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Smoke propagation in residential buildings

The main report on the field experiments conducted in a residential building with internal corridors

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Summary

Background

In recent years, the Dutch fire service has seen a rise in the number of fires in residential buildings where the actual fire is relatively limited, but there is extensive smoke propagation. A type of residential building that stands out with regard to the smoke propagation is the residential building with internal corridors. In this type of residential building, smoke can propagate to other residences through the internal corridor and can impair the escape, which is via this internal corridor, for people in many of these other residences.

Smoke propagation is thus a widely reported problem that raises fundamental questions about its consequences for fire safety, particularly for vulnerable groups, including the elderly. Therefore, limiting the smoke propagation and its effects is considered to be necessary. However, it is not yet clear which measures for risk management can contribute to significantly slower and less extensive smoke propagation. There is also still a lot of ambiguity as to how the possibilities and impossibilities encountered by the fire service during the deployment phase in order to rescue/evacuate people from a building and fight the fire affects the smoke propagation. This research therefore seeks to map the effects of smoke propagation in relation to measures for risk management and methods of firefighting on the possibility of escape and survivability in the event of a fire in a residential building with internal corridors.

The main research question of this research is:
What is the effect of smoke propagation on the possibility of escape and survivability in the event of fire in a residential building with internal corridors, and how can smoke propagation be reduced?

The effect of smoke propagation on the possibility of escape and survivability in the event of fire was examined through field experiments (19 tests) in a residential building with internal corridors.

Research results

Smoke propagation, including visible smoke propagation, in practice

In all the tests, smoke propagated outside the fire room through several horizontal and vertical routes and sub-routes. This involved both horizontal and vertical smoke propagation to different rooms in the residential building. This means that if only part of a sofa is burning in one room, high-risk situations will occur in several locations in the residential building.

This research revealed more horizontal than vertical smoke propagation. Although smoke propagation was observed in many tests on other floors, the visually observed quantities and the gas concentrations measured on these floors were lower than on the fire floor. In addition, vertical smoke propagation was less consistent than horizontal smoke propagation,

and smoke propagation was more erratic during the deployment phase than during the escape phase. It seems that, in addition to the fire service deployment, more variables and factors influence smoke propagation.

In general, smoke mainly propagates via open doors, ventilation ducts and wall sockets. Horizontal smoke propagation is mainly via doors: the highest extent of smoke propagation is visible where doors are open or when doors are opened. Vertical smoke propagation is mainly via ventilation ducts and wall sockets.

Every opening between rooms will let smoke propagate, with large openings leading to faster smoke propagation and in larger quantities. Whether smoke propagates, and to what extent it propagates, is influenced by the factors below.

- The composition of the fire object: organic or synthetic fuel. Organic fuel leads to much less smoke being produced than synthetic fuel.
- Opening doors or keeping doors closed affects the propagation of large quantities of smoke. A closed door limits the smoke propagation.
- Other openings and penetrations in the partitioning structure have a more limited effect on smoke propagation. The smaller the opening or the penetration, the less smoke will propagate.
- The presence of a mobile water mist and/or smoke resistant partition has a positive effect on reducing smoke propagation.
- The specific location of the fire room influences vertical smoke propagation.
- The fire service deployment influences the further smoke propagation as doors are opened and fans are used.

Smoke consists of solids, liquids and gases. Often, they propagate together and there will be visible smoke (soot particles and liquid particles) and invisible fire gases in the same location. However, there are situations where gases and particles propagate differently and it was found that no or hardly any visible smoke was observed in several rooms, while carbon monoxide (CO) was measured in those rooms. The opposite situation was also observed in some locations: visible smoke, without CO being measured.

The conclusion is that smoke propagates rapidly through a residential building and that smoke propagation is an unpredictable phenomenon, particularly at greater distances from the fire room. And the fact that not all smoke is visible adds to the difficulty of estimating the severity and extent of the propagation of the smoke.

The possibility of escape and survivability

Threshold values for the possibility of escape and survivability

The possibility of escape and survivability for people who are present until the moment they are rescued is determinative in preventing fire casualties. This is because it is important in a fire situation that the available safe escape time (ASET) is longer than the required safe escape time (RSET). The conditions to which people are exposed in the rooms in question, and their vulnerability for those conditions, are decisive for the available safe escape and survival time.

The conditions that influence occupants' possibility of escape and survivability in the event of fire are:
> irritant and asphyxiant gases;
> heat;
> visibility.

These fire conditions can lead to the possibility of escape being impaired, a life-threatening situation, or even a fatal situation (see the figure below).

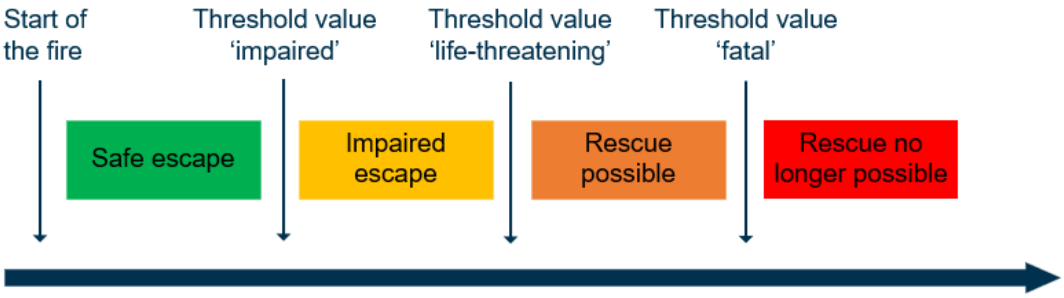

Diagram of the possibility of escape and survivability in the event fire

The threshold values where one situation transitions into another situation can be established using different standards. The methods in these standards often concern the ratio between a concentration or a dose and the limit for that concentration or dose at which the possibility of escape and survivability is threatened. The threshold values for different situations can distinguish between different groups (sub-populations), each of which has its own sensitivity factor (sf) for irritant and asphyxiant gases, heat and visibility. The groups distinguished in this report are 'general', 'vulnerable', and 'highly vulnerable'.

The effect of smoke propagation on the possibility of escape and survivability
A burning sofa will lead to a fatal situation in the fire room within 4 to 7 minutes. Almost immediately after opening the door to the fire room (t = 5 minutes), a situation will be reached in the corridor next to the fire room where the possibility of escape for people in other residences is seriously impaired, since the corridor will fill up with smoke within a matter of seconds, reducing visibility to very poor levels. The concentrations of asphyxiant and irritant gases measured in the corridor are also so high that a life-threatening situation arises, in particular for vulnerable and highly vulnerable groups.

Once the door to the fire room has been opened, people in the other residences along the same corridor are then 'stuck' in their residences. The smoke can propagate to these other residences and other corridors on the same floor. Fatal situations, particularly for vulnerable and highly vulnerable groups, can occur in these residences (where there is no fire) due to smoke entering the residences. Smoke will mainly propagate to other corridors if the doors between these corridors are opened, even if only briefly, for example by people escaping the building or trying to look into the corridor to see what is going on. This may also impair the possibility of escape for people in other residences elsewhere in the building.

Smoke also propagates to the other floors. Although, according to the analysis method used, this smoke propagation does not impair the possibility of escape, increased CO concentrations were measured on these floors.

The effect of (additional) measures for risk management on the possibility of escape and survivability

Opting for furnishing made of organic material instead of synthetic material (a foam-filled sofa) has been found to be the most effective measure to reduce smoke production, and thus smoke propagation. This makes this measure the most effective in improving the possibility of escape and survivability for all groups in all rooms. Nevertheless, if any furnishing made of organic material catches fire, and the door to the fire room is open, the possibility of escape through the corridor will also be impaired after some time (6 to 14 minutes) for all groups.

A mobile water mist system is also an effective measure of improving the possibility of escape and survivability. If the door to the fire room is left open after people have escaped from the room, the improvement created by a mobile water mist system, compared to the situation without a mobile water mist system, will be greater for the general group than for the vulnerable or highly vulnerable group. Closing the door after escaping the fire room improves the situation for all groups.

Closing the door to the fire room after escaping as an (individual) measure does not improve, or hardly improves, the possibility of escape for other people along the corridor. The possibility of escape is reduced for all groups in the corridor once the door has been opened. However, this measure does improve survivability in the other residences that do not adjoin the fire room and where the doors are closed. There is a survivable situation for all groups in the residences that do not adjoin the fire room for the first 20 minutes. This is not the case in residences adjoining the fire room or residences whose doors are open.

Applying a specific smoke resistant partition does not improve, or hardly improves, the possibility of escape or survivability compared to the situation where the (existing) door to the fire room is kept closed. While escaping, opening the door to the fire room for 30 seconds is a decisive factor in worsening the conditions in the corridor and the adjacent residences. A smoke resistant protection partition as a measure to prevent smoke propagation is more effective if the doors remain closed during the entire fire situation. A further point of consideration is that the pressure in the fire room can increase substantially, both before the door is opened (up to more than 300 Pascal) and when it is closed again (up to more than 1000 Pascal). This can lead to smoke propagating via other routes.

None of the (additional) measures for risk management tested were independently found to be able to sufficiently improve the possibility of escape and survivability for all groups in all situations. Individual measures were often found to mainly achieve an improvement for the general group, but little or no improvement for vulnerable to highly vulnerable groups.

Additional to assessing individual measures, the degree to which combinations of measures improve the possibility of escape and survivability was also examined. They are listed below, with the most effective combination listed at the top.

1) Furnishing made of organic material combined with a closed door.
2) A mobile water mist combined with a closed door or a mobile water mist in combination with a smoke resistant partition and a closed door.
3) A closed door combined with a smoke resistant partition.

The conclusion has therefore been drawn that a combination of a source and effect measure is sufficiently effective to improve the possibility of escape and survivability for all groups (options 1 and 2 from the list above). An individual effect measure or a combination of effect measures is not sufficient to improve the possibility of escape and survivability for vulnerable to highly vulnerable groups.

The deployment method

Even before the fire service takes action, the possibility of escape has often been reduced on the first floor, due to which many occupants are no longer able to escape without help. Life-threatening conditions will have also arisen in several residences. A fire service deployment (rescuing and extinguishing) is then necessary for the safety of the endangered people in the residential building.

Since smoke had already propagated outside the fire room in all tests before the deployment started, these circumstances should be assumed to be the basic situation in order for the fire service to decide how to deploy. However, the scope and severity of the situation are always difficult to determine due to the complexity of the building, the unpredictable smoke propagation situation and the fact that, if no smoke is visible, this does not mean that the situation is not unsafe for the people present. An extensive assessment of, and measuring in, the residential building is the only way to establish which residences, corridors and escape routes are safe.

Besides fighting the fire, the goal of the deployment should be to reduce any further smoke propagation as much as possible. The situation of the door to the fire room, i.e. open or closed, at the moment when the fire service arrives is decisive for determining which deployment method should be used to achieve these objectives. Where the door to the fire room is open when the fire service arrives, extinguishing the fire before rescuing was found to have the best effect on the possibility of escape and survivability. Where the door to the fire room was closed, rescuing before extinguishing the fire was found to be the most beneficial to the possibility of escape and survivability.

However, every fire service action will cause more smoke propagation, both horizontally and vertically. Walking through smoke-filled corridors, opening and closing doors and fire suppression activities are all actions that cause a certain amount of smoke to propagate to adjacent rooms. Mechanical ventilation has a dominant effect and it mostly always causes smoke, and particularly CO, to propagate further to other rooms and floors.

Measures for risk management combined with the door to the fire room being closed reduces the smoke propagation through the building during the escape phase and reduces any smoke propagation due to the fire service actions during the deployment phase.

Generalisability of the results

This research seeks to broadly map the effect of smoke propagation in relation to measures for risk management and methods of firefighting on the possibility of escape and survivability in the event of fire in a residential building with internal corridors. This is why it is important to pay attention to the generalisability – also referred to as the external validity – of the research. This external validity is constituted by:

> Ecological validity: the extent to which the research results correspond to the real-life situation.

- Generalisability of the sample: is the sample representative for the population?
- Validity of meaning: the degree to which a concept measures what should be understood by that concept or what the meaning of the concept is (exclusivity of meaning).

In this research, it was concluded that the generalisability of the sample is not high, but that the ecological validity and the validity of meaning of the research are high. Therefore, there is no reason to assume that the findings cannot be generalised sufficiently to other residential buildings with internal corridors. However, it should be noted that real-life incidents have shown that local circumstances can cause different smoke propagation patterns.

