis (58).

The reliability is basically the probability that a system will operate as designed. The reliability of a certain system can be improved by regular maintenance and testing. It is important that the reliability of a system is considered conditionally, i.e. the system should work given that there is a fire situation.

There are two different reliability aspects for fire safety systems: operational and performance reliability. Operational reliability refers to the probability that a fire protection system will operate as intended. It is a measure of the system operability. The performance reliability is a measure of the adequacy of a fire protection system to successful perform its intended functions under specific fire conditions (58).

Considering the available information about the reliability of fire protection measures, there is a big difference in data collected about active and passive fire protection measures. Relatively much research has been carried out on active measures, like sprinklers and detection systems. Compartmentation is considered as a key fire protection strategy, however very little data are available about the reliability of compartmentation systems. Compartmentation relies on the functioning of many different elements, like doors, walls, floors and ceilings, penetration seals, glazing, construction elements and fire and smoke dampers and therefore depends on the reliability of many subsystems. Some typical values for the unavailability of fire protection measures are shown in Table 16 (7) (58).

Table 16 Probability of fire protection systems to fail operating as designed (7)

Passive systems	**Failure probability Unavailability**
Compartment or floor	0.05
Fire door	0.30
Self-closing door to protected stairway	0.10

The probability of failure/unavailability of fire doors is in this 30%, which is similar to value found for self-closing fire doors in the Nibra research (28%).

6.5 Conclusions

The performance of fire resistant systems is in practice different to the expected performance according to the standard assessment conditions. Several reasons can be addressed for these differences.

The performance of structures and compartments is determined based on standardized fire conditions. The fire conditions in reality are dependent on many different factors, such as the amount and type of combustibles, the ventilation (i.e. available oxygen and heat discharge) and the dimensions of the compartment. The fire conditions will therefore in practice never be similar to the standard fire conditions. Fire conditions influence the performance of compartmentation systems, the performance for example depends on the speed of the fire development, the maximum temperature and the fire duration. For common buildings, the actual fire conditions in a real building fire are not considered when the fire safety system is designed.

The differences in fire conditions in different buildings will cause differences in the performance of compartmentation systems, but it is uncertain how the performance is exactly affected. Since the fire conditions in actual compartment fires are dependent on many factors and is highly uncertain in most cases, the performance of compartmentation systems is uncertain as well.

In case the fire conditions are similar to the standard fire conditions, for example when test pieces are tested in front of a furnace, there is already scatter in performance of the test pieces. Most compartmentation systems are characterized by many different possible failure modes and these failure modes are often hard to foresee, therefore the performance is difficult to predict, even in standard fire conditions. Furthermore, very little research has been carried out on the performance of passive fire protection in actual building fires in general, also not on the performance of compartmentation systems in particular. A lot of knowledge can be gathered by investigating actual fires in order to improve the design of compartmentation. Improvements are possible in both the fire conditions used for design and classification purposes, as well as the failure criteria as they are used nowadays.

Other aspects which are known to have influence on the performance of compartmentation systems are size effects, supporting conditions and interactions between elements. The performance of compartmentation systems is usually determined by testing relatively small pieces (< 4 * 4 m^2), whereas often much larger pieces are applied in practice. The supporting conditions and interaction with other elements, for example interaction between a compartmentation wall and the loadbearing structure is often overlooked, while these aspects can influence the performance of compartmentation, for instance by imposing mechanical actions on the compartmentation systems during fire induced by deformations where it is not designed for. It can also have an positive effect, for example in case of membrane action. The fire performance of a building as a whole is complex and there are still too many uncertainties to perform a more reliable assessment on passive fire protection systems.

Other aspects which appear to have a strong influence on the performance of compartmentation systems, are shortcomings in design and construction and wrong use, i.e. the compartmentation system is not built in compliance with assembly instructions, not designed and built according to applicable legislation etc. Also adjustments by the users to the building during the life time of the building will reduce the fire performance of compartmentation system, as well as normal deterioration of a building during its life time.

The Dutch Institute for Fire Brigade and Disaster Prevention (nl. Nederlands Instituut voor Brandweer en Rampenbestrijding, Nibra) and the Dutch National Centre for Prevention (nl. Nationaal Centrum voor Preventie, NCP) carried out some research on high damage fires (damage > 1 million euros) in 2001 in which the performance of compartmentation system was briefly addressed. Failure of compartmentation was in these researches considered as an event in which the fire was not kept inside the compartment where the fire originated. In the Nibra research it was found that compartmentation failed in 35% of the high damage fires, and in the NCP researchers found that in fires where compartmentation was relevant, the compartmentation failed in approximately 50% of the buildings. Self-closing fire doors did not function in 50% of the buildings where compartmentation failed.

The large uncertainties in the structural performance can be reduced by analysing real fires. Especially passive fire protection measures are characterized by high uncertainties regarding their performance. A lot of knowledge can be gathered here by collection systematic information about the performance of compartmentation in real building fires. Currently there is no (extensive) database available about the performance of building constructions in real fires, only fires which are noteworthy for other reasons (e.g. fatalities or significant property losses) are investigated and reported. These data could help to develop analytical models for the design of fire protection systems and it could help to improve insight and predictability of the fire performance. Currently it is still uncertain what the exact relation is between a certain fire resistance rating and the performance in practice.

In summary, the following reasons can be appointed why the actual performance of compartmentation systems is uncertain:

- Differences between fire conditions in classification methods and real fires;
- Scatter in test results;
- Lack of knowledge on reliability of fire resistant systems;
- Test criteria are not necessarily related to fire spread in reality (arbitrariness);
- Construction quality / compliance with assembly instructions;
- Size effects;
- Influence of supporting conditions;
- Interaction between elements;
- Modification of the structure by users during the life time of a building;
- Decrease in system quality during the life time of a building;
- Systems do not operate during fire (for example self-closing doors do not close).

Since the purpose of compartmentation is to limit the extension area of a fire, failure of the compartmentation systems will lead to fire propagation to other compartments. Achieving the primary objective of compartmentation therefore depends on a proper fire separation between compartments. Premature failure of compartmentation systems can endanger the safety of people and lead to large fire extension areas with high damages. To get an idea of how passive fire protection measures contribute to the safety of people and property, more knowledge about the performance of these passive compartmentation systems is essential. Several researches, among which the Nibra research and the NCP research on high-damage fires, appoint that compartmentation is in many cases not sufficient to prevent fire spread to other compartments. Frequently mentioned reasons are wrong assembly, modifications in the building during its life time and passive fire protection systems which do not operate during fire. This is also plausible, since failure of compartmentation is generally caused by its weakest spots. These shortcomings in compartmentation systems are further investigated.

7 Shortcomings in the implementation of compartmentation systems

The envisaged maximum extension area of fire is confined by the area of the fire compartment. The fire will only be kept inside a fire compartment if fire spread to adjacent compartments is prevented. The fire resistance of compartmentation systems is therefore important to prevent fire damage in adjacent compartments and to keep the fire controllable[12].

In the Dutch Building Decree, many requirements are set for the fire resistance of compartmentation systems. The failure of compartmentation systems (i.e. the fire is not kept inside the compartment where the fire started and fire spread occurs in the adjacent compartment) can be caused by different failure modes, mentioned in chapter 5. One of the reasons why compartmentation systems may fail, is because these systems have not been built according to the standards and codes or are not properly maintained and operated.

On behalf of the Dutch Government Building Agency (nl. Rijksgebouwendienst, RGD), the fire safety systems of many government-owned buildings have been inspected. The fire safety system (compartmentation, fire detection, escape routes etc.) of the buildings are checked on compliance with the legislation as prescribed in the Dutch Building Decree. If the building does not comply with the requirements at certain points, these points are indicated as shortcomings. The RGD inspection reports are used in this research to get an idea to what extent buildings comply with the fire safety regulations, what kind of shortcomings are often found in these buildings and how often these shortcomings are found. Later it is investigated how the presence of shortcomings affects the performance of compartmentation systems.

7.1 The RGD fire scans

The Dutch Government Building Agency (RGD) is responsible for the management and development of buildings owned by the national government. These buildings are used for the accommodation of government services, such as Ministries, courthouses and prisons. Also royal palaces, government-owned museums, archives and depots are for example managed by the RGD.

The RGD decided to inspect all government-owned buildings in order to determine to which extent these buildings comply with the current fire safety regulations. The inspections are performed by different independent fire safety consulting firms. In order to have comparable output of the inspections, an inspection method developed by Efectis Nederland B.V. (formerly known as TNO Centre for Fire Research (Netherlands Organisation for Applied Scientific Research)) is used and the inspections are reported according to a similar way under supervision of the RGD. The inspection reports have a common lay-out, consisting of: general introduction, general information about the building and inspection, assumptions, conclusions and recommendations. An elaboration on the inspection results according to the scan tool is given in the appendices, as well as a series of photos, a work description and cost estimation.

[12] Preventing the fire development and spread outside the fire compartment from getting out of hand.

Many aspects related to fire safety are checked during an inspection, from structural safety during fire and compartmentation to emergency lighting, escape routes, smoke production of materials and accessibility of the building by the fire brigade. The results of the inspections are used by the RGD to determine the maintenance work to be carried out and how urgent repair works in a particular building are. The outcome of the inspections on fire compartmentation is of primary importance for this research.

The information from the inspection reports of 27 buildings has been used for this research. This information is confidential for security reasons and therefore only the results of the analysis will be mentioned in this report, without naming the buildings. For the same reason, only office buildings, meeting buildings and industrial buildings are used. One of the main advantages of the RGD fire scans is that all buildings have been inspected according to a similar methodology. Therefore the RGD has a large collection of similar inspection reports from many different buildings. Still it should be kept in mind that the inspection have been performed by different inspectors, having different competences and expertise.

Inspection reports of six meeting buildings (museums, entrance buildings, heritage), ten industrial buildings and eleven office buildings of various ages and sizes have been analysed for this research, see Table 17. The industrial buildings mainly consist of buildings with a light industrial function, like laboratories, industrial heritage and storage buildings, such as archives and depots.

Table 17 List of buildings used for the analysis

	Occupancy class	Year of construction	Latest renovation	Gross floor area [m^2]	Construction material
1	Meeting	1862	1997	11.160	Masonry
2	Meeting	1929	2001	8.743	Masonry/timber
3	Meeting	1998	2009	3.835	Timber
4	Meeting	2000	n.a.	3.227	Timber
5	Meeting	1625	1990	8.261	Masonry/timber
6	Meeting	1700	n.a.	2.117	Masonry/timber
7	Industrial	1998	n.a.	3.854	Steel
8	Industrial	1996	2002	16.408	Steel
9	Industrial	unknown	2007	3.309	Steel/concrete
10	Industrial	1979	n.a.	2.583	Steel
11	Industrial	1943	2001	12.658	Concrete
12	Industrial	2000	n.a.	4.065	Concrete
13	Industrial	1999	n.a.	2.935	Concrete
14	Industrial	1979	2010	36.567	Concrete
15	Industrial	2004	n.a.	31.352	Concrete
16	Industrial	1986	n.a.	30.894	Concrete
17	Office	1981	2004	21.505	Concrete
18	Office	1987	n.a.	3.003	Concrete
19	Office	1978	1996	48.522	Concrete
20	Office	1664	1990	7.268	Masonry/timber
21	Office	1965	1997	11.530	Concrete
22	Office	1900	1998	7.654	Masonry/timber
23	Office	1995	n.a.	38.525	Steel/concrete
24	Office	1992	n.a.	94.050	Concrete
25	Office	1986	n.a.	1.550	Concrete
26	Office	1991	n.a.	3.561	Concrete
27	Office	1962	1983	4.572	Concrete

It should be noticed that most buildings have multiple functions, for example an industrial building or office building usually also contains one or more compartments with a meeting function (e.g. canteen, conference room). The buildings are therefore categorized based on their main use function as stated in the inspection reports.

The buildings have been inspected with respect to two performance levels: the required performance level for new buildings and the lowest required performance level for existing buildings, see section 3.6 and section 3.7 for the required performance level of compartmentation systems. When applicable (mainly for the fire resistance of walls and doors), the performance level for new buildings is used as the governing criterion for this research. The reason for this is that the required fire resistance for compartmentation systems in new buildings is higher than for existing buildings (60 vs. 20 minutes). When a building is inspected on compliance with the performance criteria for new buildings, the fire walls with less fire resistance are indicated as shortcomings. Using the performance level for new building as governing criterion, will therefore give a more comprehensive view on the quality of the compartmentation in the buildings.

Some inspection reports are very detailed, others are very basic. In some reports it is precisely reported which elements show shortcomings and why it is indicated as a shortcoming. In other reports it is just stated that for example doors are not certified, but is not mentioned why these doors will or will not fulfil its anticipated function. Not the entire building was checked in many inspections, but only a selected number of parts were checked, which means that only a few elements of the fire safety system are inspected, e.g. only a few ducts in the building are inspected and not all of them. Also there seems to be a relation between the inspections efforts and the number of shortcomings: the more precise and thorough the inspection, the more shortcomings have been found.

There is one building which is not divided into fire compartments, and therefore this building has one big fire compartment of 94.050 m^2. Besides exceeding the maximum compartment size, no other shortcomings regarding fire compartmentation are reported in this building, since the building does not have any fire compartments.

The inspection reports have been analysed and all observed shortcomings regarding fire compartmentation are analysed. Every element or component of a fire compartment which does not comply with the legislation is classified as a shortcoming.

7.2 Main assumptions and limitations

For the analysis of the shortcomings found in the RGD inspections reports and the determination of their consequences on the performance of compartmentation systems, quite some assumptions had to be made. The assessment therefore has quite some limitations. The main limitations of the analysis based on the RGD inspection reports are:

- The number of analysed inspection reports is limited;
- Results are strongly dependent on the quality and expertise of the inspectors;
- Many buildings are not extensively inspected, but a selection of elements are checked on a limited number of locations in the building, therefore some shortcomings will have been overlooked and the total number of shortcomings is not quantified;
- Only a rough quantification of the presence of shortcomings in compartments is possible based on the work description (which is not annexed to all the inspection reports) and in some cases the figures need to be approximated. In some inspections reports the work descriptions are quite rigorous, the shortcomings can often be solved in a less rigorous way than indicated in the work descriptions and therefore the shortcomings are often less severe than the work description suggests;
- The level of detail of the inspections is different: the least detailed reports are normative for the level of detail and accuracy of this analysis;
- 28 different groups of shortcomings are distinguished. As a consequence, similar shortcomings with different properties are assigned to the same group. Therefore not all shortcomings within one group have a different impact on the fire performance of the compartmentation system. Most RGD scans are too limited to make a more sophisticated division in shortcomings;
- The performance of many elements cannot be determined based on visual inspection and is therefore uncertain;
- The influence of deviations in fire performance of elements which do comply with regulations is not incorporated in the assessment. These elements can also fail

within the required resistance time, for example due to scatter in test results, different fire conditions, imperfections or other unforeseen factors. For example fire dampers may not operate as well;

- The failure criteria used for classification, do in many cases not relate to the failure behaviour in practice, e.g. elements which are lacking the required certification, may perform well against fire spread during fire or the other way around;
- The probability of fire spread due to a specific shortcoming depends on many factors and is estimated based on expert judgement, since any statistics on this topic do not exist and knowledge on this topic is limited, or at least not well documented;
- Buildings in the RGD inspection reports usually contain more than one use functions. Distinction between different building functions is therefore based on the main use function of the building;
- It is assumed that the presence of different shortcomings in compartments is independent, in practice there probably is a relation (e.g. in poorly maintained buildings);
- The representativeness of the RGD buildings for the entire building stock is limited, for example the ‘industrial buildings’ of the RGD mainly include archives, depots, heritage etc., and no production and or manufacturing facilities;
- Only fire spread within the building is considered, not fire spread to other premises outside the parcel where the fire originated;
- The elements are inspected on component level (per shortcoming), while in reality a combination of shortcomings is often causing critical situations. The probability of ignition and fire propagation due to sparks or small flames in the adjacent compartment increases for example when high radiation levels occur on the non-exposed side;
- The fire development and fire duration in the fire compartment are not taken into account in the analysis, as well as other factors which do influence the failure of compartmentation, such as fire brigade intervention.

Efforts were done by the RGD to get the buildings inspected according to a similar methodology and the inspections are reported in a similar way. Despite of all the above mentioned assumptions and limitations, the RGD scans are currently the only known collection of reports from which the presence of shortcoming can be derived. Therefore the RGD scans are the only possibility for a quantification of the presence of shortcomings. The results of this analysis conclusively show that shortcomings appear to have a significant stake in the failure of compartmentation systems.