Although the results of this research provide general information about which measures have the most or least influence on the smoke propagation, they cannot simply be generalised to other building types. The only exception to this is likely to be deck access flats with enclosed walkways. Elements from the research can be used in order to answer questions about fire safety in other types of buildings, such as Dutch *portiekflat* buildings (low rise blocks of flats with communal access). This may include aspects as the effect of open or closed doors, the routes along which smoke propagates, and the effect of measures for risk management.

Answering the main question

What is the effect of smoke propagation on the possibility of escape and survivability in the event of fire in the residential building with internal corridors, and how can smoke propagation be reduced?

Practice has shown that smoke propagating outside the fire room is the norm and is definitely not an exception. During the research, smoke propagated to the rest of the building, through cracks, seams and penetrations, as quickly as two minutes after the fire started. This smoke propagation was accelerated by the door to the fire room being opened (briefly), and horizontal and vertical smoke propagation occurred almost simultaneously. This means that even a small fire can cause dangerous situations to arise in several locations in the residential building.

Smoke propagation in the residential building was found to affect the possibility of escape and survivability in the following locations:

- *Corridor adjoining the residence where the fire is*
  Almost immediately after opening the door to the fire room (t = 5 minutes), the possibility of escape for people in other residences is seriously impaired because the corridor fills up with smoke within a matter of seconds. Visibility in the corridor is so poor and the concentrations of asphyxiant and irritant gases are so high that a fatal situation arises.
- *Other residences adjoining the corridor*
  Once the door to the fire room has been opened, people in the other residences along the same corridor are then 'stuck' in their residences. Fatal situations can also occur in these other residences (where there is no fire) due to smoke entering. This particularly applies to vulnerable and highly vulnerable groups.
- *The rest of the building*
  In this research, the effect on the possibility of escape and survivability in or on other parts and floors of the building was found to be limited. However, this does not mean

that no smoke propagated to other building parts and floors: increased CO concentrations were measured in several locations and they can be a health hazard if people are exposed to them for a long period. If an incident occurs, such circumstances are a reason to evacuate the building or large sections of the building.

Only a combination of source and effect measures will be effective to sufficiently improve the possibility of escape and survivability for all groups. The combination of limiting the use of synthetic materials (especially foams) in the furnishing and closing the doors is the most effective measure of improving the possibility of escape and survivability. A mobile water mist combined with closing the doors is also effective. An individual effect measure, such as closing the door or a smoke resistant partition, is not sufficient to improve the possibility of escape and survivability for vulnerable and highly vulnerable groups.

Besides fighting the fire, the goal of the fire service deployment should be to reduce further smoke propagation as much as possible. The situation of the door to the fire room, i.e. being open or closed, is decisive for determining which deployment method should be used to achieve these objectives. Where the door to the fire room is open, extinguishing the fire before rescuing was found to have the best effect on the possibility of escape and survivability. However, it was found that, where the door to the fire room is closed at the moment when the fire service arrives, rescuing before extinguishing the fire was the best course of action to improve the possibility of escape and survivability.

However, every fire service action will cause more smoke propagation, both horizontally and vertically. Walking through smoke-filled corridors, opening and closing doors, and fire suppression activities are all actions that cause a certain amount of smoke to propagate to adjacent rooms. Mechanical ventilation is a dominant action which mostly always causes smoke, and particularly CO, to propagate further to different rooms and floors.

Foreword

This report presents the results of field experiments into smoke propagation in a residential building with internal corridors. Soon after the Dutch Fire Service Academy, part of the IFV, had completed '*It depends*', research into fire growth and survivability in houses with ground-floor access in 2015, a need arose to conduct similar research into fire safety in blocks of flats. Practice had already shown that smoke propagation was becoming an ever increasing problem in these type of buildings and that the need to evacuate large parts of a residential building when there was a relatively minor fire was becoming the rule rather than the exception.

After a long time searching for funding and a suitable building for the experiments, the experiments were conducted in a former residential care complex in the municipality of Oudewater, the Netherlands, in the summer of 2019. The nineteen tests conducted yielded many thousands of measurement results and hundreds of hours of video footage. The analysis and conclusions following the processing of all this data are set out in this report. The appendixes are published separately on the IFV website. The source data will also be published and made available to other national and international research institutes.

When we started this research, we were not aware that its scope and depth would be a worldwide first. However this uniqueness was far from an advantage when preparing, carrying out, and analysing the experiments. In this respect, the Fire Service Academy's research team often found itself on its own. Many national and international colleagues offered to help, but an often heard answer was that they had never done this either. This meant that the research team had to devise, create, and try out a lot of things for themselves, thankfully with a positive conclusion. But it was not only the Fire Service Academy's research team that ensured that these experiments were successful. We would never have been able to achieve this without the support of the international advisory board, the municipality of Oudewater, the Utrecht Safety Region, the De Woningraat housing corporation, and many firefighting colleagues from all over the Netherlands.
We would therefore like to thank them all, and particularly the Oudewater fire station, for their cooperation.

The research gave us what we hoped for: better knowledge of smoke propagation and the possibility of escape and survivability when there are fires in residential buildings. It also enabled us to test, substantiate, and improve the effectiveness of measures for risk management and firefighting methods. Of course, in order to truly achieve better fire safety, this new knowledge will have to be implemented. The researchers have done their share. It is now up to legislators, policy makers, and the Dutch fire service to implement this knowledge.

René Hagen
Professor of Fire Safety

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Introduction

The first fire appliance arrives at the cafeteria and the senior citizens' residences over the cafeteria at 05.34 a.m., immediately followed by an aerial platform fire truck and a second fire appliance. Although it is dark, a lot of smoke can be seen in the main staircase to the senior citizens' residences. Several occupants of the residences are trying to draw the attention of the fire personnel by shouting and waving flashlights and towels. Reports are also coming in of occupants calling the national incident control room (112) as both their residences and the communal walkway are full of smoke and they cannot leave their residences.

Quoted from *Brand in De Notenhout [Fire in De Notenhout]* (Fire Service Academy, 2015a, p. 22).

Background

In recent years, the Dutch fire service has seen a rise in the number of fires in residential buildings where the actual fire is relatively limited, but there is extensive smoke propagation. The Fire Service Academy and the Organisation of Dutch Fire Services noted the following in 2017:

> In many cases, smoke propagation played an important role in how incidents developed, how they were handled, and the dilemmas involved. But the main finding is that the smoke propagation was much more significant than had been expected based on existing knowledge and experience (Fire Service Academy & Organisation of Dutch Fire Services, 2017, p. 8).

Fires in other types of buildings usually also involve smoke propagation; however, those buildings tend to have fewer people present – either sleeping or awake – who can be put in jeopardy by smoke.[1]

A type of residential building that stands out with regard to the smoke propagation is the residential building with internal corridors. In this type of residential building, smoke can propagate to other residences through the internal corridor and can impair the escape, which is via this internal corridor, for people in many of these other residences. This is not the case in residential buildings without any internal corridors, such as deck access flats with an open access walkway.

These real-life cases have shown that fires in residential buildings with internal corridors involve considerable fire safety and smoke propagation risks. It seems that relatively small fires can produce a lot of smoke which propagates through the building, sometimes causing

[1] Except guest accommodations and cell buildings.

inhalation trauma to occupants and requiring the entire building, or parts of the building, to be evacuated even more frequently. Evacuating not only causes major problems for both able-bodied and vulnerable occupants, but also for the fire service. They are now facing an almost impossible task given the increasing number of vulnerable people who still live on their own, many of whom have to be rescued by the fire service if a building is on fire.

The Dutch national government[2], the Organisation of Dutch Fire Services, the Fire Service Academy of the Netherlands Institute for Safety (IFV), and the safety regions work towards preventing and minimising the number of fire casualties and to reduce the impact of fires. As part of a targeted attempt to raise fire safety to a higher level, desk and case studies into smoke propagation and its impact on general and vulnerable occupants of residential buildings have been conducted in recent years. This has led to the following – and other – reports:

> *Casuïstiek uit brandonderzoek, trends om van te leren* (Fire Service Academy & Organisation of Dutch Fire Services, 2017).
> *De invloed van vergrijzing op brandveiligheid* (Fire Service Academy & Nederlandse Brandwonden Stichting, 2015a, 2015b, 2015c).
> *Branden in seniorencomplexen: regelgeving en praktijk* (Fire Service Academy, 2016a).
> *Fire safety of upholstered furniture and mattresses in the domestic area* (Hagen et al., 2017).

Further to these desk and case studies, experimental research into the actual smoke propagation in fires in residential buildings with internal corridors is of crucial importance - and this report reflects this. This experimental research involved a large-scale field research in a former residential care complex with internal corridors in the municipality of Oudewater. This was conducted in close cooperation between the Fire Service Academy, the Organisation of Dutch Fire Services and the Utrecht Safety Region.

Problem definition and goal

In the Netherlands, fires in houses and residential buildings claim between 800 and 900 casualties a year (Centraal Bureau voor de Statistiek, 2012), and, on average, 43 fatalities (Fire Service Academy, 2018a). The expectations are that the number of fire casualties will increase in the near future due to the ageing of the population and the increasing number of vulnerable people who remain living on their own (Fire Service Academy & Nederlandse Brandwonden Stichting, 2015a). This is because a combination of smoke propagation and mental and/or physical impairments often makes it impossible for these groups to escape a building on fire.

The rapid smoke propagation, which can be toxic, claims most of the fire casualties in buildings (Purser & McAllister, 2016). An important observation regarding smoke propagation is that fires nowadays tend to be fuelled by synthetic materials which produce up to ten times more smoke than the fires of the past which were fuelled by organic materials (Babrauskas, 2016). In addition, practice has shown that many fires occur in residential buildings with internal corridors where smoke is produced faster than assumed in building

[2] Represented here by the Dutch Ministry of Justice and Security.

regulations[3] and where smoke propagates quickly and extensively outside the residence where the fire started. This smoke propagation often makes escape routes unsuitable for use and can lead to unsafe situations in other residences. As a result, it is not always safe for occupants to wait in their own residences until the escape route can be used again or until they are rescued by the fire service (stay-in-place principle[4]).

When the fire service arrive on the scene, they are often faced with an extensive and acute incident involving various dilemmas with regard to the deployment method to choose as little is currently known about the effects of the actual and possible fire service action on smoke propagation. Examples are fires in Rotterdam (het Lichtpunt, 2014, 17 injured), Nijmegen (de Notenhout, 2015, 4 dead and 12 injured), Diemen (student housing, 2017, 1 dead and 4 injured), and Zwolle (senior citizens' apartment building, 2020, 10 injured).

This makes smoke propagation a frequently reported problem that raises fundamental questions with regard to its consequences for fire safety. Limiting smoke propagation and its effects is therefore considered to be necessary. However, it is not yet clear which measures for risk management can contribute to significantly slower and less extensive smoke propagation. There is also still a lot of ambiguity as to the effect of the possibilities and impossibilities encountered by the fire service during the deployment phase in order to rescue/evacuate people from a building on the rapid and extensive smoke propagation. This research therefore seeks to map the effects of smoke propagation in relation to measures for risk management and methods of firefighting on the possibility of escape and survivability in the event of fire in a residential building with internal corridors.

Field experiments were conducted to examine the actual effects of measures for risk management combined with changes in building methods, furnishing and households/occupants on smoke propagation and fire development. Based on the outcomes of these field experiments, substantiated policy principles and assumptions can be formulated to ensure fire safety in residential buildings with internal corridors and for the method adopted by the fire services when handling incidents in these residential buildings. This research therefore intends to achieve a better understanding of:
- smoke propagation and the possibility of escape and survivability in a residential building with internal corridors when there is a fire, and when fighting a fire.
- the effects of measures for risk management combined with changes in building methods, furnishing, and households/occupants.

Main and sub-questions

The main research question is:

What is the effect of smoke propagation on the possibility of escape and survivability in the event of fire in a residential building with internal corridors, and how can smoke propagation be reduced?

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[3] Where this research report refers to building regulations, this refers to all the various laws and regulations that directly or indirectly aim to promote fire safety in buildings, such as: the Dutch 2012 Building Decree, the Dutch Construction Products Regulation, Euro codes, the Dutch Crisis and Recovery Act, general administrative orders, NEN standards, the Dutch Housing Act, etc.

[4] Also referred to as 'stay put' or 'shelter in place'.

This main question led to the following sub-questions:
> How can the possibility of escape and survivability be defined?
> Based on simulations, what fire development and smoke propagation situations can be expected in the residential building?
> In the event of fire in the residential building, how does the smoke actually propagate in practice and what are the decisive factors for this propagation?
> What effect does the observed smoke propagation have on the possibility of escape and survivability in the residential building for people with different degrees of vulnerability?
> In the event of fire, to what extent are current and future smoke resistant partitions, a mobile water mist system, and furniture made of organic material effective in improving the possibility of escape and survivability in the residential building for people with different degrees of vulnerability?
> In the event of fire in the residential building, which deployment method gives the best possibility of escape and survivability?
> To what extent can the results be generalised to cover residential buildings with internal corridors?

Where the sub-questions above refer to 'residential building', this means the residential building with internal corridors that was selected for the tests.

Scope

The *It depends* research (Fire Service Academy, 2015c) established that several factors influence fire growth, thus making it impossible to sufficiently examine all the different variants and factors during field research. This requires choices to be made with regard to the design, configuration and implementation of the research. This section describes what has been included in this research and what has explicitly not been included.

Since, as described above, fires in residential buildings with internal corridors are not uncommon, it was decided to conduct research in such a residential building. However, there are many different versions of residential buildings with internal corridors, including differences in:
> the layout of the building in terms of escape routes
> the size and layout of the individual residences
> the design and construction of pipe shafts etcetera
> the construction and configuration of specific fire and smoke resistant facilities.

Since the aim of this research is to be able to ultimately make generally valid statements about smoke propagation in residential buildings with internal corridors, a residential building was sought that would meet the highest number of characteristics possible of buildings of this type. Of course, it is impossible to examine all different types of residential buildings with internal corridors.

An existing residential building was used for this research. The current state of this residential building was determined to be of the ‘level of an existing structure’. Furthermore, technical changes were made to enable the measures for risk management to be tested. These changes were based on the current level of safety and the level of safety expected for the near future in terms of smoke resistance in building regulations.

Of course, from an ethical point of view, one does not want to actually expose real people to smoke and fire. So in order to investigate the effects of fire on the possibility of escape and survivability, theoretical threshold values that apply to different groups of occupants were used, namely: (a) the general population with an average vulnerability to fire, (b) a vulnerable population, and (c) a highly vulnerable population.

Choices regarding the fire service deployment were also made in order to determine the variables that are most decisive in the event of a fire in a residential building with internal corridors. It was decided that this should be based on the most elementary choice which the crew commander has to make when arriving on the scene of a fire in a residential building: should priority be given to extinguishing the fire or evacuating the building?

Regardless of the crew commander's choice, the building will still have to be ventilated after extinguishing the fire. Therefore, ventilating the building to remove the smoke was also part of the research. Other considerations in the context of methods and techniques were not part of the research.

The choices made with regard to how the research was designed and conducted will be explained in more detail in chapter 2.

Coordination and collaboration

A field research with an emphasis on collecting data relating to smoke propagation in a large residential building with internal corridors is complex, requires a great deal of expertise and support, and is also socially sensitive due to the potential environmental effects caused by smoke nuisance, logistical (i.e. vehicle) movements, and media attention. That is why several organisations were involved in the different parts of this research; they are listed below.

Field research
The following parties were involved in the implementation of the field research:

> Utrecht safety region and in particular the Oudewater fire station.
  The Utrecht safety region joined the research as a partner and facilitated the research to the maximum possible extent whilst it was being prepared and conducted at the Oudewater location. The facilities provided ranged from providing food and drinks, staff for the deployment and/or safety crews, arranging respiratory protection and occupational hygiene, supporting the communication process, and making a room available for the VIP meeting. The Oudewater fire station played a special role in this by being extremely flexible and helpful in supporting the research team.

> The Dutch National Institute for Public Health and the Environment (RIVM).
  The RIVM's Environmental Incidents Service was invited to contribute to the research design on the basis of its expertise in measuring smoke and harmful substances, and it also conducted measurements of its own. The value of these measurements was twofold: firstly, they provided more in-depth information because the RIVM could measure more gases than the research team would be able to measure with its own equipment and secondly, the RIVM measurements could be compared to the measurements taken by the Fire Service Academy.

> De Woningraat housing corporation.
  At the request of the Fire Service Academy, the corporation made the Schuylenburcht test site available for the research and it implemented various necessary preparatory measures.
> The municipality of Oudewater.
  In its capacity as the competent authority, the municipality was not only involved in the granting of permits for the field experiments, but also in providing information to local occupants and in organising the VIP meeting.

Arrangements for the use of measuring equipment were made with researchers from the UL Firefighter Safety Research Institute and with the following suppliers: Dräger, Testo and National Instruments.

Advisory board
An international advisory board with experts on smoke propagation and stakeholders from that field was set up. This advisory board was given three tasks, to:
> Contribute their critical thoughts on the design, possibilities and limitations of the research.
> Keep the research group alert so as to avoid any tunnel vision when analysing the data.
> Assist in interpreting and explaining the results for both risk and incident control.

Structure of this report

This report is built up on the basis of the research questions. Chapter 1 discusses the current theoretical basis underlying the subject of smoke propagation. This chapter presents the main information which can be used to answer the first sub-question: 'How can the possibility of escape and survivability be defined?' To this end, the most relevant factors are discussed on the basis of previous research, including the scientific frameworks formulated. Examples are previous research into smoke propagation, the possibility of escape and survivability, and intervention in the event of a fire.

Chapter 2 goes into how the research into smoke propagation was designed. It first discusses the overall design and the test location and then goes into the preliminary research[5] and the choices made with regard to the Field experiments. And finally, chapter 2 contains a presentation of the data analysis design, as well as a paragraph describing the quality of the research in terms of uniformity, reliability, and internal and external validity.

Chapter 3 describes the actual smoke propagation during the field experiments in the Schuylenburcht building. This description enables the third sub-question 'How does smoke propagate in practice in the event of fire in the residential building, and what are the decisive factors for this smoke propagation?' to be answered. Firstly, the generation of smoke (during the tests) is discussed, after which the smoke propagation is described for the corridor, the other rooms on the first floor, and the other floors.

Where chapter 3 describes the actual smoke propagation, chapter 4 uses the theoretical framework to identify what this means for the maximum possibility of escape and survivability

[5] This briefly addresses the second sub-question 'Based on simulations, what fire development and smoke propagation situations can be expected in the residential building? A detailed answer to this sub-question is given in Appendix 6.

for the - hypothetical - general, vulnerable, and highly vulnerable occupants of the Schuylenburcht building. This leads to the basis for answering the fourth sub-question: 'What effect does the observed smoke propagation have on the possibility of escape and survivability in the residential building for people with different degrees of vulnerability?' This then concerns the possibility of escape and survivability for occupants of the residential building *in its current condition.* In particular, the effect on smoke propagation due to the door to the fire room being open or closed, as well as the effect of maximum ventilation by opening the balcony door, are discussed.

Chapter 5 describes the research results that were obtained in order to be able to answer the fifth sub-question: 'In the event of fire, to what extent are current and future smoke resistant partitions, a mobile water mist system, and furniture made of organic material effective in improving the possibility of escape and survivability in the residential building for people with different degrees of vulnerability?' Here, various *potential* measures for risk management – strengthening the smoke resistant partition, installing a mobile water mist system, and converting the fire load from synthetic to organic – are compared with the *existing* measures for risk management in the Schuylenburcht building.

Chapter 6 addresses the research results that go with answering the sixth sub-question 'In the event of fire in the residential building, which deployment method gives the best possibility of escape and survivability?' This goes into the key question 'rescue first or extinguish first', viewed in the light of the effect of the deployment on smoke propagation. An explanation is also given here of the relevant interaction observed between the measures for risk management and the deployment, as well as the influence of ventilation (after the deployment), on smoke propagation and the effect on the possibility of escape and survivability.

The research results described above focus specifically on smoke propagation that occurred in one building (the Schuylenburcht building) in a standardised fire scenario in which only a limited number of variables could be involved. These circumstances immediately raise the question of to what extent the results can be generalised for residential buildings with internal corridors – the seventh and final sub-question. This is because there are many different types of residential buildings, each with their own floor plans, structures, smoke resistance, occupants and fittings and fixtures. Therefore, chapter 7 explores the extent to which the research results can be generalised.

Chapter 8 presents conclusions regarding the main and sub-questions, based on the research results described in the preceding chapters.

Chapter 9 discusses the interpretation of the results and the possibilities and limitations of the research. Any implications for the field of research are discussed here and suggestions for follow-up research are made.

Chapter 10 has a 'separate status' within this report. In this final chapter, Professor of Fire Safety René Hagen and Professor of Fire Service Science Ricardo Weewer give their interpretations of the results of this research into smoke propagation, specifically related to their respective fields.

Since some terms used in this research report should be explained in more detail, a glossary is provided at the end of this report.

The underlying data of this research is very extensive and enormous quantities of information are available, both for the visual data and for the measurement data. The most crucial parts have been included as an appendix in a separate document. The other data will gradually be made available online to researchers and other interested parties in the months following the publication of this report.

1 Theoretical framework

This research examines the effect of smoke propagation, in relation to measures for risk management and firefighting, on the available time for the possibility of escape and survivability. This is because, in a fire situation, it is important that the available safe escape time (ASET) is longer than the required safe escape time (RSET) (Instituut Fysieke Veiligheid, 2017). The ASET is the time until the very last moment when escaping safely is still possible and the RSET is the time until the moment a safe place has been reached (see figure 1.1). Since the required safe escape time depends on the actual situation and location, and on the individual person, this research only considered the available safe escape time.

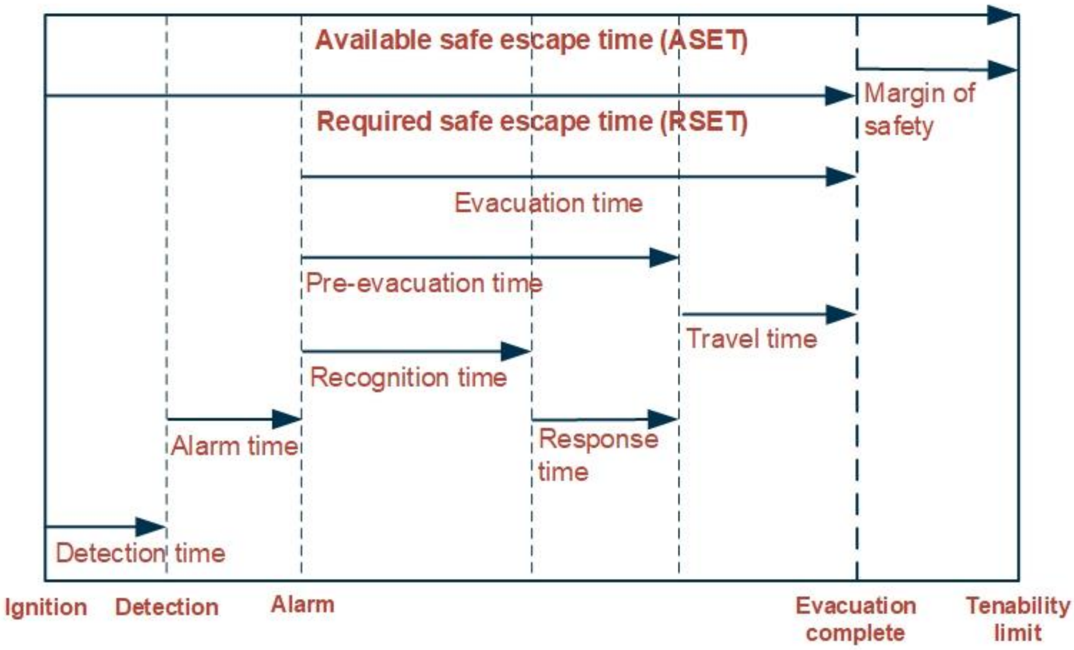

Figure 1.1 ASET and RSET

The available safe escape time depends on a number of factors that relate to the building, the fire growth and propagation of the smoke, the threshold values for the possibility of escape and survivability, and intervention. The main factors which influence the available safe escape time and which are relevant for this research are discussed in the following sections.