7.3 Frequency of shortcomings in fire compartmentation

All shortcomings regarding fire compartmentation are collected and categorized into eight main categories. Not all of the inspection reports are sufficiently detailed to quantify the frequency of occurrence of particular shortcomings within a building, for example because these buildings are checked on some selected locations. An exploratory survey is therefore carried out on the inspection reports, in order to get an idea if particular shortcomings are present in the building, no matter what their frequency is.

The shortcomings regarding fire compartmentation are divided into eight main categories:

- Compartment size: fire compartments in the building are larger than allowed according to the Building Decree 2012 without a proven equivalent solution;
- Façade: the fire resistance of the façade is insufficient to prevent fire spread to other compartments via the façade. Only compartments in the same building are considered in this survey;
- Ducting and piping: penetrations for ducts, pipes or cables are not properly sealed, no fire dampers are installed inside the ducts etc.
- Walls and floors: the resistance of walls and floors against fire spread is insufficient.
- Glazing: the fire resistance of glazing is insufficient or large areas wired glass have been applied. Wired glass is assigned to a separate subgroup, because wired glass retains its integrity longer due to the reinforcement with the wire mesh;
- Doors: doors do not close properly or are not self-closing, are not certified or the frames and fixings do not have sufficient fire resistance.
- Elevators: the doors of elevators do not close properly or have insufficient fire resistance;
- Loadbearing structure: the fire resistance of the loadbearing structure is insufficient or uncertain.

The results are shown in Table 18. These figures are based on 26 inspection reports. The building with a fire compartment of 94.050m^2 is excluded from the results, since it does not show any shortcomings in fire compartmentation systems. A more detailed description of the shortcomings is given in Appendix I.

Table 18 Observed shortcomings in the inspected buildings (n=26)

Type defect		Building in which these shortcomings are present				
		Meeting (n=6)	Industrial (n=10)	Office (n=10)	Over all (n=26)	Year of construction
1. Problems with compartment size		**67%**	**70%**	**40%**	**58%**	1625, 1862, 1962, 1965, 1979, 1979, 1965, 1978, 1986, 1986, 1996, 1998, 1998, 2000, 2004
1.1	Compartiments larger than allowed in BD2012 without demonstrated equivalent solution	67%	70%	20%	50%	1625, 1862, 1965, 1979, 1979, 1965, 1978, 1986, 1996, 1998, 1998, 2000, 2004,
1.2	Technical rooms >50m^2 not in separate fire compartments	0%	20%	20%	15%	1962, 1986, 1986, 2004
2. Problems with façade						
2.1	Fire resistance façade insufficient	17%	20%	20%	19%	1664, 1979, 1986, 1986, 1998
3. Problems with penetration for ducting and piping		**83%**	**80%**	**100%**	**88%**	1625, 1664, 1700, 1862, 1900, 1929, 1943, 1962, 1965, 1979, 1965, 1978, 1981, 1986, 1986, 1987, 1991, 1995, 1998, 1998, 1999, 2000, 2004
3.1	Penetrations not sealed	83%	80%	100%	88%	1625, 1664, 1700, 1862, 1900, 1929, 1943, 1962, 1965, 1979, 1965, 1978, 1981, 1986, 1986, 1987, 1991, 1995, 1998, 1998, 1999, 2000, 2004
3.2	No fire dampers in ducts	50%	70%	80%	69%	1625, 1664, 1862, 1929, 1943, 1965, 1979, 1965, 1978, 1981, 1986, 1986, 1987, 1991, 1995, 1998, 1999, 2000, 2004
3.3	No fire resistant casing around ducts	0%	10%	20%	12%	1986, 1991
3.4	Mounting of pipes and ducts not sufficient	0%	20%	0%	8%	1999, 2000
4. Problems with fire walls / floors		**33%**	**70%**	**80%**	**65%**	1862, 1900, 1929, 1965, 1979, 1979, 1965, 1978, 1981, 1986, 1986, 1987, 1991, 1995, 1998, 2000, 2004
4.1	Fire resistance wall insufficient or uncertain	0%	30%	60%	35%	1900, 1965, 1979, 1965, 1978, 1981, 1986, 1991, 1995, 2004
4.2	Panel or glass is missing (holes)	17%	30%	30%	27%	1929, 1978, 1981, 1986, 1998, 2000, 2004
4.3	Fire resistant separation is not continued above suspended ceiling	17%	20%	20%	19%	1862, 1979, 1986, 1986, 1987
4.4	Steel structure penetrating fire separation without fire resistant covering	0%	40%	0%	15%	1979, 1998, 2000
4.5	Fire separation in roof structure is not properly finished	0%	20%	0%	8%	1979, 1979
4.6	Steel hatch in wall	0%	10%	0%	4%	2004
4.7	Floorstructure not sufficient fire resistant	0%	10%	0%	4%	2000
5. Problems with glazing		**33%**	**40%**	**90%**	**58%**	1625, 1664, 1862, 1962, 1965, 1979, 1965, 1978, 1981, 1986, 1986, 1987, 1991, 1995, 2000, 2004
5.1	Large areas wired glass in fire separations	33%	30%	80%	50%	1625, 1862, 1962, 1965, 1979, 1965, 1978, 1981, 1986, 1987, 1991, 1995, 2000, 2004
5.2	Fire resistance glazing insufficient (wired glass excluded)	0%	10%	30%	15%	1664, 1981, 1986, 1986
5.3	Glazing beads missing	0%	10%	0%	4%	2004
6. Problems with doors		**100%**	**80%**	**100%**	**92%**	1625, 1664, 1700, 1862, 1900, 1929, 1943, 1962, 1965, 1979, 1965, 1978, 1981, 1986, 1986, 1987, 1991, 1995, 1998, 1998, 1999, 2000, 2000, 2004
6.1	Doors not self-closing	100%	60%	70%	73%	1625, 1664, 1700, 1862, 1900, 1929, 1943, 1979, 1978, 1986, 1986, 1987, 1991, 1995, 1998, 1999, 2000, 2000, 2004
6.2	Fire resistance doors uncertain and not certified	33%	70%	40%	50%	1929, 1962, 1979, 1986, 1986, 1991, 1995, 1998, 1999, 2000, 2000, 2004
6.3	Intumescent strip missing	17%	50%	50%	42%	1625, 1664, 1965, 1979, 1965, 1981, 1986, 1991, 1995, 1999, 2000, 2004
6.4	Doors do not close properly	17%	50%	40%	38%	1664, 1862, 1943, 1965, 1979, 1965, 1986, 1991, 1995, 1999, 2000
6.5	Fire resistance glazed partition uncertain and not certified	17%	10%	60%	31%	1664, 1929, 1978, 1981, 1986, 1987, 1995, 2004
6.6	Steel door frame with insufficient fire resistance	17%	50%	0%	23%	1929, 1979, 1986, 1999, 2000, 2004
6.7	Rebate depth timber door frame insufficient	17%	10%	30%	19%	1664, 1929, 1981, 1991, 2004
6.8	Door pin not fire resistant	0%	10%	20%	12%	1965, 1965, 1995, 1999
6.9	Too large gap under door	0%	10%	10%	8%	1664, 1986
7. Loadbearing structure						
7.1	Fire resistance uncertain	17%	30%	30%	27%	1664, 1862, 1965, 1979, 1965, 1995, 1998, 2000
7.2	Fire resistance insufficient	0%	0%	0%	0%	

Table 18 and Figure 30 show for example that in 88% of the inspected buildings one or more shortcomings regarding ducting and piping have been found. Also problems with self-closing doors, non-certified doors[13], seals around ducts and pipes, fire dampers and too large areas of wired glass[14] in compartmentation walls are frequently addressed in the inspection reports.

Many buildings contain one or more compartments which are bigger than allowed according to the Building Decree 2012, without having a demonstrated equivalent solution (inspectors often refer to the 'Method Controllability of Fires 2007' (nl. Methode Beheersbaarheid van Brand, BvB 2007), which is a general guideline for demonstrating of an equivalent solution for large compartments based on fire load, installations etc., see also section 3.7.2 (31)).

Shortcomings regarding the loadbearing structure are generally not determined, since it is hard to assess the loadbearing structure based on visual inspection. In some cases it is mentioned that the fire performance of the loadbearing structure is unknown. In most cases the loadbearing structure is not even mentioned at all or the loadbearing structure is addressed as 'no findings or action points'.

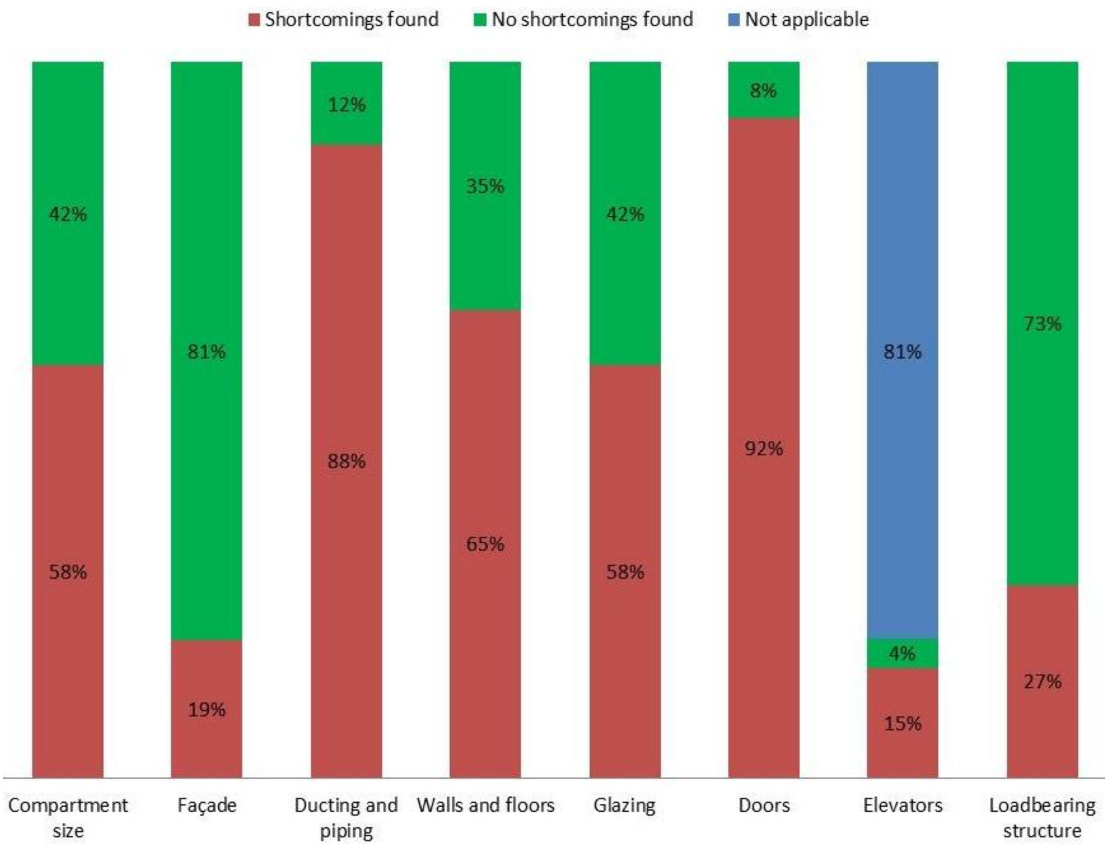

Figure 30 Presence of shortcomings in buildings

[13] No test or classification report can be demonstrated.

[14] The maximum area of wired glass in a compartmentation wall is 0.9 m^2 per 2.5*2.5m^2, in order to limit the maximum radiation level on the non-exposed side.

None of the analysed buildings meets all the requirements for compartmentation. Figure 30 shows that shortcomings with doors, ducting and piping are present in almost all buildings, no matter what the occupancy class or the age of the building is.

Not fulfilling the requirements will in practice not directly lead to failure of the compartmentation system, but it will affect the likelihood of failure in case of fire to some extent. Some shortcomings will affect the fire performance of compartmentation systems more than others. Therefore a more advanced ranking of shortcomings is made based on the severity of a particular shortcoming.

7.4 Severity of shortcomings

In order to get insight in the severity of different shortcomings, a division is made based on the expected time until fire spread due to a specific shortcoming occurs, based on an assumed fire duration of at least 60 minutes without taking into account the possibility of fire brigade intervention. Fire spread is considered as an event which leads to ignition and fire propagation in the adjacent compartment, so a small flame in the adjacent compartment or a too high surface temperature (compared to what is allowed according to test criteria) on the non-exposed site of a partition, does not necessarily lead to fire spread. Fire spread to compartments in other premises is not considered, so only fire spread within one building is considered. The shortcomings are divided into categories based on five scenarios:

- Category I: very little or no resistance against fire spread, fire spread occurs within 5 minutes;
- Category II: these shortcomings will only offer resistance for a very limited amount of time (5 - 15 min);
- Category III: these shortcomings will lead to fire spread to adjacent compartments in 15 – 30 minutes;
- Category IV: these shortcoming will lead to fire spread to adjacent compartments in 30 – 60 minutes;
- Category V: these shortcomings will not lead to fire spread to adjacent compartments within 60 minutes.

The time until fire spread to adjacent compartments is measured after a developed fire has occurred at the position of the shortcoming. From this moment onwards, the performance of compartmentation systems becomes important to prevent fire spread to the surrounding compartments.

The chosen times for the categorization (5, 15, 30, 60 minutes) are arbitrary, but 30 and 60 minutes correspond with the requirements for compartmentation systems in the Dutch Building Decree.

The listed shortcomings which are found in the inspection reports cannot directly be categorized into one of these five categories. All shortcomings have a different influence on the fire performance of the compartmentation system. For example, an open door will be categorized as an I-shortcoming if this directly leads to fire spread in the adjacent compartment, but when a door is not self-closing, it can be open, but it can also be closed.

Therefore a certain uncertainty will exist for the time until fire spread. This also holds for other shortcomings. In cases where for instance a duct is not properly sealed, fire spread to the adjacent compartment immediately after flashover is very unlikely. In some situations this will lead to fire spread within 15 - 30 minutes and in other cases it will lead to fire spread in 30 – 60 minutes or even to no fire spread at all, dependent on the circumstances. Therefore a proper distribution should be found on how different shortcomings contribute to the failure of the compartmentation system.

To take the effect of a specific shortcoming on the failure of compartmentation systems into account, a proper distribution should be found in order to rank the shortcomings into I, II, III, IV and V categories. Since any statistics/data about this topic do not exist and only a limited number of people have this knowledge, this distribution is based on the information from two experienced fire safety experts/fire investigators who are familiar with the RGD building inspections. Only for self-closing fire doors it was found in literature that approximately 30% of the doors is unavailable or does not function in case of fire, see section 6.4 (7) (57). The probability of fire spread is estimated per time interval, for example 10% probability of fire spread in 5 – 15 minutes, 30% probability of fire spread within 15 - 30 minutes and so on. An overview is given in Table 19.