1.1 Residential buildings with internal corridors

Contrary to residential buildings without internal corridors, residential buildings with internal corridors are relatively common in real-life case studies concerning smoke propagation. This is why this type of residential building was chosen as the test location in this research. A residential building[6] with internal corridors is characterised by centrally located corridors with access doors to residences on both sides of these corridors (Ministerie van Binnenlandse Zaken en Koninkrijksrelaties, 2012b). In general, both sides of these corridors are terminated by staircases through which people can leave the building (see figure 1.2). This means that, in the event of fire, the occupants who have left their own residences will have to escape the building via extra protected internal and communal escape routes. Since these escape routes are easily compromised and threatened by smoke (Fire Service Academy & Organisation of Dutch Fire Services, 2017), this type of residential building involves a greater risk of fire safety and escape safety problems caused by smoke propagation than, for example, a residential building with open walkways.

It is not known how many residential buildings with internal corridors there are in the Netherlands as this type of residential building is not featured as a separate category in the statistics. However, it is known from the research into people being rescued by the fire service during residential fires from 2016 to 2018 that most of these rescues – necessitated in part by the smoke propagation – took place in apartment buildings or blocks of flats (Fire Service Academy, 2020b). It therefore seems that such residential buildings have the greatest problems with smoke propagation and escape safety. Residential buildings with internal corridors come in various forms, such as buildings with apartments for regular use, service apartment buildings, residential care complexes, and student housing. A type of residential building of which the building characteristics strongly resemble residential buildings with internal corridors is a building with deck access flats with enclosed access walkways. This type of residential building consists of enclosed walkways with residences on one side and, generally, staircases at both ends (see figure 1.2). The type of occupants and households in residential buildings with internal corridors is quite diverse and ranges from young adults to the elderly, and from people who are single to families.

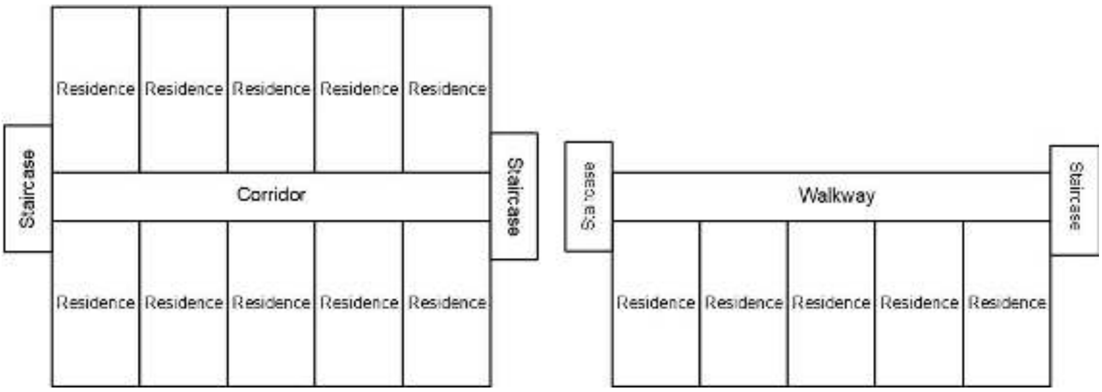

Figure 1.2 Floor plan of a residential building with internal corridors (on the left) and a building with deck access flats with enclosed walkways (on the right)

The Dutch Building Decree 2012 contains various fire safety regulations for buildings. These regulations serve to prevent casualties and the fire growth to other plots (Ministerie van Binnenlandse Zaken en Koninkrijksrelaties, 2012a). As far as fire growth is concerned, the general time assumptions are a maximum of 15 minutes after the start of the fire for detection and alerting, a further maximum of 15 minutes after alerting within which people

[6] The definition of 'residential building' used in the Dutch 2012 Building Decree is: "building or part thereof having exclusively residential functions or ancillary functions and containing more than one residential function depending on a common circulation route" (Ministerie van Binnenlandse Zaken en Koninkrijksrelaties, 2012a).

can still escape without assistance, and a maximum of 60 minutes after the start of the fire within which the last people can be rescued by the fire service. The basic principle of the regulations in the Dutch Building Decree 2012 is that occupants should be able to reach a safe location on their own before the fire service has arrived. The regulations that apply to escape safety according to the Dutch Building Decree 2012 depend on the designated use. The regulations for residential use (residential building) apply to the current research.

A general rule for residential buildings is that the building and its escape routes must be constructed such that they will not collapse for some time in the event of a fire, thus giving people the time to escape and enabling the fire service to evacuate and search the building (Ministerie van Binnenlandse Zaken en Koninkrijksrelaties, 2012a). Furthermore, every residence should be a separate fire compartment or a separately protected fire sub-compartment, implying that the residence should be isolated in a fire-resistant manner from other residences and from the escape route, with the latter possibly being constructed to offer extra protection. The walking distance between a spot in a habitable room and at least one access point of the residence (fire sub-compartment) should not exceed 30 metres for new structures and 45 metres for existing structures. According to the Dutch Building Decree 2012, the access doors to residences adjoining a corridor do not have to be self-closing[7], whereas the doors in the corridor and the entrance doors to the residential building are required to self-close. Furthermore, new structures for residential use must have smoke detectors connected to an electricity provision installed in every room which people can use as an escape route and from the exit of any room where people are generally expected to be present until the point where they leave the residence. This obligation will also apply to existing structures with effect from 1 July 2022 (Rijksoverheid, 2020).

According to the Dutch Building Decree 2012, a corridor in a newly built residential building is an extra protected escape route.[8] This escape route enables an independent escape route, namely the staircase, to be reached in both directions. The Dutch Building Decree 2012 provides requirements for resistance to fire movement between spaces (Dutch *WBDBO: weerstand tegen branddoorslag en brandoverslag*)[9] which result in a certain degree of fire resistance. For new structures, the requirement for resistance to fire movement between residences is as least 60 minutes (with possibility to reduce this to 30 minutes), and between a residence and the corridor the resistance to fire movement between spaces should be 30 minutes; for existing structures, the requirement for resistance to fire movement between spaces is 20 minutes for both cases. No specific requirements for smoke movement exist yet. The future Dutch Building Decree [*Besluit bouwwerken leefomgeving - BBL*], which is expected to take effect on 1 January 2022, will provide regulations for the resistance to smoke movement between rooms. The resistance to smoke movement of a partition (Ra or R200 criterion) between rooms depends on the smoke leakage (Sa or S200 criterion) of the various components in this partition (e.g. gaps and openings around doors, penetrations, connections and ventilation ducts). The S200 criterion according to NEN 6075 will then apply, for example, to access doors for residences adjoining a corridor. This means that additional measures, such as smoke seals, to reduce the

[7] The requirement of self-closing doors for new buildings is expected to also be applicable to the access doors of residences that adjoin a corridor with effect from 1 July 2020.
[8] These regulations use different terms for escape routes in an existing structure than in new structures. For example, the regulations for existing structures refer to a 'protected route'; this term is not used for new structures.
[9] Resistance to fire movement between spaces: the minimum time a fire needs to grow from one room to the next (Tromp & van Mierlo, 2013).

propagation of both cold and hot smoke will be required once these regulations have taken effect.

Because of the requirements for resistance to fire movement between spaces, measures to prevent fire movement will have to be applied to partitioning structures and penetrations between residences and between residences and corridors. Implicitly, reducing the smoke propagation is also part of the resistance to fire movement between spaces (according to NEN 6075, 20 minutes of resistance to fire movement between spaces corresponds to a resistance to smoke movement of 30 minutes). However, some measures, such as doors with intumescent strips, thermally activated fire dampers or shrink sleeves, have elements that only close or seal if hot smoke has been passing by for some time. They do not stop cold smoke or they only stop it to a limited extent.

Important connections in residential buildings are doors, gaps, ventilation ducts and various penetrations for installations. Doors form connections between fire compartments and corridors and can have gaps or can be opened. A building can be ventilated by either mechanical or natural ventilation; this can be via the outer wall and/or shafts. In addition, there may be shafts shared by multiple residences and there may be connections between residences resulting from various installations such as electricity, water and central heating boilers. For example, it is possible for electricity and water to share a jacket pipe in order for them to be fed to the meter cupboards of various residences above each other, after which they are distributed further in the residence. Some residential buildings which are heated by a shared central heating system have one room with central heating boilers from which the hot water spreads to the various residences. These connections can add to the smoke propagation between residences, between residences and corridors, and/or between floors.

1.2 Smoke propagation in residential fires

Research into people being rescued by the fire service during residential fires (Fire Service Academy, 2020b), fatal residential fires (Fire Service Academy, 2018a), and trends that we can learn from (Fire Service Academy & Organisation of Dutch Fire Services, 2017, 2019), shows that the increase in smoke propagation in residential buildings is a growing problem. When the fire service rescues people, the fire is mostly limited to the object of origin or the room in which the fire started. However, the smoke mostly propagates outside the fire room and even to several floors. If the escape route is blocked – usually due to smoke propagation – more than half of the rescued people are found to have come from neighbouring residences rather than from the residence/room where the fire started. And furthermore, inhalation of smoke is the most common cause of injury (Fire Service Academy, 2020b). Fatal residential fires often involve smoke propagating through several rooms and/or floors (Fire Service Academy, 2018a). At the time when the fire service arrives, smoke has already propagated to several floors or beyond. Parts 1 and 2 of *Trends om van te leren* come to a similar conclusion: often, the smoke has propagated more extensively than expected by the fire service and this often plays an important role in how an incident develops, how it should be handled, and the dilemmas involved (Fire Service Academy & Organisation of Dutch Fire Services, 2017, 2019). International research has shown that smoke propagating from the fire room to other parts of a building is the main cause of casualties (fatalities and injuries) in the event of fire in a building (Purser & McAllister, 2016).

In order to get a better understanding of the fire growth and the smoke propagation that can be expected, these two subjects are addressed in more detail in the next few sections.

1.2.1 Fire causes and fire growth

Data from twelve safety regions support the claim that the three main causes of residential fires are cooking, carelessness with open fires, and technical causes in electrical equipment (Brandweer Rotterdam-Rijnmond, 2019). Cooking and carelessness with open fires are the main fire causes in residences occupied by elderly people, aged between 60 and 80. Cooking is the main cause of residential fires involving elderly people aged more than 80 years old. Fires with high impact are fatal residential fires. The most common cause of such fires is smoking. In many cases (about half), there was a fire in mattresses or upholstered furniture, resulting in rapid fire growth and heavy smoke development. Smoking accounts for only five percent of all residential fires (Brandweer Rotterdam-Rijnmond, 2019) but, given that this is often accompanied by a mattress or upholstered furniture catching fire, it often causes severe injuries (Fire Service Academy, 2018a).

The rapid development of fire and smoke in mattresses and upholstered furniture in the event of fire is mainly due to the filling materials used. Until the 1970s, upholstered furniture was made from traditional materials, such as wood (for the frame), steel springs, filling materials consisting of cotton wool and upholstery made of natural fibres (such as wool or cotton). However, this changed in the 1970s when polyurethane foam became the main filling materials and the upholstery could be anything from thermoplastics to natural fibres (Babrauskas, 2016). At about 3 megawatts, the peak heat release rate of this more modern upholstered furniture turned out to be a lot higher than the less than 1 megawatts peak heat release rate of traditional furniture. Polyurethane foam (plastic) based filling materials are currently still the most common, but the design and construction of upholstered furniture have changed.

Research into the fire behaviour of upholstered furniture and mattresses in a residential environment has revealed that modern furnishings which catch fire produce more energy and smoke than traditional furnishings. This gives the occupants of a room with modern furniture considerably less time to escape in the event of fire (Fire Service Academy, 2015c, 2016b; Fire Service Academy, 2017; Kerber, 2010). In the event of fire in a room with modern furnishings, a flashover can occur considerably faster in the presence of sufficient oxygen than in a room with traditional furnishings. In addition, fires have changed in practice and quickly become under-ventilated[10] due to a lack of oxygen (Fire Service Academy, 2015c, 2016b; Kerber, 2010). When there is a lack of oxygen and/or a lack of fuel, the fire is often limited to the object of origin, producing relatively a lot of smoke. The changes in the materials used in upholstered furniture since the 1970s have therefore also led to changes in fire behaviour and the associated smoke production.

1.2.2 Smoke development

Smoke can be defined as the total volume of air and solid, liquid and gaseous combustion products: a mixture of soot particles, liquid droplets (such as water) and gases. The gases in the smoke can consist of decomposition gases, combustion gases and ambient air (Tromp & van Mierlo, 2013). For modern upholstered furniture and mattresses, these gases mainly include carbon monoxide (CO), carbon dioxide (CO_2), hydrogen cyanide (HCN), hydrogen chloride (HCL), nitrogen oxides (NO_x) and hydrogen bromide (HBr) (Sundström, 1996).

[10] A fire becoming ventilation-controlled before the moment of flashover.

The smoke production partly depends on the burning material (Kerber, 2010). Table 1.1 compares the smoke production of traditional and synthetic materials in a well-ventilated environment. Synthetic materials can produce two to eight times more CO and nine to fifteen times more soot per gram of fuel burned (Society of Fire Protection Engineers, 2016, p. 3466).

Table 1.1 Comparison of smoke production by traditional and synthetic materials

Material		Amount of CO, Y_{co} [g/g]	Amount of soot, Y_s [g/g]
Synthetic	Flexible polyurethane foam (GM21)	0.01	0.131
	Flexible polyurethane foam (GM23)	0.031	0.227
Traditional	Wood (red oak)	0.004	0.015
	Wood (spruce)	0.005	-

In addition to the type of material, smoke production also depends on the manner of combustion, which in turn depends on the temperature and the oxygen percentage. High temperatures and high oxygen concentrations enable complete combustion, leading to limited smoke production. Low temperatures and/or low oxygen concentrations can result in incomplete combustion and increased smoke production. An oxygen deficiency, for example, leads to a strong increase in the concentration of CO, a decrease in the concentration of CO_2, and an increase in the production of soot particles (Tromp & van Mierlo, 2013).

The smoke volume is determined by, on the one hand, the smoke produced by the fire and, on the other hand, the ambient air that is mixed in with the smoke. Close to the fire, the smoke is hot and optically dense, but its volume is low. As the smoke propagates, ambient air is mixed with the smoke and this mixing causes the smoke to cool down, makes it optically less dense, and increases its volume. In addition, the smoke is cooled down by exchanging heat with the walls, ceilings and any other objects it flows along. If the smoke is significantly hotter than the ambient air, a smoke layer will form at the top of the room. In a fire room, this is visible as a separate layer above a smoke-free layer, particularly in the early stage of the fire. If the smoke cools down even more, for example by heat being exchanged with walls and ceilings or because of cold air being mixed in, the two layers may mix. In that case, there is then no longer a separate smoke layer and a smoke-free layer (Tromp & van Mierlo, 2013).

1.2.3 Smoke propagation

Smoke can propagate through buildings by forced airflows (wind and ventilation systems), normal airflows (a stack effect), and airflows caused by the fire (Jacoby, LeBlanc, Tubbs, & Woodward, 2016). These airflows occur under the influence of pressure differences which can be caused by:

- temperature differences between the smoke and the ambient air;
- the stack effect:
- wind pressure;
- expansion of gases due to heating;
- the presence and operation of ventilation systems.

Pressure differences often occur between different rooms in buildings. If there is a pressure difference, air flows from the room with high pressure to the room with low pressure through an opening between the rooms. The pressure difference, the size of the opening, and the shape of the opening determine how much air (or smoke) flows through an opening (Tromp & van Mierlo, 2013).

In the event of fire in a room, two processes determine the outflow of gases through any openings. The gases in the heated air expand, pressing the air in the fire room through all available openings. At the same time, a plume of heated air, with smoke, rises to the ceiling. When the hot layer of smoke is low enough to hit the top of an opening, smoke will flow through the opening. The more the fire grows, the more the temperature difference between the smoke and the ambient air increases. This difference in temperature becomes a determining factor for the expansion of gases. The pressure at floor level in the fire room drops below atmospheric (ambient) pressure, allowing fresh air to enter the fire room at the bottom of the opening. A pressure difference is created over the height of the opening. At the top of the opening there is positive pressure (smoke flows out) and at the bottom there is negative pressure (fresh air flows in) (Tanaka, 2016). The pressure build-up in the individual rooms is decisive for how smoke propagates in a building with several rooms. As the smoke propagates further, the pressure build-up in the rooms will change as well. Near the fire room, there will be temperature differences and therefore pressure differences in rooms and between rooms. Further away from the fire room, the temperature differences will be less and prevailing pressure differences (stack effect, wind pressure, pressure differences due to ventilation systems) will determine the smoke propagation.

1.3 Escape in the event of fire and smoke

As identified in section 1.1, the basic assumption for fire safety in residential buildings is that the people present should be able to escape without any assistance (Ministerie van Binnenlandse Zaken en Koninkrijksrelaties, 2012a). Research into rescue operations during residential fires has shown that people often need to be rescued (for example, approximately 800 people were rescued by the fire service in 245 incidents between 2016 and 2018). Many of these people were physically mobile and should therefore, in principle, be able to escape without any assistance (Fire Service Academy, 2020b). So physical mobility is apparently not the only factor that plays a role in the process of escaping. This section discusses these other factors, such as detection and alerting and human behaviour. In addition, risk groups, the consequences of exposure to fire conditions, and methods to determine threshold values for the possibility of escape and survivability based on these conditions are examined.

1.3.1 Detection and alerting

Rapid detection of a fire is important for the possibility of escape and survivability for people in a residential building. A fire can be discovered in several ways. Research into people being rescued by the fire service during residential fires has shown that where people discovered a fire this was mostly a result of them detecting it themselves or because they were warned by neighbours or bystanders (43%); only in a limited number of cases (7%) were they alerted by smoke detectors (Fire Service Academy, 2020b). The most commonly used version is an optical smoke detector (Society of Fire Protection Engineers, 2016). Research from 2014 into the presence of smoke detectors showed that most residences (70%) had smoke detectors, but that not all of them were functioning (Fire Service Academy, 2015b). Intensive education and information provision by the Fire Service and the Brandwondenstichting (Dutch Burns Foundation) has led to an increase in the number of smoke detectors (more than 70%) (Zoonen, 2020). Since smoke detectors will be a compulsory requirement with effect from 1 July 2022 (Rijksoverheid, 2020), their presence in the residential environment will increase.

The *Basis for Fire Safety* manual (Instituut Fysieke Veiligheid, 2017) formulates several basic assumptions, starting from a model-based approach to fire safety facilities and measures in residential buildings. One of these assumptions concerns escape time: self-reliant people (people who have the ability to leave without assistance) in a residence with one or more smoke detectors in the escape route are assumed to detect the fire within three minutes after ignition and then escape the residence within one minute.

1.3.2 Human behaviour

Several studies have shown that people are not immediately aware of the dangers of fire and smoke, and also often underestimate the speed at which they can grow or develop (Nederlands Instituut Fysieke Veiligheid Nibra, 2008; Tromp & van Mierlo, 2013). As a result, people do not respond directly to warnings, for example a fire alarm; they do not recognise the urgency of a quick escape and response times can be long. Furthermore, in the first stage of a fire, people often tend to try and extinguish the fire themselves, alert others, and gather valuables before taking action aimed at protecting themselves and others or escaping/evacuating the building (Wales, Thompson, Hulse, & Galea, 2015). If people are warned of fire while sleeping, they need even more time to get ready to escape or to prepare for evacuation (e.g. because they dress themselves or help others) (Kuligowski, 2016). When people try to escape, they will be inclined to choose a route they know, even if it is full of smoke. Some actions by people during the escape process can also influence fire growth and smoke development. Examples are opening or closing doors or attempts to extinguish the fire (Kuligowski, 2016).

1.3.3 Risk groups

There are many differences with regard to the probability that someone will be a casualty in the event of a residential fire. One group that stands out as a high-risk group in this context is the elderly group (Fire Service Academy, 2019a; Instituut Fysieke Veiligheid & Nederlandse Brandwonden Stichting, 2016). Although the elderly (60+) run a relatively low risk of a residential fire, they do have a relatively high probability of dying in the event of a residential fire. Research into residential fires in the Netherlands has shown that most fatal casualties of residential fires are 61 or older, whereas most people who were rescued by the fire service and survived the fire are between 21 and 40 years old (Fire Service Academy, 2018a, 2020b). Furthermore, fatal casualties of a residential fire are often single or alone at the moment the fire starts, and usually their self-reliance is limited. This is in line with what can be found in the literature on risk groups and fire safety: the elderly are particularly vulnerable to fire due to physical and mental impairments, and people who live on their own are more vulnerable because there is a lower probability that they will discover the fire and there are no other self-reliant people around (Fire Service Academy, 2019a). This means that people's self-reliance – rather than their age – plays an important role in the possibility of escape and survivability.

1.3.4 Conditions for the possibility of escape and survivability

The conditions that people are exposed to in the event of fire in a building significantly impact their possibility of escape and survivability (ISO 13571, 2012; Purser & McAllister, 2016). These fire conditions are:

1. toxic gases which can be divided into two types:
   - irritant gases
   - asphyxiant gases
2. heat, which can be divided into four types:
   - radiant heat directly from the fire
   - radiant heat from the hot smoke layer
   - conducted heat from heated objects
   - convected heat from contact with hot smoke
3. visual obscuration due to the smoke (visibility).

The influence of these fire conditions on the possibility of escape and survivability are discussed below.

Toxic gases

One of the most common causes of injuries or fatalities in a fire is exposure to toxic gases in the smoke (Purser & McAllister, 2016). This smoke is not only present in the fire room, but it can also propagate to the available escape route or to other rooms in the building. The main toxic gases can be divided into two types: irritant gases and asphyxiant gases.

Irritant gases cause irritation of the eyes and the upper respiratory tract; this is also referred to as sensory irritation (Purser & McAllister, 2016). This irritant effect is often noticed immediately and does not worsen with prolonged exposure.[11] Therefore, with irritant gases, the concentration is of importance. Irritant gases can be distinguished into different compounds, based on their water solubility. This distinction is explained in the *Gebrand op inzicht* report (Fire Service Academy, 2015b). The most common irritant gases that can be released in the event of fire and that can affect the possibility of escape and survivability of people who are exposed to them are hydrogen chloride (HCl), hydrogen bromide (HBr), hydrogen fluoride (HF), sulphur dioxide (SO_2), nitrogen oxides (NO_2, NO, NO_x), acrolein (CH_2CHO) and formaldehyde (HCHO) (ISO 13571, 2012; Purser & McAllister, 2016).

Asphyxiant gases are gases which – upon inhalation – do not cause any direct respiratory or pulmonary damage, but they will lead to respiratory problems when combined with higher oxygen consumption while escaping (Meulenbelt, de Vries, & Joore, 1996). In addition, these gases are absorbed by the body, resulting in reduced oxygen supply in tissues of the body, also referred to as hypoxia. This can lead to loss of consciousness and ultimately be fatal (ISO 13571, 2012). The effect of asphyxiant gases is not directly visible. Often, there is a sudden transition from mild to severe and persistent effects. That explains why the dose, i.e. their concentration and the duration of exposure, is important in the case of asphyxiant gases. If the dose increases, the severity of the effects will also increase. Acute exposure to a higher dose is therefore tricky: once the person in question notices the effects, such as confusion, dizziness, or loss of consciousness, it is often too late to take action (Purser & McAllister, 2016). The main asphyxiant gases that have a significant impact on the possibility

[11] However, prolonged exposure might lead to serious lung irritation several hours or even days later. However, as this does not directly influence the available time to get to safety, it is not considered here (ISO 13571, 2012).

of escape and survivability are carbon monoxide (CO) and hydrogen cyanide (HCN) (ISO 13571, 2012; Purser & McAllister, 2016).

In general, CO is considered to be one of the most important parameters affecting the possibility of escape and survivability (Purser & McAllister, 2016). Since fires always produce high concentrations of this asphyxiant gas[12], exposure to CO is considered to be the main cause of fire fatalities. A good indicator of the harmful effects of CO exposure is the percentage of carboxyhemoglobin (%COHb), i.e. the inhaled CO dose (Purser & McAllister, 2016). The inhaled CO binds to hemoglobin in the blood, which results in carboxyhemoglobin (COHb) and reduces the oxygen supply in the body. The effects of the COHb percentage in the blood according to the Nationaal Vergiftigingen Informatie Centrum (NVIC), the Dutch national intoxications information centre, are presented in the *It depends* report (Fire Service Academy, 2015c).

A certain level of HCN is always released when nitrogenous materials are involved in a fire (Purser & McAllister, 2016). High concentrations of HCN will be found if fires are under-ventilated. The eventual effects of exposure to HCN are the same as those of exposure to CO; however, their mechanism is different. This is because HCN not only binds to the blood, but it also spreads rapidly to the brain. As a result, the effects of HCN occur shortly after exposure and are immediately severe. And furthermore, HCN is approximately twenty-five times more toxic than CO (ISO 13571, 2012).