Table 19 Assumed values for the effect of different shortcomings on the fire performance of compartmentation

	Probability of fire spread to adjacent compartment									
	I (0 - 5 min)		II (5 - 15 min)		III (15 - 30 min)		IV (30 - 60 min)		V (> 60 min)	
	Expert 1	Expert 2	Expert 1	Expert 2	Expert 1	Expert 2	Expert 1	Expert 2	Expert 1	Expert 2
Fire resistance façade insufficient	0%	0%	0%	10%	40%	30%	40%	40%	20%	20%
Penetrations for ducts, pipes and cables not sealed	0%	0%	10%	10%	20%	10%	50%	20%	20%	60%
No fire dampers in ducts	0%	0%	10%	10%	30%	20%	50%	20%	10%	50%
No fire resistant casing around ducts	0%	0%	10%	10%	20%	10%	50%	10%	20%	70%
Mounting of pipes and ducts not sufficient	0%	0%	0%	10%	25%	20%	50%	30%	25%	40%
Fire resistance of wall insufficient or uncertain	0%	0%	10%	10%	30%	30%	30%	30%	30%	30%
Panel or glass is missing (holes)	10%	10%	40%	30%	50%	50%	0%	10%	0%	0%
Fire resistant separation is not continued above suspended ceiling	10%	0%	40%	10%	50%	30%	0%	40%	0%	20%
Steel structure penetrating fire separation without fire resistant covering	0%	0%	0%	0%	30%	10%	50%	20%	20%	70%
Fire separation in roof structure is not properly finished	0%	0%	0%	20%	20%	30%	50%	30%	30%	20%
Steel hatch in wall/floor	0%	0%	0%	0%	20%	10%	40%	20%	40%	70%
Floorstructure not sufficient fire resistant	0%	0%	0%	10%	10%	20%	50%	30%	40%	40%
Large areas wired glass in fire separations	0%	0%	30%	0%	70%	10%	0%	20%	0%	70%
Fire resistance glazing insufficient (excluding wired glass)	0%	0%	60%	30%	30%	50%	10%	20%	0%	0%
Glazing beads missing	0%	0%	20%	10%	80%	20%	0%	20%	0%	50%
Doors not self-closing	10%	10%	20%	10%	0%	10%	0%	0%	70%	70%
Fire resistance doors uncertain and not certified	0%	0%	10%	10%	30%	20%	30%	30%	30%	40%
Intumescent strip around door missing	0%	0%	0%	0%	20%	10%	40%	20%	40%	70%
Doors do not close properly	5%	0%	20%	10%	50%	20%	25%	20%	0%	50%
Fire resistance glazed partition uncertain and not certified	0%	0%	20%	10%	30%	20%	30%	30%	20%	40%
Steel door frame with insufficient fire resistance	0%	0%	0%	0%	30%	10%	70%	20%	0%	70%
Rebate depth timber door frame insufficient	0%	0%	0%	0%	20%	10%	50%	20%	30%	70%
Door pin not fire resistant	0%	0%	0%	0%	20%	10%	40%	20%	40%	70%
Too large gap under/around door	0%	0%	0%	10%	30%	20%	50%	20%	20%	50%
Elevator doors do not close properly / have insufficient fire resistance	0%	0%	0%	0%	20%	10%	50%	10%	30%	80%

It should be noticed that many shortcomings in the table are actually general terms for shortcomings which are closely related to each other. For example, there can be many ways in which a wall is not sufficient fire resistant, all having different severities. Some RGD inspection reports give a detailed description of why the wall is not sufficiently fire resistant, but most of the inspection reports do not, so therefore a more sophisticated division is not very meaningful, since the RGD scans are simply not adequate for this purpose. The shortcomings within one group therefore differ in severity. It was attempted to take these differences into account during the determination of the values in Table 19.

One example is given on how the quantification is done of the effect of a shortcoming on the fire performance of the compartmentation system. ‘Penetration not sealed’ may imply an electric cable through a concrete wall without proper fire resistant sealing. It is very unlikely that this particular penetration will cause fire spread, since the passage of heat and flames through a hole with approximately 15 mm diameter is very limited. ‘Penetration not sealed’ may also refer to an air duct of 400*400 mm^2 which is penetrating a hole with a size of 600*600 mm^2 without a sealing. Fire spread within 30 or 60 minutes is much more likely in this case. An elaborated explanation for the assumed values in Table 19 is given in Appendix II.

When the effect of shortcomings on the probability of fire spread to adjacent compartments is applied on the analysed buildings, it turns out that on average 11% of the analysed building has one or more category I shortcomings, 51% has category II shortcomings, 72% has category III shortcomings and 76% of the buildings has category IV shortcomings. This is illustrated in Figure 31.

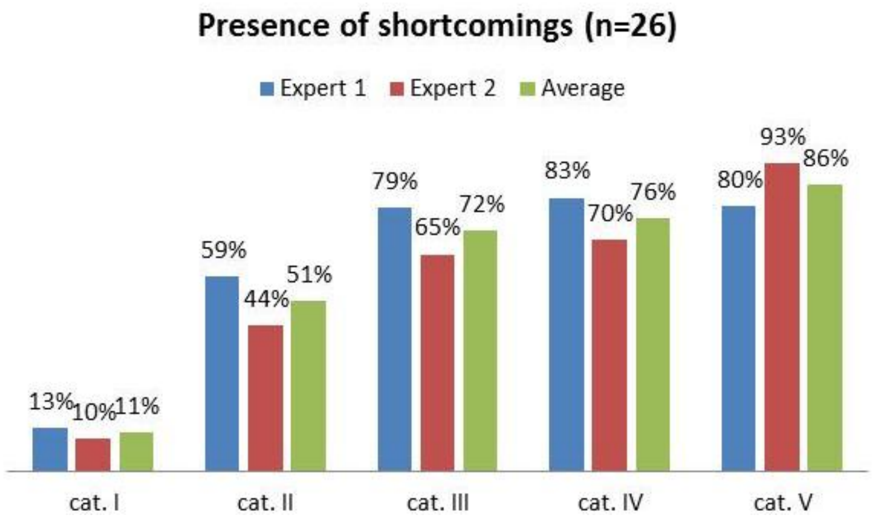

Figure 31 The presence of shortcomings in buildings categorized by their severity[15]

In order to determine the likelihood of fire spread between compartments, the presence of shortcomings in the fire compartment is important. The presence of a particular shortcoming in the building does not give any detailed information about the probability of shortcomings in one of the compartments in the building. Therefore it should be figured out how often a particular shortcoming is present and how these shortcomings are distributed among the compartments in the building.

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[15] The following calculation method has been used to get the results of Figure 31, expressed in mathematical formulas:

- SC_j is a shortcoming of type j
- $SC_{i,j}$ is a shortcoming of category i (i = I to V) of type j;
- $P(SC_{i,j})$ is the probability that a shortcoming of type j leads to fire spread category i (Table 19);
- X_i is defined as a building in which shortcomings of category i are present;
- $P(X_i) = (1 - P(SC_{i,1})*P(SC_1))*(1-P(SC_{i,2})\, P(SC_2))*...*(1-P(SC_{i,j})\, P(SC_j))$.

7.5 Probability of fire spread between compartments

The level of detail of many of the RGD inspection reports is insufficient to make an estimation on how often particular shortcomings are present in a compartment. However, a work description is given in eleven (out of 27) inspection reports, which states for example which ducts have to be sealed or how many doors in the building are not self-closing. When it is assumed that these shortcomings are randomly distributed over the building's compartments, a rough estimation can be made about the probability that a particular shortcoming is present in the compartments.

Still there is a problem with the limitations of some inspection reports. In some reports it is stated that all doors need to be replaced because these doors are lacking the right classification. In other reports it is mentioned how the doors can be improved without completely replacing the doors. Some inspection reports also mention that for example intumescent strips around the doors are missing, while it is in the work descriptions just mentioned that these doors need to be replaced because these doors are lacking the right classification. This makes it difficult to appoint the shortcomings to the right group in an objective way.

In addition, for some shortcomings it is not stated how often they occur, but in the work description a total (summed) number of square meters is given. The frequency of this type of shortcomings can therefore not directly be derived from the reports and should be approximated. For glazing or wall elements it is for example mentioned how many square meters need to be replaced in the entire building. With the help of attached photos, it is figured out how many of these systems are present in separate pieces. For example, if wired glass partitions are applied in the building with a total area of $50m^2$ and based on the photos it turns out that every wired glass partition is approximately $5m^2$, it is assumed that the building contains in total ten of these glazed partitions.

The results for the eleven analysed buildings are shown in Table 20.

Table 20 Number of shortcomings per building

	Building no.										
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
Estimated number of compartments	**14**	**11**	**10**	**5**	**37**	**3**	**58**	**7**	**14**	**46**	**10**
Penetrations for ducts, pipes and cables not sealed	25	22	4	9		7	148	10	39	335	2
No fire dampers in ducts	25	9				8	80	8	3	35	2
Doors not self-closing		2	3	1	27	2	4	74		40	
Large areas wired glass in fire separations	3		1		50	5		25			
Fire resistance doors uncertain				5	35		17		7		
Fire resistance glazing insufficient (excluding wired glass)		5					45		5		
Fire resistance wall insufficient or uncertain							53				
Panel or glass is missing (holes)		1		1		47	1				
Doors do not close properly								17	1	20	
No fire resisting casing around ducts	25		1								2
Fire separation in roof structure is not properly finished					9						
Fire resistance glazed partition is uncertain								6			
Steel structure penetrating fire separation without fire resistant covering				4							
Rebate depth timber door frame insufficient		3									
Door pin not fire resistant									3		
Fire resistant separation is not continued above suspended ceiling					1						
Intumescent strip around doors missing			1								

It should be noticed that these figures are based on 11 out of 27 inspection reports and therefore the total number of different shortcomings is smaller compared to Table 18. Also it is not mentioned how many doors are for example not good relative to the total number of doors inside the building. Moreover, it depends on the inspectors how correct and accurate the reports are. These figures give therefore only a rough quantification of fire safety related errors and shortcomings in buildings.

In order to estimate the probability that a certain shortcoming is present in a fire compartment, it should be figured out how many compartments the building has. This is not explicitly mentioned in the RGD inspection reports, therefore the number of compartments has been estimated based on the gross floor area and the number of floors in the building. It is assumed that the building has at least one fire compartment on every storey. If the area per floor is larger than 1000 m^2, than it is assumed that the floor area of a compartment is 850m^2 on average, so the number of compartments is estimated to be equal to the number of floors in the building or equal to the total floor area divided by 850 m^2.

The number of shortcomings per compartment is now approximated by dividing the values from Table 20 by the number of compartments in the building. The distribution of category I to V-shortcomings among the compartments is now as shown in Figure 32.

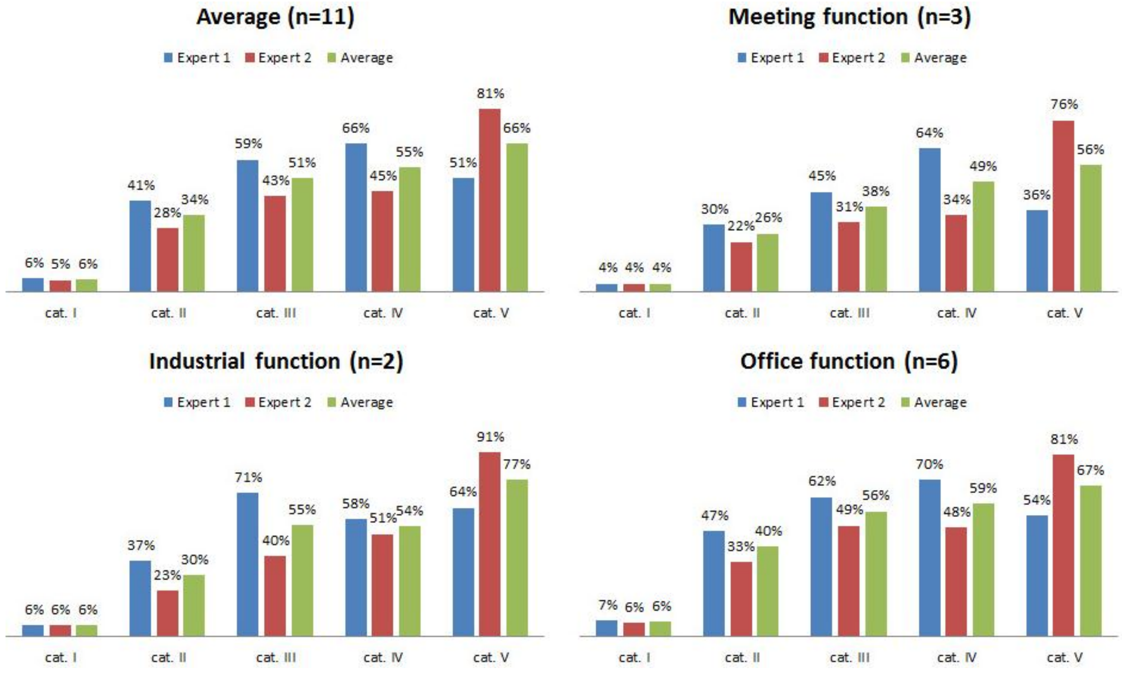

Figure 32 The presence of shortcomings in compartments categorized by their severity[16]

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[16] The following calculation method has been used to get the results of Figure 32, expressed in mathematical formulas:

- SC_j is a shortcoming of type j;
- $P(SC_j)$ is the probability that a shortcoming of type j is present in a compartment (Table 20);
- $SC_{i,j}$ is a shortcoming of category i (i = I to V) of type j;
- $P(SC_{i,j})$ is the probability that a shortcoming of type j leads to fire spread category i (Table 19);
- Y_i is defined as a compartment in which shortcomings of cat. i are present, where i = I to V;
- $P(Y_i) = (1 – P(SC_{i,1})*P(SC_1))*(1-P(SC_{i,2}) *P(SC_2))*…*(1-P(SC_{i,j})*P(SC_j))$.

Expressed in words, on average 6% of the compartments has one or more shortcomings which will lead to fire spread within 5 minutes (category I). Shortcomings which lead to fire spread within 5 - 15 minutes have been found in 34% of the compartments, 51% of the compartments have one or more shortcomings which lead to fire spread within 15 – 30 minutes, 55% of the compartments show shortcomings which cause fire spread within 30 – 60 minutes and in 66% of the compartments shortcomings are present which will probably not lead to fire spread within 60 minutes.

With these values about the presence of I, II, III, IV and V shortcomings in compartments, an estimation can be made about the probability of fire spread to adjacent compartments. 6% of the compartments shows I-shortcomings which cause fire spread within 5 minutes, so these compartmentation systems will fail within 5 minutes after the occurrence of a fully developed fire. A part of the 94% of the compartments which have not failed immediately, will fail in the next 10 minutes. When it is assumed that the presence of I, II, III, IV and V shortcomings is independent[17], 36% of the compartments will have failed within 15 minutes[18]. After the next fifteen minutes 56% will have failed and after an hour fire spread will occur in 67% of the compartments to adjacent compartments. This implies that based on the presence of shortcomings, on average 33% of all compartmentation systems will survive a fire duration of 60 minutes without the occurrence of fire spread. This is shown in Figure 33.

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[17] A complete independency between shortcomings is in practice not likely, since different categories of shortcomings are all depending on the condition of the building.

[18] The following calculation method has been used to get the results of Figure 32, expressed in mathematical formulas:

- Z is the time until fire spread occurs expressed in minutes;
- $P(Z < 5) = P(Y_I)$
- $P(Z < 15) = P(Z < 5)+P(Z \in 5 – 15)$ with $P(Z \in 5 – 15) = P(Y_{II} \mid \overline{Y}_I)*P(Z>5)$;
- $P(Z < 30) = P(Z < 15)+P(Z \in 15 – 30)$ with $P(Z \in 15 – 30) = P(Y_{III} \mid \overline{Y}_I \& \overline{Y}_{II})*P(Z>15)$;
- $P(Z < 60) = P(Z < 30)+P(Z \in 30 – 60)$ with $P(Z \in 30 – 60) = P(Y_{IV} \mid \overline{Y}_I \& \overline{Y}_{II} \& \overline{Y}_{III})*P(Z>30)$;

The probability of fire spread between compartments (e.g. $P(Z < 15)$)is the sum of the probability that fire already occurred (e.g. $P(Z < 5)$) in the previous time interval and the contribution of the last time interval, which is the product of the probability that fire spread did not occur yet (e.g. $1-P(Z < 5)$) and the probability that fire spread occurs in that time interval. The last term is the product of the probability that shortcomings are present which lead to fire spread in that time interval (e.g. $P(Y_{II})$) and the probability that the compartments with these shortcomings did not fail in the previous time interval (e.g. $P(Z > 5)$).

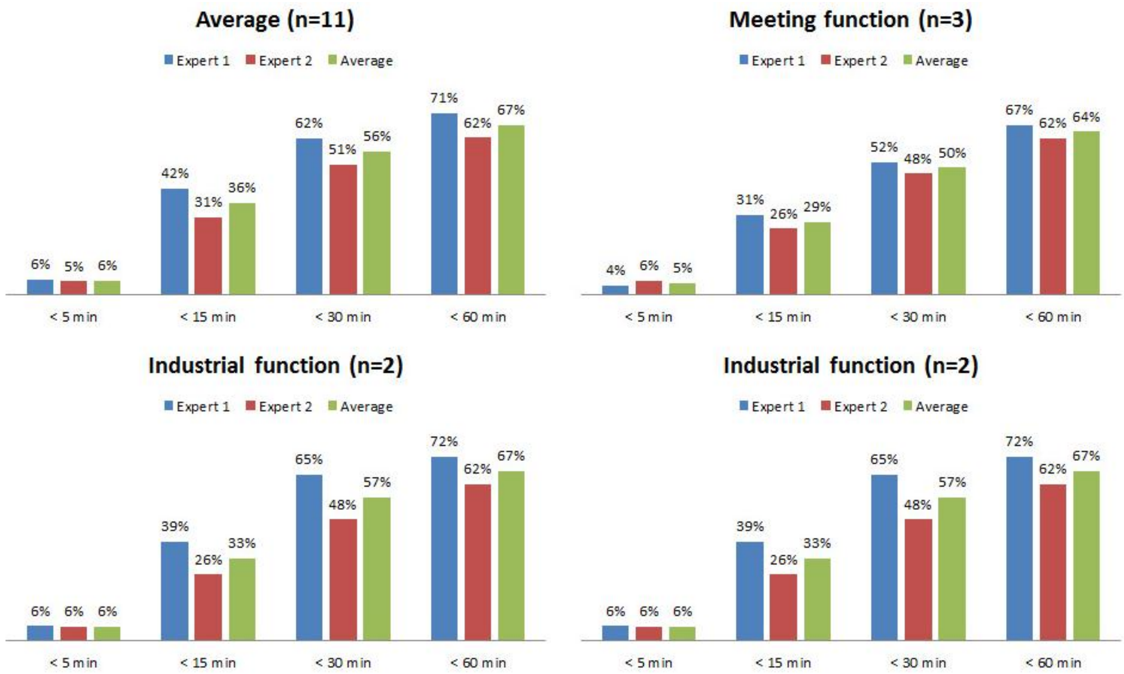

Figure 33 Time until failure to be expected due to the shortcomings

The contribution of different shortcomings on the failure in the given time periods are shown in Figure 34. The figure is based on the average values for meeting, industrial and office buildings. The main causes for fire spread after the given time periods are:

- Fire spread within 5 minutes: the main causes for fire spread are missing panels and open doors;
- Fire spread within 15 minutes: open doors, glazing with insufficient or no fire resistance, and ducting becomes the most important cause for fire spread. The last group of shortcoming does not have a large probability of fire spread in the time interval 5 - 15 minutes, but these shortcoming are frequently present and these shortcomings therefore have a significant stake in the occurrence of fire spread;
- Fire spread within 30 minutes: ducts and pipes are the shortcomings which have the most important influence on the failure of compartments. Also the contribution of open doors, glazing with insufficient fire resistant glazing and missing panels is still increasing. Doors with insufficient fire resistance also get an important contribution in the failure of compartmentation systems;
- Fire spread within 60 minutes: shortcomings regarding ducting and piping are in this period the most important reasons for failure. The contribution of other shortcomings increases just a little.

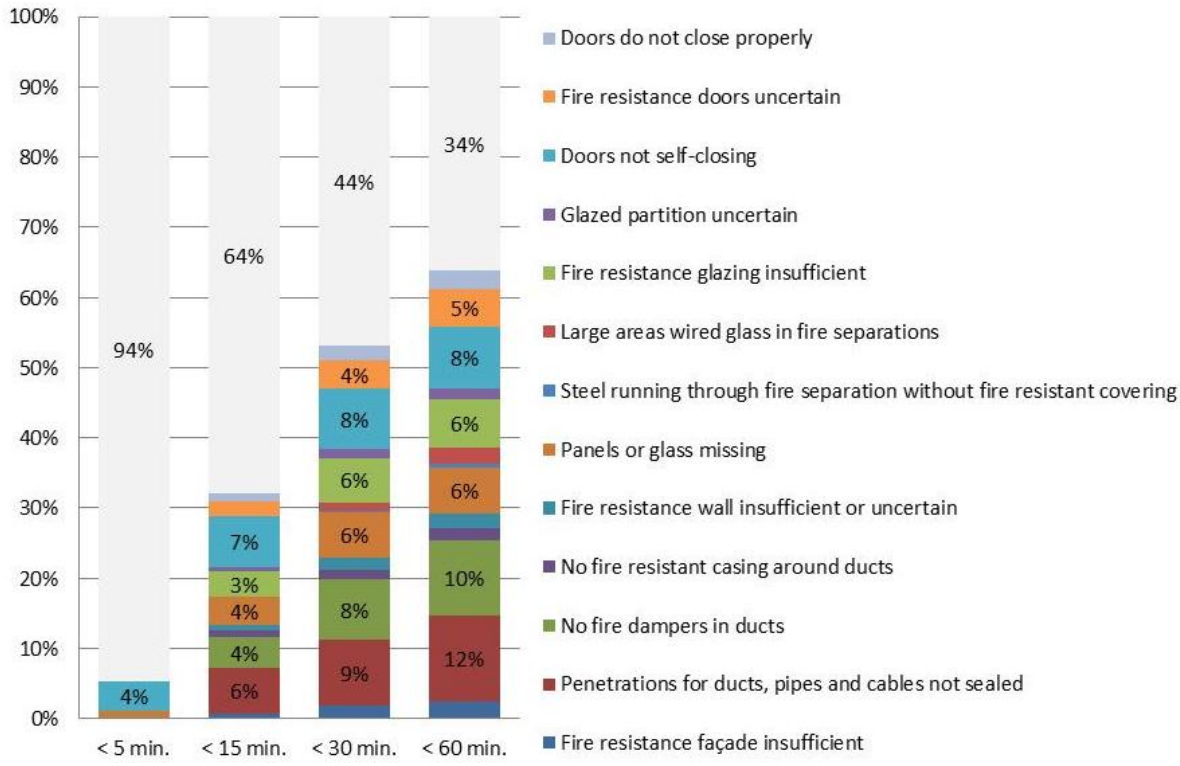

Figure 34 Causes of fire spread in the different time periods

It can be concluded that the presence of shortcomings will not always lead to fire spread within 60 minutes; the percentage of failed compartmentation systems would than approach 100% after 60 minutes. But it can also be concluded that shortcomings are frequently present in building and significantly reduce the performance of many compartmentation systems.

The fact that not all shortcomings will lead to fire spread is for example because the classification criteria are often not directly related to fire spread in reality. For example when the temperature of a partition wall becomes too high on the non-exposed side, this will in many cases not lead to fire ignition in the adjacent compartment. On the other hand, the risk of fire spread depends not only on elements in a compartmentation system which do not comply with the regulations, but also elements which do comply with the regulations might fail within the required time. A window which is tested for a 60 minutes fire rating, can also fail after a couple of minutes when some imperfections are present in the panel, for example when the intumescent layer is locally not functioning.

Other factors which might help to prevent the fire spread to adjacent compartments, are for example fire brigade intervention and burnout of the compartment. If the fire is extinguished after 30 minutes, then there is obviously no risk for fire spread anymore. In addition, not in all building fires a fully developed compartment fire with the same severity as the fire conditions used for classification purposes will occur, which will also improve the chances of successful limiting the fire extension area.

7.6 The influence of fire development and duration on fire spread due to shortcomings

The presence of shortcomings becomes in general more critical with increasing fire severity and fire duration. The fire development and fire duration are important influence factors on the effect of shortcomings on the performance of compartmentation.

A fully developed fire will not occur in all compartments or a fire will develop gradually and flashover is unlikely, or the fire will only occur in a small part of the fire compartment (for example in a subcompartment). Also the fire duration will influence the potential risk on fire spread. In the previous analysis it is assumed that a fully developed fire has occurred at the location of the shortcoming and that the fire will last for at least 60 minutes.

7.6.1 Fire development in the fire compartment

The fire development in a compartment depends on many factors, such as the characteristics of combustibles, the availability of oxygen, active fire suppression measures like sprinklers, dimensions of the fire compartment or the division of the fire compartment into smaller rooms and/or subcompartments. These factors result in many possible fire scenarios: from a very fast fire development which affects the entire compartment, to a smouldering fire in a small part in the fire compartment. In other compartments there might be combustibles present which cause a very rapid fire development, but the fire might start decaying immediately after a short but intense fire development (this is for example what happened in the Volendam New Year's fire (66)). The energy output during the combustion of the fast burning materials (decoration) is in this case insufficient to cause ignition of other combustibles in the compartment, or there is a lack of oxygen.

Requirements are set for the flammability and combustibility of many (construction) materials, for example for fire propagation via carpets, walls coverings etc. Compliance with these regulations will reduce the risk of having a rapid fire development in the compartment.

When a fire spreads slowly through the compartment, for example due to subcompartmentation, this will reduce the risk of fire spread to the adjacent compartment, since less shortcomings are exposed to the fire at the same time or in an early stage. Dependent on the location of fire ignition, it might of course also happen that fire spread occurs from the subcompartment to the adjacent fire compartment before the fire spreads from the subcompartment to other parts in the fire compartment, but in general, the probability of rapid fire spread to adjacent fire compartments will decrease with increasing division of the fire compartment into subcompartments and separated rooms.

A fully developed fire in the entire compartment is unlikely in many buildings due to subcompartmentation. Especially in the analyzed office buildings, subcompartmentation is frequently applied. Also in case of relatively large compartments with a limited fire load, the occurrence of a fully developed fire in the entire compartment is unlikely. The location with the worst fire conditions than moves through the compartment. The result is that not the entire compartment's boundary will be exposed to a fully developed fire at the same time.

Therefore not all weak points in the compartmentation system will be affected by the fire at the same time.

7.6.2 The fire duration

The fire duration is another important influence factor on the occurrence of fire spread, since shortcomings become in general more critical with increasing fire duration. When the fire duration in a compartment is only 15 minutes (for example due to fire brigade intervention, burnout), then the probability that the compartments will lose their separating function is 36% (see Figure 33). When the fire lasts for 30 minutes, than the compartments will lose their separating function in 56% of the buildings. Suppose for example that 50% of the compartment fires will be extinguished 15 minutes after flashover and 50% will be extinguished after 30 minutes, than fire spread can be expected in 46% of the buildings. To find a feasible expectancy of the number of compartments in which fire spread will occur, it is therefore important to get some quantification/statistics about the duration of a compartment fire.

The fire duration in compartments is, among others (see section 2.1.2) dependent on the fire load. An in practice widely applied but very indicative rule of thumb is that a fire load density of 1 kg pinewood/m^2 corresponds with 1 minute fire duration after a fully developed fire has occurred (31). For example, when the fire load is 60 kg pinewood/m^2, the expected fire duration is 60 minutes[19]. In Table 21 some values are given. It should be noticed that the fire load in most buildings is not constant and can vary from time to time.

Table 21 Some typical values for the mean fire load according to NEN-EN 1991-1-2 and corresponding estimated fire duration

Use function	Mean fire load [MJ/m^2]	Estimated fire duration* [min]
Dwelling	780	41
Hospital	230	12
Hotel	310	16
Library	1500	79
Office	420	22
School	285	15
Shopping centre	600	32
Theatre, cinema	300	16
Transport function	100	5

* Assumption: 19 MJ/m^2 corresponds with 1 minute fire duration in fully developed fire

For offices, a typical value for the fire load is 420 kg/m^2 (≈ 22 kg pinewood/m^2). According to the rule of thumb, this will result in a fire duration of approximately 20 - 30 minutes in case of a fully developed fire. Assumed that the fire duration in compartments is somewhere between 15 - 30 minutes, approximately 35 to 55% of the fire compartments will have failed based on the analysis of the RGD inspection reports.

Also according to other sources, a maximum fire duration of 30 minutes seems to be plausible in many compartment fires. Some measured temperature - time curves of fifty compartment fires in a test set-up are shown in Figure 35. The fire load densities in these

[19] 1 kg pinewood/m^2 ≈ 19 MJ/m^2 (31)

tests were varied between 200 MJ/m^2 and 900 MJ/m^2 (52). Most of these fires reach their maximum temperature 10 - 20 minutes after flashover and many fires are decaying after 30 minutes, but the gas temperature in the compartment can still be relatively high (±500°C), which implies that there still is a danger of fire spread during the decaying stage. Also the fire curves in Figure 4 show that most fires are decaying after 30 minutes.

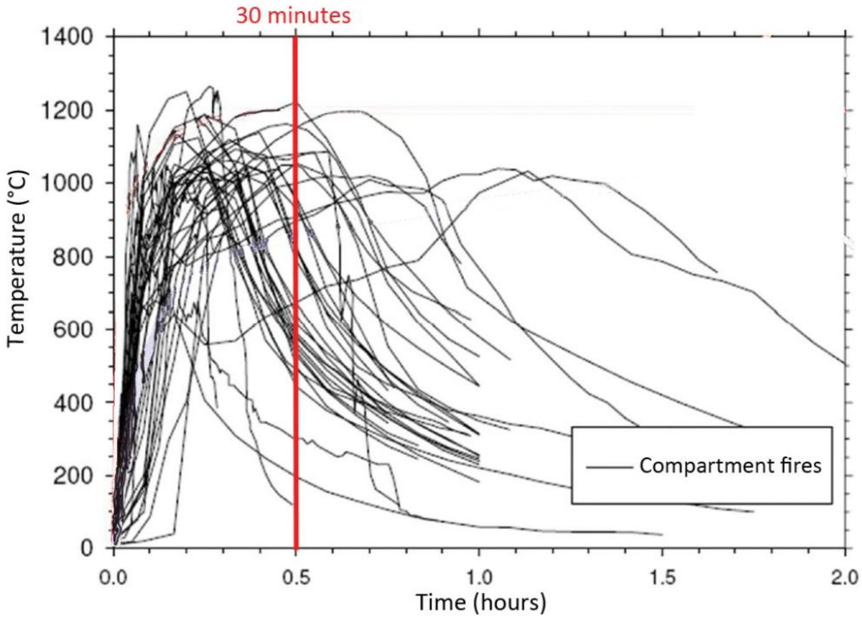

Figure 35: Measured temperature - time curves of fifty compartment fires in laboratory set-up (53)

The probability of fire spread is in practice further reduced by efforts of the fire brigade (in both offensive and defensive approach), for example by cooling the roof and façade with water. The ability of the fire brigade to limit fire spread due to shortcomings which lead to fire spread in an early stage is limited, since it takes some time before the fire brigade is alarmed, arrives on site and gets prepared for firefighting actions. The fire brigade arrives in most cases within 15 minutes after alarm at location according to statistics of CBS (Statistics Netherlands), see Figure 36 (64).

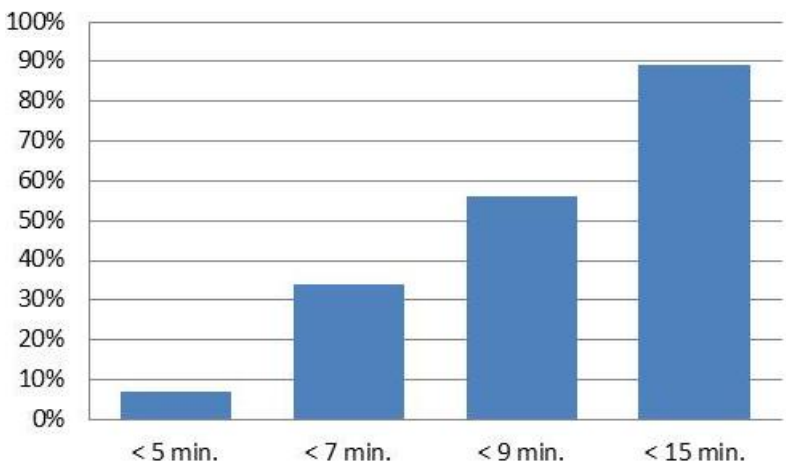

Figure 36 Arrival time of the fire brigade based on statistics of the CBS in the period 2002 – 2010

If fire spread already occurred and flashover occurred in the adjacent compartment before the fire brigade is able to intervene, the fire brigade is too late to save this compartment. In case the occurrence of fire spread takes longer, efforts of the fire brigade to suppress and control the fire will reduce the probability of fire spread. Especially risk on fire spread mechanisms via the exterior (façade, roof) of the building can be reduced by the fire brigade, since in these situation the firemen do not need to enter the building, which may entail high safety risks for the fire fighters. So due to fire brigade intervention, the risk of fire spread due to for example category III and IV shortcomings becomes smaller, see Figure 37.