Besides CO and HCN, low oxygen concentrations (O_2 less than 15%) and high carbon dioxide concentrations (CO_2 more than 5%) can have asphyxiating effects (Purser & McAllister, 2016). A fire consumes the oxygen in the room, resulting in a low-oxygen environment for the people in the room. This low-oxygen environment can cause people to lose consciousness when the oxygen supply to their brain drops to below a critical value and can therefore be life-threatening (Purser & McAllister, 2016). The *Gebrand op inzicht* report (Fire Service Academy, 2015b) lists the different health effects of low oxygen percentages. Just like CO, CO_2 is released in all fires, but as long as its concentration does not exceed 5% it is not toxic. However, inhaling CO_2 can accelerate people's breathing and eventually lead to hyperventilation. This hyperventilation can result in increased inhalation of other toxic gases that are released (Purser & McAllister, 2016).

Heat

During a fire, people can be exposed to radiant heat (from the actual fire, the hot layer of smoke or heated objects) or convected heat (from hot smoke). This exposure can cause three different physical consequences and thus affect people's possibility of escape and survivability:

- hyperthermia;
- body surface burns (skin);
- respiratory tract burns.

Hyperthermia is a gradual increase in body temperature due to prolonged exposure to heat (Purser & McAllister, 2016). This can occur if people are exposed to heated environments at temperatures too low to cause burns (less than 121 degrees Celsius for dry air and less than

[12] Although the dose inhaled is decisive in case of CO intoxication, there is also information available about the physical effects of different CO concentrations. A summary of this can be found in the *Gebrand op inzicht* report (Brandweeracademie, 2015b).

80 degrees Celsius for saturated air) for 15 minutes or longer. If someone's body temperature has gone up to more than 40 degrees Celsius, there is a risk of them losing consciousness. Body temperatures of more than 42.5 degrees Celsius can be fatal.

Burns can result from exposure to both radiant heat and convected heat. The threshold value for skin exposure to radiant heat is approximately 2.5 kilowatts per square metre (ISO 13571, 2012; Purser & McAllister, 2016). The threshold value for unprotected skin being exposed to convected heat is approximately 120 degrees Celsius. At values above this threshold, people often experience considerable pain within a matter of minutes and burns can occur. Since respiratory tract burns rarely occur without body surface burns, the threshold values for body surface burns are generally lower than the threshold values for respiratory tract burns (Purser & McAllister, 2016).

Visibility
After a fire has started, the smoke in a room will gradually become more dense (due to soot particles), reducing visibility for the people in the room. This causes them to become disorientated, reduces their walking speed, and it also affects the visibility of escape routes, frustrating escaping and evacuation (Hadjisophocleous & Mehaffey, 2016). Visual obscuration due to smoke therefore mainly affects people's possibility of escape.

1.3.5 Threshold values for the possibility of escape and survivability

The above fire conditions can lead to the possibility of escape being reduced and can create a life-threatening or even fatal situation for people exposed to them (see figure 1.3). In order to be able to determine when these three situations occur, threshold values[13] have been determined by several international standards.

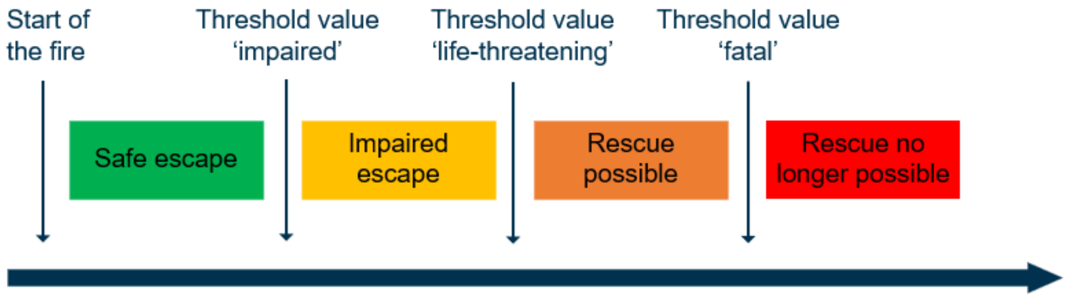

Figure 1.3 Diagram of the possibility of escape and survivability in the event of fire

According to the ISO standard (ISO 13571, 2012) and the SFPE Handbook (Purser & McAllister, 2016), the following methods are important for determining when people's possibility of escape and survivability are threatened.

- The Fractional Effective Concentration (FEC) or Fractional Irritant Concentration (FIC). This is the ratio between the exposure concentration at any time during a fire and the exposure concentration predicted to significantly compromise the possibility of escape and survivability.
- The Fractional Effective Dose (FED) or Fractional Lethal Dose (FLD). This is the ratio between the exposure dose – the concentration and the duration of exposure – and the exposure dose predicted to significantly compromise the possibility of escape and survivability.

[13] Please note that these values can change due to new scientific findings.

In order to determine the FED/FLD or FEC/FIC value at which exposed people can no longer escape safely or survive, a sensitivity factor (sf) has been established (ISO 13571, 2012). This sensitivity factor depends on the vulnerability of the people in question and the fire conditions to which they have been exposed. The main sub-populations that may have over-average sensitivity to fire conditions are very young people (infants and young children), the elderly, and people with lung diseases. Infants and young children are more sensitive to asphyxiant gases because, given their low body weight, they inhale relatively more air per minute. Their skin also tends to be thinner, making them more susceptible to burns. The elderly, especially if they have cardiovascular problems, are also more sensitive to asphyxiant gases and run a higher risk of burns due to their thinner skin. People with lung diseases such as asthma and chronic obstructive pulmonary disease (COPD) are more sensitive to irritant gases, even if they have been exposed only briefly (ISO 13571, 2012). By definition, in the ISO standard and the SFPE Handbook, the value sf = 1 represents the median of the distribution (average population), meaning that 50% of the population are less susceptible and 50% are more susceptible. In addition, sensitivity factors are mentioned that take into account people's vulnerability, namely a value of sf = 0.3 for the vulnerable population (11.4%) and a value of sf = 0.1 for the highly vulnerable population (1.1%) (ISO 13571, 2012; Purser & McAllister, 2016).

The Acute Exposure Guidelines (AEGL) represents levels of threshold exposure limits for different exposure periods (10 minutes, 30 minutes, 1 hour, 4 hours and 8 hours):

- AEGL-1: experiencing discomfort, irritation or certain asymptotic non-sensory effects. There is no lasting effect upon cessation of exposure.
- AEGL-2: experiencing irreversible or other serious, long-lasting adverse health effects or an impaired ability to escape.
- AEGL-3: experiencing life-threatening health effects or death.

The AEGL values are expressed as concentrations above which health effects may occur, depending on the exposure duration and level selected (National Research Council, 2001). These values represent the threshold values for the average population, including its vulnerable groups. The AEGL is a guideline specifically for gases.

Based on a comparison of the ISO standard, the SFPE Handbook and AEGL (see Appendix 1), the SFPE Handbook was found to be the most complete and up-to-date guideline for determining the possibility of escape and survivability. It was therefore decided to follow the SFPE guideline in this research. An overview of the fire conditions, the associated methods and sensitivity factors for the possibility of escape being impaired, a life-threatening situation, and a fatal situation can be found in table 1.2.

Table 1.2 Overview of the threshold values according to the SFPE handbook

Fire condition	Method	Impaired	Life-threatening	Fatal
Irritant gases	FIC FLD	sf * 1	sf * 5	 sf * 1
Asphyxiant gases	FED_{IN}		sf * 1	sf * 2
Heat	FED_{heat}	sf * 1	sf * 8	sf * 12
Visibility	FEC_{smoke}	sf * 1		

1.4 Fire service deployment (intervention)

This research specifically looks at the influence of the deployment (as external emergency assistance) on the possibility of escape and survivability for people in a residential building with internal corridors. The objective and possibilities for external emergency assistance are determined by several factors. Examples are the risk of collapse and failure of fire resistant structures, people's self-reliance, and the occurrence of fire phenomena such as fire movement or smoke explosions (Fire Service Academy, 2014b). Important aspects of the deployment with regard to this research are the operational time of the fire service, the deployment method, the evacuation and the ventilation.

1.4.1 The operational time of the fire service

In order to be able to determine when a deployment starts, it is important to determine what the operational time of the fire service is. The operational time is defined as the time period between the moment the fire starts and the moment the fire service can start their initial action (Herpen & Witte, 2015). A schematic representation of operational time is shown in figure 1.4. The operational time of the fire service is a product of various parameters such as the detection and alerting by smoke detectors, the response time of volunteers versus that of professionals, the information obtained in advance, the information obtained when asking specific information about the incident, etc.

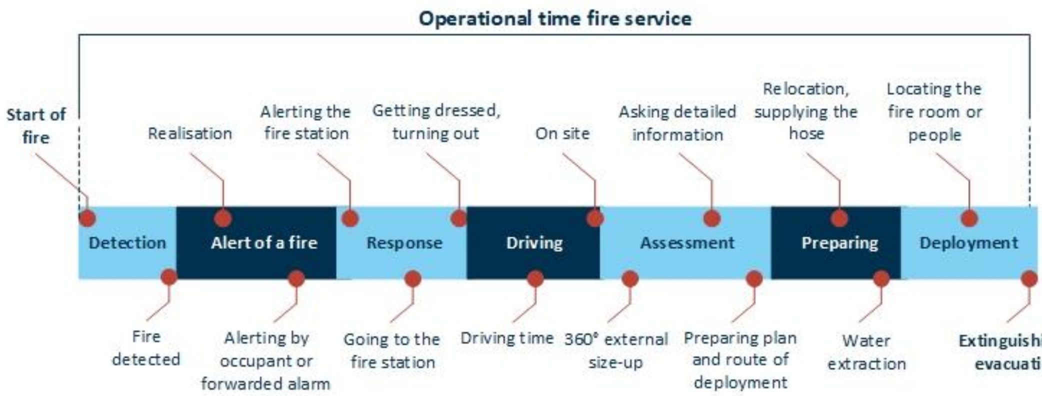

Figure 1.4 The operational time of the fire service

Statutory standards for response times prescribe that, after having received an alert of a fire in a building with a residential function, the fire service should be at the scene of the fire within 5 to 8 minutes (Rijksoverheid, 2017). Gathering as much relevant information as possible, both at the scene and previously whilst on route to the incident, is important for the crew commander. This information helps the crew commander making decisions during the deployment. Examples of relevant forms of information are:

> a digital accessibility map: a floor plan with all the fire prevention and repressive facilities of the building;

> a deployment map: a floor plan with accesses, deployment routes, risks, hazardous materials, etc.;

> an indication of where the fire is located, whether there are still people inside and whether the evacuation of the building has already started.

1.4.2 Deployment method

The Dutch fire service has been working according to the basic firefighting principles during a deployment for some time now (Fire Service Academy, 2020a). According to these principles, one of the first questions to be answered is where the fire is located. An indication of this can be information provided when reporting the fire, information given by the occupants or – if present[14] – the fire alarm system detector that was triggered first. In addition, an external size-up is performed from the outside using a thermal imaging camera. This camera searches for heat or smoke phenomena that are visible on the outside. The external size-up gives input for the choice of quadrant, method, deployment route and possible increase of capacity.

To support decision-making during incidents, the fire service uses the quadrant model (Fire Service Academy, 2014c). Each quadrant has its own objectives and associated deployment possibilities. When selecting a quadrant in the event of a fire in a residential building with internal corridors, the first thing one should know is whether any internal emergency services (the in-house emergency response team) have already carried out any interventions, such as keeping the fire under control or evacuating the surrounding area. However, most residential buildings, except those housing residential functions combined with care functions, do not have an in-house emergency response team. The next piece of information that is important for the choice of quadrant is whether people need to be rescued, whether the fire has propagated or may potentially propagate, and whether the fire can be extinguished. Based on this information, one of the following three quadrants can be chosen in the event of fire in a residential building with internal corridors.

> Offensive interior attack: a deployment inside the fire compartment with the aim of extinguishing the fire and rescuing occupants. Evacuating the other occupants will not start until the fire has been extinguished.

> Defensive interior attack: a deployment outside the fire compartment to prevent the fire moving to other fire compartments and to evacuate occupants in residences near the fire room.

> Offensive exterior attack: a deployment aimed at fighting the fire from outside the building in order to improve the conditions in the fire compartment. This quadrant is often chosen when the fire has reached the outside of the building.