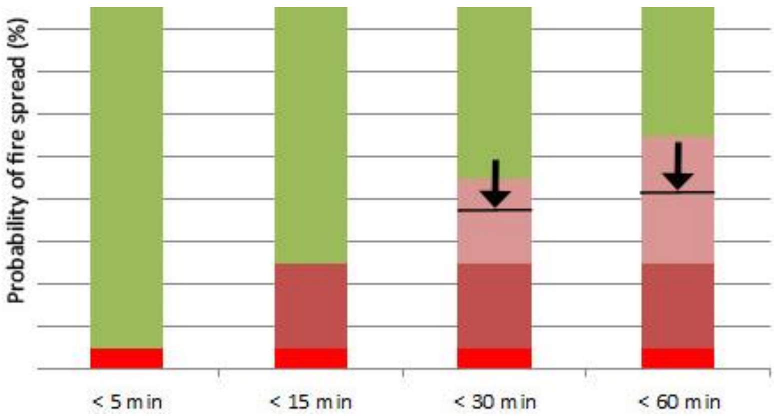

Figure 37 The effect of fire brigade intervention on the risk of fire spread to adjacent compartments

Other aspects which influence the probability of fire spread are for example the location of the ignition source, the location of the fire compartments relative to the other compartments and the accessibility of the fire compartment by the fire brigade. Also elements which do have the required certification and/or test report, can fail in case of fire within the required resistance time, for example due to scatter in test results, different fire conditions, imperfections or other unforeseen factors.

7.7 Comparison with fire statistics from practice

The Dutch Institute for Fire Brigade and Disaster Prevention (Nibra) investigated the large fires in 2001 with a damage of more than 1 million euros, see also section 6.3.3 (57). This research included fires in many different building types and functions. A small part of this research was related to the performance of compartmentation systems in these fires.

Table 22 Performance of compartmentation in high damage fires in 2001 (57)

Construction year	Fires kept inside fire compartment	Fires that are no danger to adjacent premises
Before 1992	56%	88%
After 1992	83%	92%

Table 22 shows that in 56% of the buildings which have been built before 1992, the fire was kept inside the fire compartment (in that year a national Building Decree was introduced, with national applicable fire safety requirements, mainly technical requirements for dwellings, offices and lodging buildings (28)). Since most buildings in the RGD inspection reports are also build before 1992, it is possible to compare this value with the figures in Figure 33.

The compartmentation systems in buildings which are constructed after the introduction of the national Building Decree perform much better according to the Nibra research: in 83% of the buildings constructed after 1992, the fire was kept inside the fire compartment. This cannot be explained based on the RGD inspection reports, since the shortcomings which can cause premature failure of compartmentation systems appear to be present in buildings of all ages, also in buildings constructed after 1992 and even in relatively new buildings severe shortcomings are found, see Table 23.

Table 23 Presence of shortcomings in buildings constructed before 1992 and after 1992

Type defect		Buildings in which these shortcomings are present	
		Constructed before 1992	Constructed after 1992
1. Problems with compartment size		**53%**	**63%**
1.1	Compartiments larger than allowed in BD2012 without demonstrated equivalent solution	41%	63%
1.2	Technical rooms >50m^2 not in separate fire compartments	18%	13%
2. Problems with façade			
2.1	Fire resistance façade insufficient	24%	13%
3. Problems with penetration for ducting and piping		**94%**	**75%**
3.1	Penetrations not sealed	94%	75%
3.2	No fire dampers in ducts	76%	63%
3.3	No fire resistant casing around ducts	12%	0%
3.4	Mounting of pipes and ducts not sufficient	0%	25%
4. Problems with fire walls / floors		**71%**	**50%**
4.1	Fire resistance wall insufficient or uncertain	41%	25%
4.2	Panel or glass is missing (holes)	24%	38%
4.3	Fire resistant separation is not continued above suspended ceiling	29%	0%
4.4	Steel structure penetrating fire separation without fire resistant covering	6%	25%
4.5	Fire separation in roof structure is not properly finished	12%	0%
4.6	Steel hatch in wall	0%	13%
4.7	Floorstructure not sufficient fire resistant	0%	13%
5. Problems with glazing		**71%**	**38%**
5.1	Large areas wired glass in fire separations	59%	38%
5.2	Fire resistance glazing insufficient (wired glass excluded)	24%	0%
5.3	Glazing beads missing	0%	13%
6. Problems with doors		**94%**	**88%**
6.1	Doors not self-closing	76%	75%
6.2	Fire resistance doors uncertain and not certified	35%	75%
6.3	Intumescent strip missing	41%	50%
6.4	Doors do not close properly	41%	38%
6.5	Fire resistance glazed partition uncertain and not certified	35%	25%
6.6	Steel door frame with insufficient fire resistance	18%	38%
6.7	Rebate depth timber door frame insufficient	24%	13%
6.8	Door pin not fire resistant	6%	25%
6.9	Too large gap under door	12%	0%

Also when the severity of shortcomings is considered, the quality of compartmentation in the analysed buildings which are constructed after 1992 is not much better. The differences are small, see Figure 38. It is not possible to make a more detailed quantification of the presence of shortcomings in buildings constructed after 1992, since the level of detail of the inspection reports is insufficient.

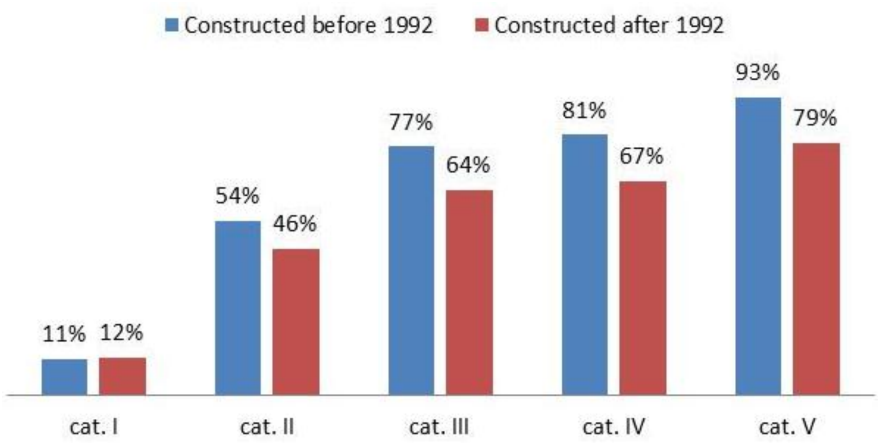

Figure 38 Presence of shortcomings in buildings constructed before 1992 and after 1992

Another possible explanation is that the buildings which are built after 1992 in the Nibra research are maximum nine years old. The age of 8% (approximately 25% of the buildings constructed after 1992) of the buildings investigated by the Nibra is even less than one year, see Figure 29. The limited age of these buildings can improve the behaviour of these buildings, since less changes and adjustments have been made in the compartmentation system (e.g. new or additional ducts, automatic door closers broken etc.). The RGD inspection are conducted from 2007 onwards, so the buildings which are constructed after the introduction of the Building Decree in 1992 are at least six years older compared to the Nibra research. Since no significant differences are found between buildings constructed before 1992 and after 1992 in the RGD inspection reports, the age of buildings seems to be more important for the presence of shortcomings than the construction year. The aging of the buildings therefore seems to have a higher influence on the presence of shortcomings and the performance of the compartmentation systems in this case than the introduction of the Building Decree.

In the Nibra research it was shown that compartmentation did not function in 15 out of 43 cases where compartmentation was present. The self-closing doors did not function in 12 cases, for example because these doors were blocked or removed. Whether or not this resulted in fire spread to other compartments, is not clear. It means that in circa 30% of the reported fires where compartmentation was present, the self-closing fire doors did not function. When this unavailability-rate for the self-closing doors is used as input for the analysis of the RGD-scans, this results in approximately 8% of the compartments to fire spread within 30 minutes, see Figure 34. It can be verified by investigation real building fires whether this 8% is correct, this would support the results of this analysis.

In the NCP research on high damage fires, it was found that self-closing doors lead to fire spread in 25% of the high damage fires. When this is compared to the analysis of the RGD inspections, fire spread within 15 minutes due to shortcomings with self-closing doors occurs in about 20% of the fires and in 14% of the fires where fire spread occurs within 30 minutes. These figures are in order of magnitude similar to the results of the Nibra research. The lower value found for longer fire durations, can be explained by the fact that shortcomings which cause fire spread in an early stage cannot be influenced by fire brigade intervention. The effect of for example defect self-closing doors (which lead to fire spread in an early stage) on the occurrence of fire spread to adjacent compartments is therefore proportionally higher.

It should be noticed that the Nibra research includes fires in industrial buildings with a manufacturing or production function, schools, shops, dwellings etc., while the RGD reports only contain information about meeting buildings like museums, offices and buildings with a light industrial function, such as archives.

7.8 Causes of shortcomings

The presence of shortcomings can be caused by different factors, during different stages in the life time of the building. Based on the available information, six main sources for shortcomings related to compartmentation can be distinguished in the RGD inspection reports:

- Mistakes during construction/maintenance: these shortcomings were created during construction and maintenance works of the building by incorrect assembly, incorrect or no finishing of particular elements etc. Unfortunately it is not possible to make a distinction between construction and maintenance works based on the RGD inspection reports. This type of shortcomings may relate to for example: penetrations not sealed, no fire dampers inducts, no fire resistant casing around ducts, no door closers installed on doors, no intumescent strips around doors, doors do not close properly.
- Design mistakes: these shortcomings are caused by wrong design or composition of the compartmentation system. This type of shortcomings may relate to for example: fire resistance façade insufficient, fire resistance of walls insufficient, steel running through fire separation without fire protective covering, large areas of wired glass, intumescent strips missing (wrong doors), door pin not fire resistant.
- Lack of maintenance: elements which are damaged or do not function properly anymore, are not replaced. This type of shortcomings may relate to: panel or glass missing (panel not replaced after it got broken), doors not self-closing (door closer broken), intumescent strips missing, doors do not close properly (warping, jamming on floor, doors do not lock).
- Caused by users: activities of the users of the building are the source of shortcomings, for example doors which are blocked by a trash bin, wedge etc.
- Caused by differences in legislation. The elements do not comply with the performance level for new buildings, but do comply with the required performance level for existing buildings. These shortcomings relate to: fire resistance of glazing insufficient, fire resistance façade and walls insufficient, large areas of wired glass;
- Lacking right certification: some elements in the compartmentation system do not have a right certification. In many inspection reports it is stated that no certification is available for particular elements, the fire resistance is therefore uncertain. This may for example relate to insufficient fire resistance of glazing, glazed partitions not certified, doors not certified.

The main causes of the shortcomings are shown in Figure 39. The majority of shortcomings in compartmentation system are created during construction and or maintenance works

(67%). The majority (61 out of 67%) of the mistakes during construction/maintenance is caused by the many shortcomings related to ducting, piping and cables.

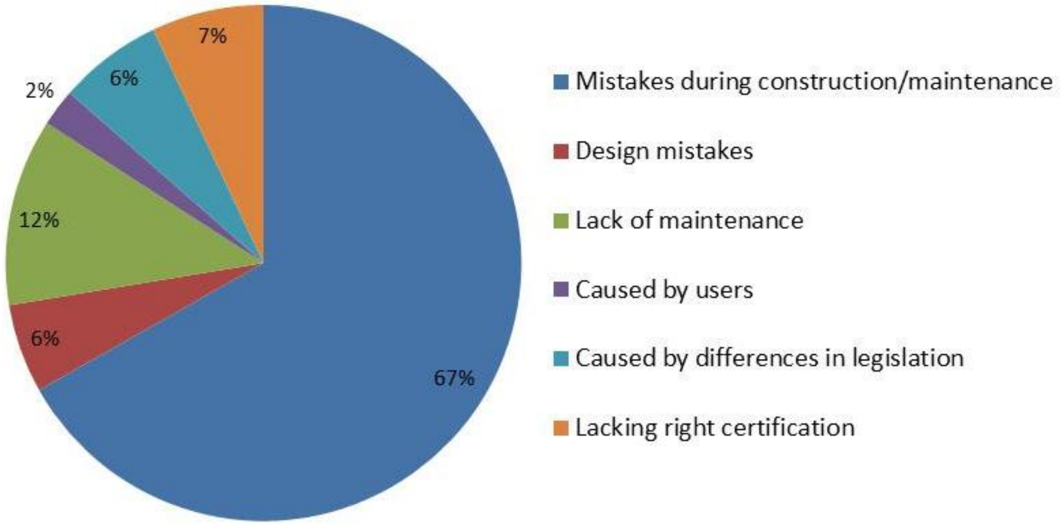

Figure 39 Causes of shortcomings related to fire compartmentation

When the severity of shortcomings is taken into account, the influence of shortcomings caused during construction/maintenance works is much smaller, since the probability of fire spread due to shortcomings related to ducting, piping and cables is relatively small. Still, the influence of these shortcomings is relatively large, see Figure 40. The probability of fire spread within 30 minutes caused by shortcomings created during construction/maintenance works is approximately 24%. Also the lack of maintenance has an important influence on the performance of compartmentation. Design mistakes, such as steel structures penetrating fire separations, do not affect the performance of these buildings much.[20]

[20] It should be noticed that most buildings in the dataset are concrete buildings.

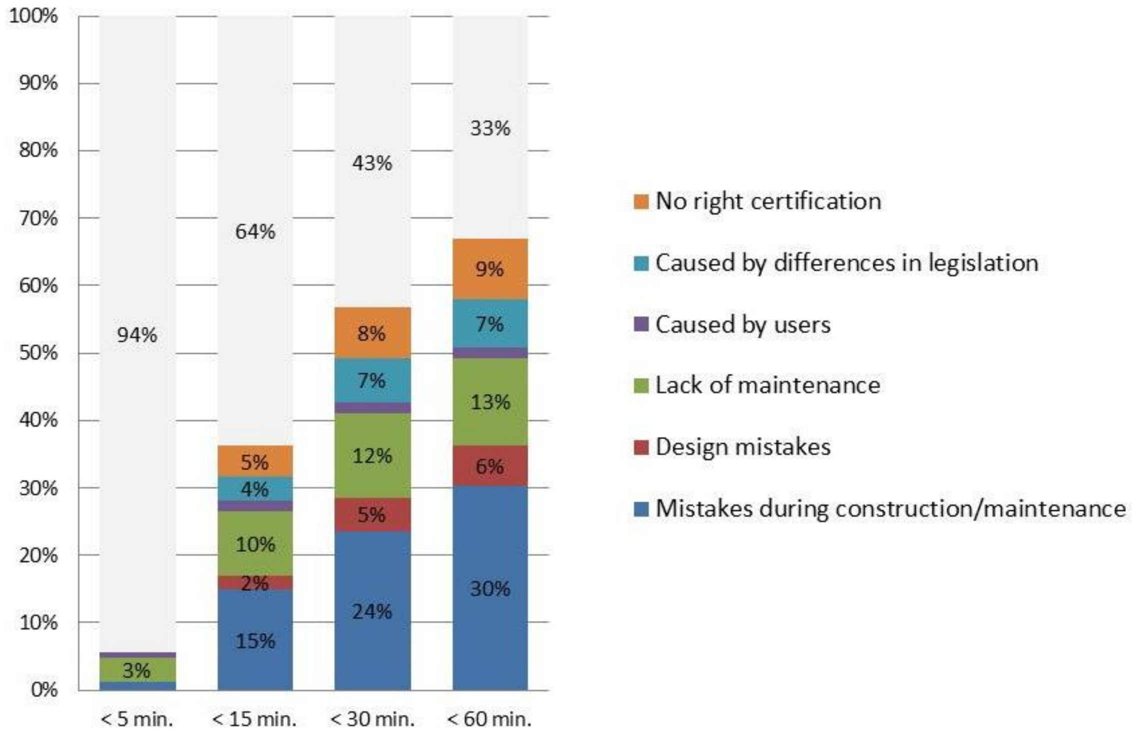

Figure 40 Probability of fire spread due to shortcomings with corresponding causes

In the research of Nibra of was found that the performance of compartmentation is better in newer buildings, see Table 22. Many of the building investigated by Nibra were less than one year old. The limited age of these building might be an explanation of the better performance. This might imply that most shortcomings which arise during construction/maintenance works are actually caused during maintenance works, since shortcomings caused during construction will also affect the performance of relatively new buildings.

The compartmentation systems of the buildings have been inspected with respect to two performance levels: 60 minutes fire resistance (nl. WBDBO) for new buildings and 20 minutes[21] for existing buildings, independent of the occupancy class, see Table 5. Most shortcomings are not related to one of these two performance levels (only 6%, see Figure 39), but are shortcomings with respect to both performance levels. For example missing panels in a fire wall are not allowed for both the new and the existing performance level. The same holds for many other shortcomings, for example self-closing doors, no fire dampers in ducts, penetrations for ducts, pipes and cables not properly sealed, fire walls not continued above suspended ceiling, doors do not close properly etc. are all things which are not allowed in both new and existing buildings. The differences in legislation do therefore not have a big influence on the performance of compartmentation systems. Especially the contribution to early fire spread (<15 minutes) of this type of shortcomings is limited see Figure 40.

Every building in the inspection reports is in principle ‘existing’, and the compartmentation system should therefore have a fire resistance between 20 and 60 minutes, dependent on

[21] Fire resistance rating according to standard (test) conditions, see also section 3.6.

what building permit has been issued. This is not achieved in most buildings since many problems have been found, especially on component level (doors, glazed partitions etc.). For the analysis of the RGD inspection reports, the buildings are compared using the required performance level for new buildings (60 minutes resistance against fire spread), to get an idea to what extent the buildings do comply with this requirement and for what reasons compliance with legislation is not achieved. The main points of attention are related to doors, glazed partitions and penetrations for ducts, cables and pipes. These are often shortcomings with respect to both performance levels.

It can be concluded that mistakes during construction and maintenance works have the largest influence on the failure of compartmentation systems. The severity of these shortcomings is generally limited, but these shortcoming are very often found in buildings, and therefore roughly half of the probability of fire spread is caused by shortcomings caused during the construction of the building and maintenance works. Many of these shortcomings may be prevented by creating more awareness about the importance of it. It can also be concluded that the number of shortcomings which resulted from the fact that the buildings have been analysed based on the performance level of new buildings instead of the performance level of existing buildings, is relatively small (only 6% of the total number of the shortcomings) and also their contribution to the probability on fire spread is relatively small. Most existing buildings comply globally with both performance levels, but on element level, the buildings do often not comply with both performance levels.

7.9 Relation with occupancy class of the building

The analysed inspection reports consist of buildings from three different occupancy classes (nl. gebruiksfuncties): offices, industrial buildings and buildings with a meeting function. Based on the inspection reports, there are some differences between the use functions regarding the presence of shortcomings related to compartmentation, but these differences are very small. In fact there are only two types of shortcomings where the differences between the different functions are significant.

The number of compartments which exceed the maximum compartment size is lower in office buildings than in the meeting and industrial buildings (40% vs. 67% and 70%, 58% on average). The exceedance of the maximum compartment size varies from 50 m^2 to 15 000 m^2, but is in general the largest in industrial buildings. Most shortcomings related to glazing are found in office buildings (90% vs. 33% and 40%, 58% on average). An obvious reason for this is that partitioning systems with glazing are frequently applied in office buildings and not so often in meeting and industrial buildings.

Based on these (limited number of) inspection reports, it can be concluded that the shortcomings which are found in the compartmentation systems in different occupancy classes are quite similar.

Since it can be concluded that most shortcomings are related to passages and links between compartments, such as doors, piping and ducting, the performance will generally be better in buildings where these passages and links are not necessary. For example in dwellings and apartment buildings the probability of fire spread will be smaller, since there are no doors between the compartments and the building services are usually decentralized, and therefore there is less need for ducting and piping between compartments in these buildings.

7.10 Conclusions

All 27 buildings (6 meeting buildings, 11 offices and 10 industrial buildings) which have been inspected on behalf of the Dutch Government Building Agency (nl. Rijksgebouwendienst, RGD) have multiple shortcomings in their fire compartmentation system, i.e. the compartmentation systems do not comply with the applicable legislation. Most shortcomings which have been found are related to ducting, piping and doors. In fact, 88% of all the inspected buildings has one or more shortcomings related to ducts and piping, and 92% of the inspected buildings has one or more shortcomings related to doors. Other frequent shortcomings are related to glazing, compartment size, walls and floors. The fire resistance of the loadbearing structure is sufficient in most buildings or it was not possible to check the loadbearing structure based on visual inspection.

For compartmentation systems, 60 minutes fire resistance is taken as the reference value (Building Decree 2012, performance level for new buildings). Elements with a fire resistance of for example 30 minutes (which is in compliance with the performance level (>20 min.) for existing buildings) are therefore also included in these figures as shortcomings. As a result, it can be determined to what extent the existing buildings comply with the performance level of new buildings. It is found that all buildings globally comply with both performance levels, but on element level, the buildings do often not comply with both performance levels.

The buildings have been checked during the inspections on compliance with the legislation, but when a compartmentation system does not comply with the regulations, this does not directly imply that fire spread to adjacent compartments will occur. It depends on the type and characteristics of the shortcoming and the fire conditions how a particular shortcoming will affect the performance of a compartmentation system in case of fire. Also there is a difference between the classification (test) criteria according to legislation and fire spread in reality. Failure of a compartmentation system is in this case therefore considered as the event which leads to the ignition and fire propagation in the adjacent compartment.

In order to classify the shortcomings based on their severity, the shortcomings have been divided into five categories (I to V). Shortcomings in the first category will lead to fire spread to the adjacent compartment within 5 minutes after the fire has reached its location, second category shortcomings will lead to fire spread in 5 - 15 minutes, third category shortcomings will lead to fire spread within 15 to 30 minutes, fourth category shortcomings will result in fire spread in 30 – 60 minutes and shortcomings in the fifth category will not lead to fire spread within 60 minutes. Possible efforts of for example the fire brigade to prevent fire spread are neglected, it is assumed that a fully developed fire occurs in the fire compartment with a duration of at least 60 minutes and the compartmentation is the only means to prevent fire spread to the adjacent compartments within the building.

Not every shortcoming can directly be appointed to one of the five categories, therefore a distribution is made to get some insight in how likely it is that a particular (group of) shortcomings will lead to fire spread within the given time intervals, taking into account the range of different shortcomings which are assigned to one group and for example the presence of combustibles close to the location of the shortcoming which can ignite due to the shortcoming and initiate fire propagation in the adjacent compartment.

Eleven RGD inspection reports provide a rough quantification on how often a particular shortcoming has been found in a compartment. With these figures, it has been determined what the probability of I to V shortcomings is in a compartment. After this rough quantification of the probability and severity of different shortcomings, the next step was to determine the probability of fire spread from the fire compartment to adjacent compartments.

According to the collected figures and the assumptions, on average 6% of the compartments will fail within 5 minutes after the occurrence of a fully developed fire, 36% will fail within 15 minutes, 56% within 30 minutes and 67% of the compartments will fail within 60 minutes. It should be noticed that t = 0 starts at the moment that the fire has reached the location of the shortcoming. For this analysis it was assumed that the presence of shortcomings is independent. Also other effects, like failure due to other aspects than compliance with legislation are not incorporated, but can have significant influence on the fire performance of compartmentation.

The fire development in the compartment influences the probability of fire spread. For instance the occurrence of flashover and the fire severity and duration, influenced by for example the fire brigade is of eminent importance. When the results of this analysis are compared with figures from practice, these influences should be incorporated. The following aspects can reduce the probability of fire spread to adjacent compartments:

- The fire brigade can prevent fire spread. The longer the fire is kept inside the compartment, the more likely a successful fire brigade intervention becomes.
- The shorter the fire duration (low fire load), the smaller the number failure modes, since fire spread due to many shortcoming becomes more likely with an increasing fire duration;
- A fully developed fire in an entire compartment is unlikely in many buildings. The presence of subcompartments will for example reduce the probability of fire spread, since it takes longer before a fully developed fire occurs in the fire compartment and the occurrence of a fully developed fire gets more unlikely.

Of course, there are also some aspects which will lead to a larger probability of fire spread:

- Elements in a compartmentation systems which do comply with legislation and have the right certification can fail and cause fire spread, since these elements have a certain deviation in their performance due to for example imperfections or other unforeseen factors. Different elements in a partition also have a different reliability. For example, a fire door in a concrete wall which has the right certification, is still the weakest point in this wall with a certain unreliability. Moreover, these elements are classified according to standard fire conditions, and not according to real fire conditions (this might have a positive as well as a negative influence, dependent on the real fire conditions in the compartment);

- High fire load and a high fire intensity;
- Rapid fire spread in the compartment, whereby a large part of the compartment's enclosure is exposed to the fire in an early stage.

The Nibra research on high damage fires in 2001 shows that compartmentation did not function in 44% of the buildings which have been constructed before 1992 (the year of the introduction of the first national Building Decree). When a fire duration of less than 30 minutes is assumed, this figure is in order of magnitude comparable to the figure found in the analysis of the RGD reports (56%). In case the compartmentation did not function, the Nibra researchers mainly attributed this to non-technical issues like blocked or removed fire doors. The analysis of the RGD inspection reports confirm that many shortcomings are present in compartmentation systems and that fire spread between compartments due to these shortcomings is likely in many cases.

In the Nibra research it was found that buildings which are constructed after the introduction of the Building Decree in 1992 perform much better in case of fire: 83% of the fires was kept inside the fire compartment against 56% in the buildings constructed before 1992. The analysis of the RGD inspections reports does not confirm nor explain a possible difference in performance of buildings constructed before 1992 and after 1992. Severe shortcomings appear to be present in buildings of all ages. A possible explanation of the differences in performance found in the Nibra research is that many of the buildings constructed after 1992 (approximately 25%) was less than one year old when the fire occurred. Less changes and adjustments to the compartmentation systems are to be expected in those relatively new buildings. This implies that most shortcomings appear in the years after construction.

Most shortcomings (67%) are caused during the construction of the building and maintenance works and are mainly related to ducts, piping and cables. These shortcoming do generally not result in a high probability of fire spread, but since these shortcomings are very frequently found in buildings, the contribution of these shortcomings on the failure of compartmentation systems is relatively large (approximately 50% of the total probability of failure). Also the lack of maintenance has a significant contribution on the failure of compartmentation system. Shortcomings related to the change of regulations and the analyses of the buildings based on the required performance level for new buildings, does only have a small influence on the failure probability of compartmentation systems. Since most shortcomings are related to passages (doors) and other links (ducting and piping) between compartments, the performance of buildings where these passages and links are not necessary can be expected to be better.

It can be concluded that the probability of fire spread to adjacent compartments is rather big in most buildings due to the presence of shortcomings. Based on the analysis of the RGD inspection reports, there is not a clear relation between the presence of shortcomings, the occupancy class (nl. gebruiksfunctie) and the age of the buildings. Many shortcomings are not related to the required fire resistance rating of a compartmentation system, i.e.

components which do not comply with the 60 minutes requirement (performance criterion for new buildings) do often also not comply with the performance criterion for existing buildings (20 minutes fire resistance against fire spread). Problems with self-closing doors and problems related to ducts are examples of this. Also the opposite is true, for example concrete of masonry walls do generally comply with both the performance level for new buildings and existing buildings. This implies that increasing the required fire resistance rating of compartmentation will not necessarily improve the fire performance in practice due the presence of many shortcomings on element level. It can also be concluded that the majority of buildings analysed in this research does not meet the required performance criteria, neither the performance level for existing buildings as the performance level for new buildings.

8 Conclusions, recommendations and future research

This thesis focusses on the performance and reliability of compartmentation systems and its adequacy for its envisaged objectives. This research was mainly of an exploratory character, since too little information and knowledge is currently available about the performance of fire compartmentation and its importance for the safety of people and property for an in-depth analysis. Due to the exploratory character of this research, many conclusions are based on assumptions and a limited amount of evidence/indications. Further research and data collection is therefore necessary to increase the assurance of these conclusions. The main conclusions, recommendations and recommendations for future research are presented in this section.

8.1 Conclusions

In this section the main findings of this research are presented. First the major findings of this research are presented, while the following sections give a more detailed presentation of the findings followed by a final conclusion in which the main research question is answered. The main findings of this research are:

- Shortcomings in design, construction and maintenance seem to reduce the performance of compartmentation systems strongly in the analysed buildings, no matter what the original fire resistance rating of the compartmentation system is;
- Many shortcomings related to compartmentation occur during construction of the building or are a result of maintenance and modification works and are found in the vast majority of the analysed buildings. Solutions for this problem should mainly be found in creating more awareness about the importance of compartmentation systems and legislation among stakeholders;
- Given the many shortcomings found in buildings analysed in this research, the implementation of compartmentation systems is currently unsatisfactory;
- No fatalities are in practice attributed to insufficient performance of compartmentation systems in office, meeting and industrial buildings as considered in this research, although the performance is often worse than intended. Improving the quality and (therewith) the actual performance of compartmentation compared to the modern day standard will probably not lead to a lower fatality rate in these buildings;
- Improving the quality and (therewith) the actual performance of compartmentation compared to the modern day standard might reduce property damages in a building in case of fire, but it should be investigated what exactly the nature and causes of fire damages are (smoke and/or flames, in relation with failure of compartmentation and occupancy class);
- It is uncertain what the performance of compartmentation systems is in practice, since little research has been carried out on the actual performance. Shortcomings are main causes when premature failure of compartmentation occurs. Whether shortcomings are the main cause of failure of compartmentation systems and what the influence is of other factors (scatter in performance, fire conditions, interaction between elements etc.), should be investigated in real building fires;

- The robustness of compartmentation systems (i.e. the ability to deal with circumstances different from anticipated) seems to be quite poor, since when one or more important elements in a compartmentation systems are not properly constructed, installed, maintained or used, it strongly affects the performance of compartmentation in case of a fully developed compartment fire. In addition, compartmentation is vulnerable for improper construction, wrong use and bad maintenance. On the other hand, when compartmentation is considered as part of the entire fire safety system in buildings, the robustness seems to be sufficient, since when compartmentation performs (much) worse than intended, the consequences for human safety appear to be limited considering the available statistics about fire casualties in the last decade;
- A lack of information from actual building fires (both for evacuation and performance of compartmentation systems) is hindering further optimisation of fire safety regulations and design methodologies. Conceptual judgement by skilled engineers is therefore currently the best available method for designing buildings beyond the boundaries of legislation.

The main findings from the literature review and the analysis of building inspection reports are presented in the next sections. Recommendations and recommendations for future research are given afterwards.

8.1.1 Legislation for compartmentation

First the general rationale behind the current building legislation is investigated, and how this is applied on the requirements for fire compartmentation.

The main objectives of fire compartmentation are:

- Prevent or limit fire spread within the building[22] and maintain the integrity of the separating function of the building for a sufficient period of time. This provision aims to increase the time available for escape, protect escape routes, facilitate fire fighter access during rescue operations, limit the area of possible loss, reduce the impact of the fire on the structure, separate different occupancies, isolate hazards and contain releases of hazardous materials[23].

The means prescribed to achieve these objectives are:

- The building is divided into fire enclosures (i.e. compartments) with barriers (walls and floors, i.e. compartmentation) which keep the fire in the enclosure in which the fire originated.
- The maximum compartment size and the fire resistance of compartmentation is prescribed depending on the function and type of the building;

[22] In this research only fire compartmentation within one building with multiple compartments is considered, so fire spread to adjacent compartments in buildings which are on a distance from the parcel where the fire originated is not considered.
[23] Casualties and property damages are in this research used as main benchmarks to measure the achievements of fire compartmentation.

- Fire compartmentation is classified based on the fire endurance of compartmentation in standard fire conditions and failure criteria which are intended to be a conservative (i.e. safe) approximation of fire spread in reality and are based on international consensus;
- The size requirements for compartments and the fire resistance requirements for compartmentation are depending on the function of the building, and whether or not it concerns a new or an existing building.

The following can be noted about the rationale behind these prescriptive requirements:

- There is no well substantiated reasoning behind the fire safety legislation, which resulted in arbitrary values. The general idea behind the requirements is evident, but how this is translated into quantifiable requirements is unclear. Due to a lack of knowledge and the fact that many changes have been disaster-driven, based on past-experience and consensus among stakeholders, an integral risk assessment is generally missing. As a consequence, it is not known how compartmentation exactly contributes to the safety of people and property.

8.1.2 Actual performance of structures and compartments

A literature review has been carried out on the performance of structures and compartmentation in real building fires. It was investigated what aspects are important for the fire performance of compartmentation. More research on the presence of shortcomings has been carried out afterwards.

The following main factors affect the difference between actual performance and the intended (design) performance level of compartmentation:

- The performance of compartmentation is determined based on standard fire conditions and performance criteria. The actual fire conditions in real buildings are different and are depending on many different factors, this introduces uncertainty in the performance of compartmentation systems;
- Besides the differences in fire conditions, other factors such as size effects and (restrained) deformations have influence on the performance of compartmentation when not properly designed;
- The construction quality in buildings is often lower than envisaged, i.e. the construction, assembly and maintenance in not properly executed. In fact, 92% of the analysed buildings has one or more shortcomings related to doors and in 88% of the building one or more shortcomings have been found related do ducting and piping. Many buildings (± 50%) contain shortcomings which can lead to premature failure of shortcomings in an early stage (< 15 min.).