When there is a fire in residential buildings where there are still people inside, the crew commander has to choose: will the deployment give priority to rescuing (evacuation) occupants or extinguishing the fire? Professional literature shows that fire extinguishing is often the preferred method (Fire Service Academy, 2014c, p. 33; Lambert, 2012). The idea behind this is that extinguishing a fire stops its ‘motor’ which automatically stops the production of fire gases and any increase in temperature. However, it is also a known fact that this choice is often inconsistent with fire prevention concepts in buildings (Organisation of Dutch Fire Services, 2012; Instituut Fysieke Veiligheid, 2017). Examples of this are penetrating fire resistant and smoke resistant partitions with hoses. Furthermore, actual incidents have shown that fighting the fire can actually worsen the situation in the escape routes (Fire Service Academy, 2014a, 2015a; Moore-Bick, 2019). Neither the teaching and learning materials for firefighters nor the literature on deployment methods give any handles or rules of thumb that enable the choice between offensive or defensive methods to be made.

[14] However, most residential buildings, except those housing residential functions combined with care functions, do not have a fire alarm system.

Current teaching and learning materials and various publications (Fire Service Academy-IFV, 2019a, 2019b; Fire Service Academy, 2014c, 2020a) give a lot of information about firefighting, choosing quadrants and the basic principles of firefighting. They also pay a lot of attention to fighting fires in senior citizens' homes, in high-rise buildings, and fires involving people who are not self-reliant (Fire Service Academy, 2016a; Instituut Fysieke Veiligheid, 2017; Madrzykowski & Kerber, 2010; Nederlands Instituut Fysieke Veiligheid Nibra, 2008). However, hardly any specific attention is given to smoke propagation and a matching repressive deployment based on building, fire, human, environment and intervention characteristics.

1.4.3 Evacuation

As an intervention strategy to limit the risks for the occupants, it may be decided to evacuate one or more residences. For the fire service, the decision whether to evacuate a residence, floor or building, depends on how threatening the situation is. For the fire service, the lower limit for evacuating a residence is the presence of visible smoke in the residence and/or a concentration of 25 ppm CO having been measured. This latter value matches the maximum acceptable concentration (MAC) for a dwell time of 8 hours for the general group.
When evacuating a residential building, it may be decided to do this at several levels, depending on the situation in the building at the time when internal or external emergency assistance is provided. Here the possibilities are to evacuate one or more residences, a fire compartment or sub-compartment, a floor, or a part of the building (Nederlands Instituut voor Bedrijfshulpverlening, 2019).

Several evacuation strategies exist. They can be chosen depending on the situation and the characteristics of the incident (Ronchi & Nilsson, 2013).

- Evacuating the total building: all the occupants leave the entire building at more or less the same time. They may leave it without assistance, or under supervision of internal and/or external assistance providers.
- Phased building evacuation: priorities will be assigned, based on the most critical or endangered floors, compartments or building sections. The occupants of these parts of the building are the first to leave the building, followed by the other occupants. They may leave it without assistance, or under supervision of internal and/or external assistance providers.
- Stay-in-place: occupants stay in their own residences/compartments or sub-compartments. The internal and/or external emergency assistance providers first bring the incident under control before starting to evacuate. Occupants wait for the emergency assistance providers to come and collect them.
- Delayed building evacuation: occupants are taken from their residences, fire compartments or sub-compartments to a safe area ('refuge area') in another compartment or escape to this area themselves. They wait there until the incident is under control or until internal and/or external emergency assistance providers take them to another location.

Every strategy comes with its benefits and drawbacks; the human factor, i.e. the occupants, is often the limiting factor. When people are under pressure, possibly because time is running out, or they are stressed or panicking, they do not always follow the instructions given by the internal and/or external emergency assistance providers. Since this is especially the case when smoke has propagated into a residence or corridor which should be available as an escape route, it is important to anticipate the expected behaviour, rather than assuming that people who are being evacuated will strictly comply with instructions, and to reckon with relatively long evacuation times in residential buildings (Ronchi & Nilsson, 2013).

1.4.4 Ventilation

There are several reasons for the fire service to ventilate during or after a fire. It improves visibility, lowers temperatures, and increases any casualties' chances of survival since gas concentrations are lowered (Zevotek, 2015). However, ventilation also introduces oxygen which enables the fire to grow or a new fire to start. Therefore, as part of the basic principles, if a building is on fire as little oxygen as possible should be supplied until the fire is under control (Fire Service Academy, 2018b).

There are several ways to ventilate (Lambert, 2015).

> Natural ventilation: ventilating a building or part of a building by using the flow that is created by pressure and temperature differences caused by the fire.
> Mechanical ventilation (PPV[15]): ventilating a building or part of a building by creating a forced flow (positive pressure) using a fan.
> Hydraulic ventilation: creating an airflow by spraying from an opening, possibly in the outer wall, using a spray jet (cone). Here the venturi effect of the jet nozzle creates a pressure difference causing ambient air and fire gases to be drawn along in the spray direction (Weinschenk, Stakes, & Zevotek, 2017).

With regard to ventilation, it is important that a flow path is created. Here it should be ensured that there are intake and outflow openings, that the route is kept as short as possible, and that the ratio between the intake and outflow openings is correct. The longer the flow path, and/or the greater the volume it contains, the less effective ventilation will be. The prevailing wind direction should also always be taken into account: the intake opening should ideally always be on the wind pressure side.

1.5 Comparable previous research

In an attempt to maximise the added value of the current research, this section describes previous research that has, either directly or indirectly, provided valuable information about smoke propagation. Because of the multitude of research that has been conducted, no exhaustive overview is given and only relevant research projects are addressed.

1.5.1 General field research into residential fires and fires in residential buildings

Evaluations of actual real-life incidents have shown that smoke propagates to a greater extent in practice than was theoretically assumed (Fire Service Academy & Organisation of Dutch Fire Services, 2017). Smoke propagates through a building via all kinds of routes. Examples of common routes along which smoke propagates are ducts, lift and other shafts, ventilation systems and inadequate structural fire prevention facilities. The deployment can also cause smoke propagation. Smoke propagation plays an important role in how the incident develops, how it is handled, and the dilemmas involved. Large-scale evacuation demands a lot of capacity from the fire service. If there has been significant smoke propagation, an important dilemma for the fire service is whether to put the fire out first or to

[15] PPV: positive pressure ventilation.

evacuate/rescue people first. It differs from incident to incident which of these two options is preferred.

Field experiments concerning residential fires have been conducted in the past. For example, in 2014, the Fire Service Academy conducted research into fire growth and survivability in the event of residential fires (Fire Service Academy, 2015c). One of the conclusions of this research was that a residential fire grows quickly and is then smothered due to a lack of oxygen. However, this smothered fire can quickly flare up again due to new oxygen being supplied, for instance in case of an interior attack by the fire service, and this creates risks for the fire service. The survival times in different situations in residences were also examined during these experiments. It was found that a closed door between the fire room and the other rooms in the residence significantly improves survivability outside the fire room. However, as these tests were conducted in a terraced house, they do not say anything about how smoke propagates in a residential building.

Underwriters Laboratories conducted field research into the influence of modern furnishings on residential fires and their impact on the fire service methods for ventilation (Kerber, 2010). During this research, it was observed that a residence with modern furnishings has a higher heat release rate and produces more smoke than a fire in a residence with old-fashioned furnishings. It was also found that fires involving modern furniture are often under-ventilated. A closed door between the fire room and another room increases survivability in the other room. This research also gives information about residential fires and the situations that then apply, but it does not go into fires in residential buildings and the relevant situations.

Exova WarringtonFireGent NV and Ghent University conducted research, involving field experiments, into the effectiveness of various fire safety measures in residential care centres (Exova WarringtonFireGent NV & Universiteit Gent, 2016). Using a sofa as the fire object, several different measures were considered, such as doors that offer extra smoke resistance (S200 criterion), a sprinkler, smoke control, and a sprinkler combined with smoke control. The main conclusions from these tests are listed below.

- A fire causes pressure to build up which in turn causes smoke propagation. A sprinkler or a sufficiently large opening in the fire room can negate this pressure build-up. Before the sprinkler is activated, sufficient pressure may have built up to allow smoke to move through, for example, seams and cracks.
- The difference in smoke movement between a 'normal' fire-resistant door and a door offering regular or extra smoke resistance could not be demonstrated in these tests because the pressure build-up of the 'zero test' was very low.
- Only the combination of smoke control and a sprinkler ensured good visibility in the fire room, but that was only after the sprinkler had been activated. In order to maintain sufficient visibility, a high exhaust flow rate was required for controlling the smoke.
- The sprinkler failed to extinguish the fire.

In these tests, the fire was in the combined corridor with a communal room. No tests were conducted with a fire in one of the rooms.

1.5.2 Research into measures for risk management

There has been much research into the effectiveness of automatic fire suppression systems in residential environments, including residential care environments. Conclusions from these investigations are listed below.

- Survivability in the fire room improved by the use of automatic fire suppression systems, but they are not always guaranteed. Survivability is almost always guaranteed outside the fire room (Ahrens, 2017; Herpen, Rojas Garces, & Braber-Vossestein, 2018; Shipp & Clark, 2006).
- In the event of fire in a room that adjoins the corridor, visibility in the corridor will be reduced, even if the sprinklers have been activated (British Automatic Fire Sprinkler Association (BAFSA), 2010). This was concluded by doing CFD simulations, not by conducting field experiments.
- Water mist systems are more efficient than sprinklers. The performance of a stand-alone water mist system is almost as good as that of other water mist systems, in spite of the lower flow rate (Arvidson, 2017).
- The influence of automatic extinguishing systems on smoke behaviour and smoke propagation depends on many factors and is hard to predict (Li, Chen, & Li, 2011; Tang, Fang, Yuan, & Merci, 2013; Tang, Vierendeels, Fang, & Merci, 2013).

With regard to smoke resistant doors, data is available from standard tests according to NEN-EN 1634-3:2004+C1:2007. These tests measured smoke leakage at pressures of 10, 25 and 50 Pascal. Furthermore, field research has shown that the pressure in a fire room can exceed 50 Pascal (Exova WarringtonFireGent NV & Universiteit Gent, 2016; Hostikka, Janardhan, Riaz, & Sikanen, 2017). However, how the smoke resistant doors behave when subjected to such higher pressure is not known. Furthermore, the composition of the smoke in a laboratory test can be completely different than in a real-life fire. It is not known whether this different composition of smoke affects the movement of smoke through the doors.

Previous research also looked into the possibility of lowering the flammability, toxicity and smoke production of flammable objects in residences (Kerber, 2010; Liempd, 2015). This showed that objects which burn less fast and less vehemently can lead to a much better possibility of escape and survivability. The focus was on the effect on the situation in a residence or apartment in which there was a fire; the effects in corridors and in other residences in a residential building were not considered.

1.5.3 Research into the deployment

Research has been conducted into the influence of the fire service deployment on smoke propagation in a building, including in residential buildings. Experiments conducted in an apartment in a three-storey building showed that positive pressure ventilation is an effective and useful means, provided it is applied properly and with all due care (Svensson, 2002). Since, in these experiments, the building housed one apartment on every storey, adjoining a staircase, the research did not look into the horizontal smoke propagation to other apartments in a residential building. Research by NIST (Kerber & Madrzykowski, 2009) shows that door control is a good means of limiting smoke propagation. Positive pressure fans were also found to work well, but if there was a strong wind outside, the fan was sometimes not strong enough to blow against the wind. Extinguishing the fire quickly lowered the temperature in the building.

In the Netherlands, the influence of the fire service deployment on smoke propagation in a residential building was examined by looking at experiences gained during deployments in response to incidents and evaluations of these incidents (Fire Service Academy & Organisation of Dutch Fire Services, 2017). So far, the experiences from real-life incidents have not given sufficient information about smoke propagation in residential buildings or about the effect of the deployment on smoke propagation. Information about the possibility of escape and survivability can only be generated by conducting measurements. For the time being, this is only possible through field tests.

1.5.4 Cases studies and simulations

The Fire Service Academy analysed 77 actual fires in senior citizens' complexes in order to determine whether the influence of the fire development and smoke propagation was consistent with the basic assumptions of the Dutch Building Decree 2012 (Fire Service Academy, 2016a). Here it was found that the combination of elderly people who cannot escape without assistance and smoke propagating through the building at high speed can cause casualties even if the fire is relatively small. In practice, smoke propagates faster than assumed by the building regulations, and it was found that people needed more time to escape a building than assumed. This case study was elaborated on in more depth by conducting simulations in a residential building with internal corridors (Fire Service Academy, 2019b). However, these simulations did not consider ventilation and ventilation shafts as this would overcomplicate the calculations. Different types of fuel and different door opening scenarios were tested during the simulations. Survivability and the possibility of escape for people with different degrees of vulnerability in case of fire were also examined (Beyler, 2002).