The following can be concluded about the performance of compartmentation in actual building fires based on the available information:

- In researches on high damage fires in 2001 it was found that compartmentation was in many situations (±35% on average) not sufficient or of insufficient quality to prevent fire spread between compartments in the building;

- When premature failure of compartmentation occurs, bad construction, wrong use or lack of maintenance are frequently mentioned as main causes;
- In general, the performance of compartmentation is only investigated in fires which are noteworthy for other reasons, such as considerable property damages or fatalities. Only cases in which failure occurred are generally investigated and/or reported, therefore little attention is paid to the cases in which compartmentation functioned well. This may create a one-sided view. Moreover, the available information and knowledge about the performance of compartmentation in actual building fires is very limited.

8.1.2.1 Research on the presence of shortcomings in compartmentation and their influence on the performance of compartmentation systems

The performance of compartmentation seems to be affected by a bad quality of construction, design mistakes, wrong use and lack of maintenance. To check this hypothesis, inspection reports have been used to get insight in the presence of shortcomings (i.e. elements in a compartmentation system which are not properly designed, executed or used and the compartmentation system does therefore not comply with the legislation as prescribed in the Dutch Building Decree) and it is estimated what the effect is of these shortcomings is on the performance of compartmentation. The analysed reports contain buildings with an industrial function, meeting function and offices of different ages. These inspection reports are provided by the Dutch Government Building Agency (nl. Rijksgebouwendienst, RGD), but it is presumable that these inspection reports are representative for most other similar buildings in the Netherlands, as confirmed by expertise from experienced fire engineers/investigators.

Based on the inspection reports of the RGD, the following conclusions can be made about the presence of shortcomings:

- Many shortcomings are present in the analysed buildings. Most shortcoming are related to ducting, piping, cables and fire doors. Shortcomings related to these aspects are found in almost all inspected buildings (relatively in 88 and 92%). In buildings where these 'linking' elements (which are usually essential) between compartments are not applied, less shortcomings will generally be present and therefore the performance will probably be better;
- The maximum compartment size is exceeded in many buildings (±60% of the analysed buildings) relative to the applicable legislation for new buildings[24];
- The majority (±70%) of shortcomings in compartmentation systems is caused during construction, maintenance and modification works;
- No clear relation between the presence of shortcomings and the occupancy class (nl. gebruiksfunctie), age and type of building can be distinguished based on the limited number of analysed buildings.

[24] The buildings have been inspected with respect to the requirements for new and existing buildings, for which different requirements are applicable in the Netherlands. When applicable, the required performance level for new buildings has been chosen as reference.

The following conclusions can be made about the influence of shortcomings on the performance of compartmentation:

- The presence of shortcomings has a strong influence on the performance of compartmentation. The probability of fire extension to adjacent compartments due to the presence of shortcomings within 30 minutes is estimated to be 40 – 60% in the analysed buildings when fire brigade intervention or extinguishment by other means are neglected. This figure is in order of magnitude similar to the figures found in other studies on the performance of compartmentation.
- There is a relatively large probability that fire spread in an early stage (< 15 minutes) will occur due to presence of shortcomings. This probability is estimated to be 30 – 40%. Important factors are: not self-closing doors, missing panels or glass, glazing with insufficient fire resistance rating, no fire dampers in ducts and penetrations for ducting and piping which are not properly sealed (because the latter two are very often present in the analysed buildings).

The inspection reports are performed by different inspection agencies, with different insights and precision and many similar shortcomings have slightly different characteristics. This made it necessary to divide the shortcomings which are found in the reports into quite arbitrary groups. Moreover only shortcomings are reported (which is logical considering the purpose of these inspections), when particular elements are correct, this is not reported, therefore it is mainly reported how bad it is and not how good it is.

The effect of the presence of shortcomings on performance of compartmentation is based on (intuitive) judgement/estimation by fire engineers since little information is available on the circumstances and characteristics of shortcomings. Also there is no information available to verify the results of the analysis.

8.1.3 The adequacy of compartmentation for its envisaged objectives

It is tried to figure out what is achieved in the current building practice by applying compartmentation in terms of casualties and property damages. As far as possible based on the available information, it has been investigated what the importance of compartmentation is for the prevention of casualties and property damages.

The following can be concluded about the occurrence of casualties in building fires and its relation with fire compartmentation:

- The majority (±85% on average in 2001 - 2008) of fire casualties occurs in dwelling fires. The probability of casualties in a dwelling fire is approximately eight times higher than in any other building type;
- The occurrence of fatalities in building fires is in general not related to or attributed to fire compartmentation. The current performance of compartmentation against fire spread in real building fires is therefore sufficient to prevent casualties in practice, although the performance is in practice often worse than intended.

The following can be concluded about the occurrence of fire damages and its relation with compartmentation:

- Financial fire damages (both direct and indirect losses) show an increasing trend, mainly due to market technical issues (both for insurers as for insured parties), the nature of goods (high-tech and vulnerable goods and equipment) and the use of more complex buildings with multiple functions. The highest direct financial damages per fire occur in industrial buildings, shopping malls and school buildings;
- For the protection of property it is important to limit the extension area of fire and smoke (smoke can potentially result in large damages);
- In research on fire damages in the UK it was found that probability of fire occurrence per m^2 and fire damages are under proportional with the compartment size, however this is not confirmed or disproved by other researches.

In general, only the cases in which a building fire lead to high damages or fatalities get attention and are investigated and reported. Situations with relatively small consequences are generally not reported. The same holds for fire compartmentation, in cases where it performed sufficient (even when the performance was questionable and/or critical) are generally not reported. This might result in a one-sided and possibly too negative view, since the cases in which compartmentation played an important role and was successful for the prevention of casualties or damages are not reported. The safety margin between the available safe egress time (ASET) and the required time for building egress (RSET) is therefore uncertain in practice, but there are no indications found in statistics and reference researches on fire casualties and fatalities that the contribution of compartmentation to this safety margin is critical or near to critical. It can only be concluded that in fires investigated in reference studies, the occurrence of fatalities was not attributed to insufficient performance of compartmentation in those particular cases.

8.1.4 Effectiveness of legislation and policies for compartmentation

Considering the actual performance of buildings in case of fire, a number of conclusions can be made about the current compliance level with legislation and policies regarding fire compartmentation.

The following can be concluded about the effectiveness of compartmentation for the prevention of casualties:

- In building fires where fatalities occurred which have been investigated (see section 4.4), the importance of compartmentation for human safety is limited. Most casualties are attributed to the rapid fire and smoke development in dwellings. For a reduction of fire casualties it would therefore be effective to focus on the fire development and smoke production in dwellings, for example by setting requirements for the reaction to fire of furniture;
- The cases in which casualties were prevented by compartmentation are not recorded (since casualties did not occur). Also more disastrous fires with multiple deaths which are thoroughly investigated, are (fortunately) very rare in the Netherlands. It is therefore hard to determine what the importance of compartmentation and its performance in practice is for the safety of people. The margin between the available building egress time and the required building egress time is in practice apparently sufficient to prevent fatalities, even though the quality

of compartmentation is in many cases worse than intended. It is uncertain how big this safety margin is in different building functions.

The following can be concluded about the effectiveness of compartmentation for limiting property damages:

- For damage prevention, compartmentation should function as long as property outside the fire compartment is endangered by the fire. The latter seems to be difficult, since fire spread occurred in approximately 40 – 50% of the buildings where compartmentation was relevant (constructed before 1992) according to the Nibra research. Especially when larger fire durations are considered, the presence of shortcomings make it very likely that fire compartmentation will not succeed in keeping the fire inside the compartment where the fire originated. For this purpose, the quality of compartmentation system should be very high, or possible failure of the compartmentation systems should be considered in the design of the building;
- To design an efficient and cost-effective compartmentation system for damage prevention in non-standard buildings, it is necessary to consider the content (euro/m^2), the performance and reliability of compartmentation (and possible failure of compartmentation due to high fire severity, long fire duration, elements in compartments which can destroy compartmentation (e.g. collapsing steel racks)), possible property damage due to smoke, risk reducing measures such as sprinklers and the probability of fire occurrence, possibly supplemented with function specific fire prevention measures. The owner (and its insurer) should determine a tolerable damage level, for example based on economical optimisation of the total costs.

The following can be concluded about the extent to which compartmentation complies with the intended quality level:

- The quality of compartmentation systems is generally worse than intended: all of the analysed buildings do not comply with the applicable legislation and approximately 50% of the buildings contain shortcomings which can lead to premature failure of compartmentation within 15 minutes. This has probably strong influence on the actual performance level of buildings;
- The presence of many shortcomings reduces the effectiveness of both low-standard and high-standard compartmentation systems, since the presence of shortcomings often seems to be governing for the performance of compartmentation. Since many shortcomings are not related to the intended performance level, even high-standard compartmentation systems may fail in an early stage due to the presence of shortcomings;
- Many shortcomings have a ‘human’ cause (i.e. the human factor). Many shortcomings are caused by errors in construction and assembly (±60 – 70%). Many systems are very vulnerable for mistakes, wrong assembly, wrong use and lack of maintenance;
- One of the main factors contributing to the occurrence of mistakes is a lack of awareness about the importance of proper fire compartmentation and knowledge

about fire compartmentation among people who are responsible for structural facilities in buildings (nl. bouwkundige voorzieningen).

8.1.6 Final conclusions

The main research question was posed at the beginning of this research:

What is the actual performance and reliability of compartmentation systems against fire spread and what is in practice achieved by applying fire compartmentation?

Considering the findings of this research, the answer to this research question is as follows:

- In the buildings considered in this research (industrial, meeting and office buildings), the performance of compartmentation systems is often worse than intended. Shortcomings are present in most buildings, and it appears that these shortcomings have a strong influence on the performance of compartmentation systems. These shortcomings can cause fire spread between compartments in an early stage (< 15 min.), reducing the reliability of compartmentation (i.e. a relative large amount of compartments (30 - 40%) will fail in an early stage);
- In many building fires (40 – 50%) where fire compartmentation was relevant, the performance of these systems is insufficient to prevent fire spread to adjacent compartments;
- Data about the performance and reliability of compartmentation in real building fires are currently very limited. The same holds for what is actually achieved by applying compartmentation;
- Casualties are generally not attributed to bad performance of compartmentation, especially not in the buildings considered in this research (industrial, meeting and office buildings). The prevention of damages by limiting the maximum extension area of a fire seems to be the most important purpose in these buildings, but also the relation between fire damages and the performance of compartmentation is uncertain.

It can be concluded that it is complicated to determine the performance and reliability of compartmentation and its usefulness for the safety of people and property. Not only because many factors influence the performance of compartmentation and the occurrence of casualties or damages, also because very little well-structured data and information is available from practice. Little fires have been investigated and reported, therefore little information is available about the failure modes of compartmentation and how critical its performance is for the safety of people, but considering the available statistics it is not probable that this safety margin is currently critical.

For the legislator it can therefore be concluded that (when prevention of fatalities is the main objective):

- Considering the fact that no fatalities are attributed to insufficient performance of compartmentation, it is not necessary to require high fire resistance ratings (more than 30 minutes) in the mainstream of industrial, meeting and office buildings;

- Considering the number of buildings which contain shortcomings which strongly affect the performance of compartmentation, better control and enforcement of the current requirements is necessary to make compartmentation more effective;
- It is questionable if regulatory changes or simplifications will improve the implementation of compartmentation, solutions for this should be found in creating more awareness about the importance of compartmentation and the legislation in the building industry and enforcement of the legislation.

For building-owners/insurers it can be concluded that:

- It should be noted that investments in high-standard (e.g. 60 minutes fire resistance or more) compartmentation systems for limiting fire damages are inadequate, if compartmentation is not regularly checked and maintained. Also the uncertainties in the performance of compartmentation system should be considered, especially when larger fire duration and fire severities are to be expected, these uncertainties become larger and there is definitely no guarantee that fire compartmentation systems are able to prevent fire spread to other compartments. This should be taken into account when priorities are set on the budget for compartmentation and its maintenance. More attention and budget for correct assembly and maintenance of compartmentation subsequently or instead of investments in high-quality systems which are poorly maintained during the exploitation phase of the building is more cost effective and makes compartmentation more effective.

8.3 Recommendations

Regarding the many uncertainties in the performance of compartmentation, the presence of many shortcomings in compartmentation and the uncertainty about the contribution of compartmentation for life safety and safety of property, improvements can be achieved in design and construction of compartmentation as well as in building legislation to make compartmentation more effective. Most buildings do not comply with the current legislation and standards for compartmentation, even new buildings are no exception. Still, the consequences of not complying with the legislation seem to be limited: generally no casualties can be attributed to bad performance of compartmentation, while the performance of compartmentation is often worse than anticipated. In many cases this can be attributed to the presence of shortcomings in compliance with legislation and standards.

The following recommendations are made:

- Improve the performance of compartmentation systems in practice by reducing the presence of shortcomings, not by raising the required performance level, since the difference between the required performance level and the actual performance level seems to increase with increasing required performance level due to the presence of shortcomings. Control and inspection should be intensified for this purpose;
- Consider the unreliability of different compartmentation systems in design and in the organisation of building evacuations and do not rely on high fire resistance

ratings, especially not when the compartmentation system is not regularly checked and maintained;

- The main stakeholders should be informed about the possible consequences of not having suitable constructions to limit fire spread and inform them about the legislation;
- Set up a database in which information about the performance of compartmentation in actual building fires is systematically collected. This information can be used for future research.

Several means are prescribed to achieve the objectives of fire safety regulations, among which requirements for compartmentation, but it is not known how compartmentation exactly contributes to the realization of these objectives. It is furthermore uncertain how compartmentation performs in reality. The aim of future research should be on getting these aspects more clear. Creating a database with relevant and sufficiently detailed information about actual building fires can help to learn from practice and improve the design of fire safety systems and regulations.

Also it should be found out what a reasonably (and practically) achievable fire resistance is for compartmentation in actual building fires, so that the risk of premature failure of compartmentation is reduced and/or can be taken into account in design, both for the purpose of human safety as for the safety of property.

8.4 Future research

In the design of compartmentation, there are many uncertainties and there is a lack of knowledge on the actual performance of compartments as well as their contribution to the safety of people and the protection of property, in which also human behaviour is an important aspect.

More research on the performance of compartmentation and its importance for human safety and safety of property is therefore recommended. The following issues for future research are recommended:

- Research on the performance of compartmentation in actual building fires: how often does fire spread occur in building fires? If fire spread to adjacent compartments occurs, what are the main failure modes (when traceable) and how long does it take before failure of compartmentation occurs? What is the difference between the intended fire resistance and the fire resistance in practice? Was fire spread prevented by fire brigade intervention?
- Research on fire conditions: what was the fire duration of the compartment fire?
- Research on property damages: what was the cause of fire damages (damages due to smoke and/or fire) and how does this relate to the building type and occupancy class?
- Research on building evacuation: how much time does it take in practice to evacuate buildings?
- Research on the presence of shortcomings and how to prevent or reduce the presence of these shortcomings.

It should be noticed that it takes a long time to create an extensive database in which the performance of compartmentation in actual building fires is systematically recorded. Moreover it needs the co-operation of for example fire investigators, insurers and emergency services such as the fire brigade etc. and is this undermines the feasibility of such a database. On the other hand, a lot of investments are currently required in fire compartmentation, while the usefulness of these investments is uncertain. Further research can therefore certainly be profitable for many stakeholders.

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Appendix I – Description of the observed shortcoming in the RGD fire scans

In this appendix the shortcoming as observed in the RGD fire scans are specified with a brief description and when possible, an example is given from one of the inspection reports by means of a photo.

	Shortcoming	Description	Example
1.1	Compartments larger than allowed in BD2012[25] without demonstrated equivalent solution		
1.2	Technical rooms >50m^2 not in separate fire compartment	Due to the higher fire risk, technical rooms >50 m^2 need to be in a separate fire compartment.	
2.1	Fire resistance façade insufficient	If the fire resistance of the façade is insufficient (for example glass in the façade is not fire resistant), fire spread to adjacent compartments can occur via the façade, both in horizontal direction as in vertical direction. The fire resistance is classified as insufficient if the resistance against fire spread is less than 60 minutes (BD2012). In the RGD inspection reports only fire spread to other compartments within the same building is considered.	

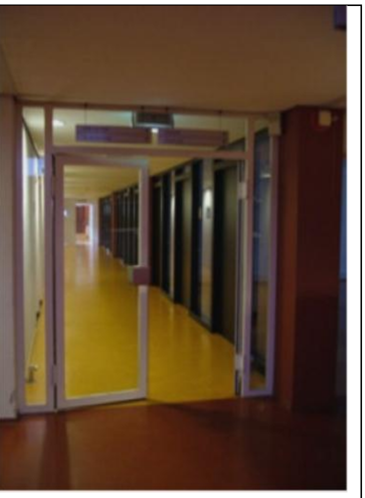
[25] BD2012 is an abbreviation for Building Decree 2012

3.1	Penetrations not sealed	The space around penetrations in compartment walls and floors for ducts, pipes and cables needs to be sealed off to prevent fire spread to the adjacent compartment. It involves penetrations for ducts of various dimensions, single cables or bundles of cables. In general, the larger the gap size, the worse the situation.	  
3.2	No fire dampers (nl. brandkleppen) in air ducts	In addition to a proper sealing around ducts, ducts also need to be closed internally by a fire damper in case of fire to prevent fire spread via the duct.	
3.3	No fire resistant casing around ducts	The section of the duct between the fire damper and the fire wall needs to be protected by an insulating material to prevent failure of the duct in this section.	
3.4	Mounting of pipes and ducts not sufficient	Pipes and ducts need to be properly fixed, in order to prevent collapse in case of fire due to strength loss of the materials, causing an opening in the wall.	

4.1	Fire resistance of wall insufficient or not proven (glass blocks)	Wall sections have insufficient resistance to prevent fire spread to adjacent compartments for a 60 min. time duration (BD2012). Examples are glass blocks (photo) or missing gypsum board on one side of a metal stud wall.	
4.2	Panel or glass is missing (holes)	There is a hole in the wall caused by missing or damaged elements. For example the window above a door is missing (nl. bovenlicht). Dependent on the size of the hole, fire spread will occur in an early stage.	
4.3	Fire resistant separation not continued above suspended ceiling	The fire wall is not continued above the suspended ceiling, therefore there is an opening between the lowered ceiling and the loadbearing floor.	
4.4	Steel structure penetrating fire separation without fire resistant covering	The steel structure continues through a fire wall, and is therefore conducting heat from the exposed site to the non-exposed side of the wall or floor.	
4.5	Fire separation in roof structure is not properly finished	Fire spread occurs via the roof structure.	

4.6	Steel hatch in wall/floor	A steel hatch is used in the fire wall or floor and in case of fire this hatch will conduct heat.	
4.7	Floor structure not sufficient fire resistant	Floor structure has insufficient fire resistance to prevent fire spread to another building level for a specified amount of time (BD2012).	
5.1	Large areas of wired glass in fire separations	Large areas wired glass do not provide sufficient fire resistance. Wired glass will retain its integrity for a certain amount of time, but the radiation level on the non-exposed side can be very high.	
5.2	Fire resistance glazing insufficient	Glazing which does not have and certain fire resistance rating and is not reinforced with a wire mesh, will break quickly when it is heated.	
5.3	Glazing beads missing	Glass panels are not fixed properly and might fall out of its frame, because some of the glazing beads are missing or the panel is kept in place with some nails.	
6.1	Doors not self-closing	Doors in fire walls do not close in case of fire because these doors are blocked or the door closer does not function or is missing. When fire doors are not closed in case of fire, immediate fire spread will occur after flashover. It should be noticed that not all doors	

		which are not self-closing, are open in case of fire.	 
6.2	Doors not certified	Doors lack any certification and therefore it is unknown what their performance will be in case of fire.	
6.3	Intumescent strip (nl. opschuimende band) missing	Intumescent strips will close off the gaps around doors in case of fire. When these strips are missing, fire might spread via these gaps.	
6.4	Doors do not close properly	Doors cannot close properly for several reasons, for example because the doors jams on the floor or the door lock does not function or is missing.	

6.5	Glazed partition (nl. puiconstructie) not certified	A glazed partitioning system does not have the required classification or is not composed in compliance with the assembly instructions.	
6.6	Steel door frame with insufficient fire resistance	Steel door frame is for example hollow and does therefore not have sufficient fire resistance.	
6.7	Rebate depth (nl. sponningsdiepte) time door frame insufficient	The rebate depth of the door frame is insufficient to prevent burning through for a certain amount of time.	
6.8	Door pin (nl. deurnaald) is not fire resistant	The door pin is not fire resistant and therefore the door will open during the fire. Door pins are used to fix double doors in its frame.	
6.9	Too large gaps around door	The gaps are too big around the doors, and therefore flames can pass between the door and the door frame and/or floor.	
7.1	Fire resistance of loadbearing structure unknown	There are no documents/calculations available that show the fire resistance of the loadbearing structure. Based on visual inspection it is not possible to	

		assess the fire resistance.	
7.2	Fire resistance of loadbearing structure not sufficient	The fire resistance of the loadbearing structure is insufficient based on visual inspection.	

Appendix II – Division of shortcomings based on their severity

The probability of fire spread due to a specific shortcomings as defined in Appendix I, depends on different aspects. The characteristics of the shortcomings (gap size, configuration) are of eminent importance for the fire performance and the probability of fire spread to adjacent compartments. The different characteristics of the shortcomings which are assigned to the same group should therefore be incorporated in order to determine the severity of a particular group of shortcomings.

To incorporate the effect of the characteristics of shortcomings within one group on the severity of the shortcomings, weighing factors are determined based on expert judgement. A more sophisticated division of shortcomings is currently not possible for this purpose. The explanation of these weighing factors is given in this appendix.

	I	II	III	IV	V
Fire resistance façade insufficient	**0%**	**0%**	**40%**	**40%**	**20%**
	0%	**10%**	**30%**	**40%**	**20%**
When the façade offers insufficient fire resistance against fire spread, immediate fire spread within 15 minutes is very unlikely, since a façade will always offer some resistance against fire spread. In some cases fire spread via the façade will occur in 15 – 30 minutes, for example when the fire is intense and the windows get broken. When the façade does not have sufficient fire resistance according to the legislation, this will in practice not always lead to fire spread within 60 minutes.					
Penetrations not sealed	**0%**	**10%**	**20%**	**50%**	**20%**
	0%	**10%**	**10%**	**20%**	**60%**
When a penetration is not properly sealed, the occurrence of fire spread depends on the dimensions of the gap, the fire intensity and the presence of combustibles on the non-exposed side of the fire wall. When the size of the gaps are very small, fire spread to the non-exposed side is very unlikely. When the gap size increases and there are combustibles on the non-exposed side, fire spread becomes more likely. In this case fire spread might already take place within 15 minutes, but this is not very likely. When no combustibles are present on the non-exposed side, it will take much longer before fire spread will occur.					
No fire dampers in ducts	**0%**	**10%**	**30%**	**50%**	**10%**
	0%	**10%**	**20%**	**20%**	**50%**
In case no fire dampers are installed in ducts, fire spread might occur via the ducts. It depends on the diameter of the duct how likely fire spread via the duct is. In addition, heat and flames should get in the duct (and also get out of the duct on the non-exposed side of the fire wall) before possible fire spread will occur. A duct without fire dampers will therefore always have some fire resistance against fire spread, but the longer the fire					

duration, the more likely it gets that fire spread will occur.					
No fire resistant casing around ducts	**0%**	**10%**	**20%**	**50%**	**20%**
	0%	**10%**	**10%**	**10%**	**70%**
The fire dampers are usually placed at a certain distance from the fire wall, therefore the section between the fire damper and the wall needs to be insulated with a fire proof insulation material. If this section is not insulated, this section is weakened and damaged by the fire. The probability of fire spread due to this type of shortcomings depends on the size of the ducts, the configuration and the presence of combustible materials on the non-exposed side of the fire wall. The probability of fire spread will increase with an increasing fire duration and fire severity.					
Mounting of pipes and ducts not sufficient	**0%**	**0%**	**25%**	**50%**	**25%**
	0%	**10%**	**20%**	**30%**	**50%**
Pipes and ducts should be sufficiently supported to prevent collapse of elements, causing a hole in the fire wall and making fire dampers useless. Since the duct will lose its strength gradually with increasing temperature, it will take some time before this type of failure occurs. The probability of fire spread will increase with an increasing fire duration and fire severity.					
Fire resistance of wall insufficient or not proven	**0%**	**10%**	**30%**	**30%**	**30%**
	0%	**10%**	**30%**	**30%**	**30%**
The fire resistance of a wall system can be insufficient because wrong materials are applied (glass blocks, timber sheeting), since wrong or insufficient insulation material is used or gypsum board is missing on one side of a metal stud wall. Another possibility is that the fire resistance in a particular configuration is unknown. This type of shortcoming therefore has many possible failure modes. It is unlikely that the wall will fail within 15 minutes, but there is also a good possibility that the wall fire survive a 60 minute fire duration.					
Panel or glass is missing (holes)	**10%**	**40%**	**50%**	**0%**	**0%**
	10%	**30%**	**50%**	**10%**	**0%**
When a panel is missing in a wall, this creates a hole in the wall which will cause immediate fire spread. Only when the size of the hole is small, fire spread can be prevented for a limited amount of time. This also depends on the presence of combustible materials close to the opening.					
Fire resistant separation is not continued above suspended ceiling	**10%**	**40%**	**50%**	**0%**	**0%**
	0%	**10%**	**30%**	**40%**	**20%**

When a fire resistant wall is not continued above the suspended ceiling, it depends on the fire resistance and integrity of the lowered ceiling how long it will take before fire spread to the adjacent compartment will occur. Since most lowered ceiling systems will not offer sufficient fire resistance and generally contain many holes (tl-armatures), fire spread will in the majority of cases occur within 15 minutes.					
Steel hatch in wall/floor	**0%**	**0%**	**20%**	**40%**	**40%**
	0%	**0%**	**10%**	**20%**	**70%**
It is unlikely that a steel hatch in a wall or a floor will lose its integrity during a fire. However, a solid steel element will conduct a lot of heat to the non-exposed side. Therefore fire propagation to the adjacent compartment might occur after some time. Of course, there should be some combustibles nearby the steel hatch which can be ignited due to the radiation or high temperatures. If these materials are not present, fire spread is unlikely.					
Floor structure not sufficient fire resistant	**0%**	**0%**	**10%**	**50%**	**40%**
	0%	**10%**	**20%**	**30%**	**40%**
The floor structure is not sufficient fire resistant to prevent fire spread for a sufficient fire duration. Fire propagation within 30 minutes is very unlikely, since most floor structures will in practice have a fire resistance of at least 30 minutes, but for longer fire durations this will become more critical.					
Large areas of wired glass in fire separations	**0%**	**30%**	**70%**	**0%**	**0%**
	0%	**0%**	**10%**	**20%**	**70%**
Glass will break within a couple of minutes when it is heated. The idea of wired glass is that the wire mesh keeps the glass fragments together and therefore the panel will keep its integrity for a certain amount of time. Before wired glass loses its integrity, high radiation levels can occur on the non-exposed side. Fire spread will occur when materials are ignited in the adjacent fire compartment due to these high radiation levels.					
Fire resistance of glazing insufficient	**0%**	**60%**	**30%**	**10%**	**0%**
	0%	**30%**	**50%**	**20%**	**0%**
There is an important difference between glass which does not have any fire resistant properties at all and glazing with insufficient fire resistance. When a glass panel without any fire resistant properties is heated, it will break within a couple of minutes and fire spread will occur. When glazing is applied with insufficient fire resistance, for example 30 minutes where 60 is required, it will fail after approximately 30 minutes of fire exposure. Of course, due to some deviation in fire performance it might also break after 10 minutes or 40 minutes.					
Glazing beads missing	**0%**	**20%**	**80%**	**0%**	**0%**

	0%	**10%**	**20%**	**20%**	**50%**
If some glazing beads are missing, the glass panel might fall out of its frame during the fire. This will not happen immediately, because it will take some time before the remaining glazing beads have burned away and the glass panel loses its fixation into the frame. Another possible failure mode is flames going around the glass panel, causing ignition in the adjacent compartment.					
Doors not self-closing	**10%**	**20%**	**0%**	**0%**	**70%**
	10%	**10%**	**10%**	**0%**	**70%**
If doors are not self-closing, there are several possibilities. The door can be blocked and will therefore not offer any fire resistance. The door can also remain open, and in this case the door will also not offer any fire resistance. Not all doors which are not executed as self-closing doors will be open. In this case, no problems are to be expected if the door has sufficient fire resistance. It is assumed that 30% of the doors which are not self-closing, will remain open in case of fire (based on figures from Table 16). The remaining 70% is closed.					
Intumescent strip missing	**0%**	**0%**	**20%**	**40%**	**40%**
	0%	**0%**	**10%**	**20%**	**50%**
The function of an intumescent strip is to close the groove around the door to prevent flames passing around the doors. If the strips are missing, small flames will occur around the door on the non-exposed side. Due to these flames, the groove will become bigger and after a certain amount of time (for instance dependent on the density of the timber and the fire intensity), large quantities of flames and hot gasses will pass through the groove causing fire propagation in the adjacent compartment.					
Doors do not close properly	**5%**	**20%**	**50%**	**25%**	**0%**
	0%	**10%**	**20%**	**20%**	**50%**
If the doors do not close properly, for example because the door lock is defect, the door might open up during the fire due to overpressure in the fire compartment. If the doors do not close properly because they are jamming on the floor, this will cause a permanent opening which will lead to immediate fire spread. So this type of shortcomings comprehend many different possible failure modes, the main part is assumed to cause fire spread within 30 minutes.					
Glazed partitions not certified	**0%**	**20%**	**30%**	**30%**	**20%**
	0%	**10%**	**20%**	**30%**	**40%**
Non-certified partition systems will generally provide some fire resistance. It depends on the quality of the glazing, the framing, composition and also on how it is assembled what the fire performance will be. Lacking a certification will in practice of course not always lead					

to fire spread within 60 minutes.					
Steel door frame with insufficient fire resistance	**0%**	**0%**	**30%**	**70%**	**0%**
	0%	**0%**	**10%**	**20%**	**70%**
A steel door frame will conduct heat and will also deform during fire, therefore openings may occur which allow flames and heat to pass.					
Rebate depth timber door frame insufficient	**0%**	**0%**	**20%**	**50%**	**30%**
	0%	**0%**	**10%**	**20%**	**70%**
The cross section of timber elements will decrease in case of fire due to the combustion of the material. The rebate depth should therefore be sufficient to take this material loss into account and prevent flames passing around the door. It depends on the dimensions of the rebate depth how long it will take before the rebate depth has decreased to a critical level.					
Door pin not fire resistant	**0%**	**0%**	**20%**	**40%**	**40%**
	0%	**0%**	**10%**	**20%**	**70%**
Door pins fix double doors in the door frame and prevent the door from opening. When these door pins are made of materials which are not sufficient fire resistant (aluminium), these door pins might lose their strength whereby the doors open up due to overpressure in the fire compartment. It will always take some time before the door pin is heated and loses its strength. In some cases with double doors, the doors might also stay closed due to the door closer on one of the two doors. When the doors open up, this will lead to fire spread.					
Too large gap around door	**0%**	**0%**	**30%**	**50%**	**20%**
	0%	**10%**	**20%**	**20%**	**50%**
It mainly depends on the size and the location of the gap how long it takes before fire spread occurs. When the door has a 50 mm gap at the top, than large quantities of flames and heat will pass through the gap, probably causing ignition in the adjacent compartment. When the door has a 30 mm gap at the bottom, than fire spread is less likely. Not only because the gap is smaller, but also due to the pressure distribution inside the building (air is sucked in below the neutral line, see Figure 5). When only small quantities of heat and smoke pass the door and no combustible materials are present close to the door, fire spread to the adjacent compartment is unlikely.					
Elevator doors do not close properly / have insufficient fire resistance	**0%**	**0%**	**20%**	**50%**	**30%**
	0%	**0%**	**10%**	**10%**	**80%**
When the doors of elevators do not have sufficient fire resistance, fire spread might occur via the elevator shaft. Since the access area and the elevator shaft generally do not contain					

much combustible materials, rapid fire spread within 15 minutes is not to be expected via the elevator shaft. With increasing fire duration, the probability of fire spread fire the elevator shaft becomes more likely.