The results of the simulations show that if the door to the fire room is closed, this has a considerable positive effect on the conditions for the possibility of escape and survivability in the other rooms. The type of fuel also influences the possibility of escape and survivability – a cellulose fire is more favourable to the possibility of escape and survivability than a foam fire – but to a lesser extent than the door to the fire room being opened or closed. Furthermore, it was found that risk groups who are vulnerable to smoke can get into trouble more quickly than the average population. These simulations sketched a good initial picture of the consequences of a fire in a residential building with internal corridors. However, as stated above, the disadvantage was that the ventilation of the building was not considered.

The outcomes of the simulations depend on the input chosen and all calculations by simulation software differ from the actual situation. Although the validity of simulation software continues to improve, and for an ever wider scope, the output remains highly dependent on the input chosen for the simulation, which is often a simplification of the actual situation. Furthermore, simulation software has, in general, not yet been sufficiently validated to provide reliable results for the interaction between water and fire. Field experiments enable such insecurities in the simulation input to be excluded. The results of such experiments can also be used to further validate simulation software.

1.6 Summary and choices

As mentioned above, this research maps the smoke propagation in residential buildings with internal corridors. Real-life cases have shown that relatively small fires often go together with the development of quite a lot of smoke. The fire is often limited to the object of origin, often upholstered furniture (sofa or mattress), and produces a lot of smoke. This smoke then quickly propagates under the influence of air flows – caused by the fire, weather conditions, ventilation systems and stack effects – outside the residence on fire, causing escape routes to become obstructed or blocked. However, the speed and extent of this smoke propagation are, as yet, not sufficiently known, nor are the factors that play a decisive role in this. There has been quite a lot of research into fire development in residential environments and the effectiveness of measures for risk management and firefighting. However there is currently insufficient scientific evidence as to the associated smoke propagation and its effect – in relation to measures for risk management and firefighting – on the possibility of escape and survivability. There is also no current knowledge of any field research having been conducted into smoke propagation on the scale of a residential building in the event of fire in a residence. Simulations can provide further information and improve understanding, but their results cannot be guaranteed and their applicability is limited. That is why field experiments were conducted for this research.

Since upholstered furniture often causes considerable smoke propagation in fires, and smoke propagation in residential buildings with internal corridors occurs relatively frequently, it was decided to use a sofa as the fire object and a residential building with internal corridors as the object of the research (see also chapter 2).

Besides observing the smoke propagation, this research also examined the effect of smoke propagation on the possibility of escape and survivability for the people present. This assumed the presence of a working smoke detector, a period of 3 minutes for the fire to be detected by the people present, and a period of 2 minutes for escaping the house and reporting the fire. According to the basic assumptions referred to in section 1.3.1, the time needed for detecting a fire and escaping is a total of 4 minutes, but given the increase of vulnerable people living on their own and taking into account the reporting of the fire, this research assumes a total time of 5 minutes. In order to be able to determine when the possibility of escape and survivability is threatened by the different fire conditions, the method and threshold values from the SFPE Handbook were chosen. Because of the relatively high share of the elderly and people with reduced self-reliance in fire fatalities, these threshold values were established for the different groups concerned.

Finally, the effect of various measures for risk management and the fire service deployment on the possibility of escape and survivability is examined. At the moment, little or nothing is known about which measures for risk management are effective in improving the possibility of escape and survivability. There is also insufficient information on the effect of the deployment on smoke propagation. For the purpose of this research, measures for risk management were examined at various levels:

- Fire object: since there are major differences in smoke production between traditional and modern furniture, both the smoke production of modern furniture (the sofa) and the smoke production of an organic fire load (wood) were examined.
- Fire room: an automatic fire suppression system can be placed in the fire room as a measure for risk management. Since water mist systems are more efficient than sprinklers, a mobile water mist system was chosen.
- The partition between the fire room and the corridor: given the future regulations for resistance to smoke movement in the Future Dutch Building Decree, both the existing and future smoke resistant partitions were examined.
- The fire service deployment: since there is currently no framework of action for the options of rescuing (evacuation) or extinguishing, both offensive and defensive attacks by the fire service were examined.


1.23
2
4
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2 Research design

2.1 General design

The field experiments took place from 24 June to 5 July 2019 in an existing residential building with internal corridors. Every day, with exception of the first day, two fire tests were conducted in two different rooms, with the first test starting at 10.30 a.m. and the second test at 3 p.m. A total of nineteen tests were conducted to examine several different variables and their influence on smoke propagation and the possibility of escape and survivability.

The tests assumed one baseline scenario: a fire which started in a sofa without any measures for risk management having been taken, no fire service deployment taking place (for the duration of the experiment), and a fictitious person being present who leaves the door to the residence open during the escape. This baseline scenario was tested twice (tests 1 and 17, see table 2.2). The other tests are variants of the baseline scenario where variations were introduced to several variables (see section 2.4) in order to test the influence of measures for risk management[16] and different deployment methods. In addition, two variants serve as the basis for the comparison with the variants where measures for risk management were applied (see section 2.4.4 for further information).

2.2 Test site

2.2.1 Selection of the test site

A building had to be found which would be suitable for conducting the field experiments. This building should comply with the following criteria:

> at least four storeys high with a (straight) internal corridor of approximately 20 metres,
> corridors with residences / rooms on both sides,
> ten identical rooms / corridors,
> with pipe and lift shafts and common building installations,
> built between 1960 and 2012, and
> of an adequate overall condition.

Given the average year of construction of residential buildings with internal corridors, a building built after 1960 and before 2012 was the obvious choice. Buildings from before this period are no longer representative for the current building stock, and buildings from after 2012 were built to comply with the regulations for new structures in the Dutch Building Decree 2012 and form only a small part of the current building stock. The choice of at least four storeys is due to the fact that this number is representative for the average residential building. More importantly, four storeys offered the possibility to examine smoke propagation to storeys below or above the storey where the fire started. Real-life cases have shown that smoke often propagates to several floors, mainly upwards.

[16] Measures for risk management can be divided into source and effect measures. Source measures in this study are the furniture being made of organic materials and the mobile water mist. The closed door and the smoke resistant partition are effect measures.

Several potentially suitable buildings were viewed. The vacant De Schuylenburcht building was found to fulfil the above criteria, making it a suitable test site.

2.2.2 Layout of the test site

De Schuylenburcht is a former residential care home in the municipality of Oudewater (see figure 2.1), built in 1973. The concrete and brick building has two wings and an L-shaped layout (see Appendix 2 for a top view). The long side of the building consists of four storeys. A ventilation system with an exhaust opening in the roof structure provides natural ventilation for the entire building. Appendix 3 contains further information about the building's ventilation principle and the building installations.

Figure 2.1 De Schuylenburcht

Upon entering the building through the main entrance on the ground floor, staircases on the right and the left-hand sides of the building lead to the first, second, and third floors. These staircases can be reached via internal corridors. There is also a lift in the building. The first, second and third floors of the four-storey building section are basically all laid out identically. Each of these floors has an internal corridor, both sides of which end in a staircase. This means that people can escape the building in two directions. The requirements of the Dutch Building Decree for existing structures apply to this building. The staircase and the lift in the building have been separated from the floors by a fire-resistant structure. Every residence is a separate fire compartment and the residences are separated from the internal corridor by fire-resistant structures. Double doors on the upper floors form partitions between the different corridor sections. These double doors are fitted with wired glass and only their sealing function offers fire-resistance.

The first floor (i.e. the second storey) of the building (i.e. of the building section with four storeys) was chosen as the floor where the fire test would be conducted. This means that the fire room was located on this floor (see figure 2.2 for the floor plan). Since real-life case studies showed that smoke often propagates to several floors, especially floors at a higher level, it was required that there was more than one floor above the floor where the fire room was located. To be able to also examine the smoke propagation to a lower floor, the first floor was chosen. The floor plans for all floors (ground floor and first to third floor) can be found in Appendix 4.

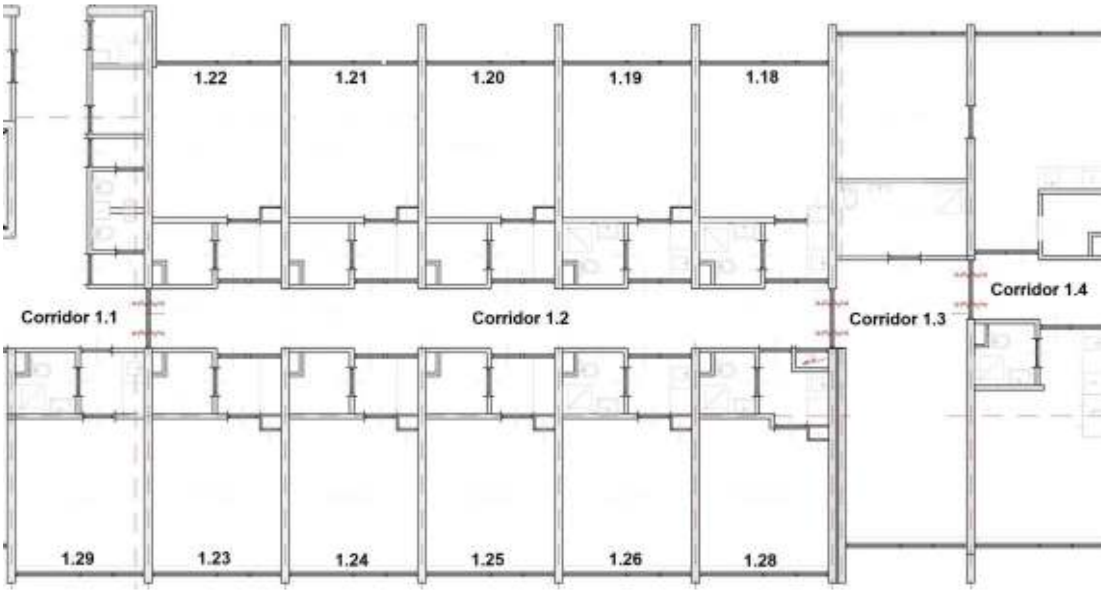


Figure 2.2 Floor plan of the first floor

The central part of the first floor (corridor 1.2 and residences along corridor 1.2 in the floor plan) is the most representative for a residential building with an internal corridor. This part consists of an internal corridor – which can be reached by double doors at both ends – onto which ten almost identical residences open; five residences on each side of the corridor (see figure 2.3 for a floor plan and figure 2.4 for a photo). This internal corridor is approx. 19 metres long, approx. 1.8 metres wide and approx. 2.4 metres high, and has a volume of approx. 82 cubic metres. The double door on the right-hand side of the corridor leads to a former 'living room' (corridor 1.3) which leads to a staircase via a double door and corridor 1.4. On the left-hand side, the internal corridor leads to a staircase and a lift via the double door and corridor 1.1 (see figure 2.2). Figure 2.5 shows photographs of the double door in the corridor and the front door of a residence on the first floor.

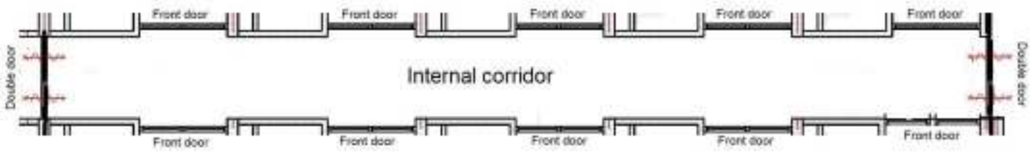


Figure 2.3 Floor plan of an internal corridor

Figure 2.4 Internal corridor on the first floor

Figure 2.5 Double door and front door of a first-floor residence

The floor plan of a residence on the first floor is shown in figure 2.6. The front door[17] opens into a small lobby. This lobby features a kitchen on the right-hand side and a door leading into the bathroom on the left. There is an open connection between the lobby and the living room/bedroom. There are windows in the outer wall side of the living room/bedroom. The residences on the east side of the building have balconies which can be accessed by means of a balcony door in the outer wall. The surface area of the residence is approx. 21 square metres and the volume is approx. 53 cubic metres.

Figure 2.6 The floor plan of a residence

The bathroom of every residence accommodates a shaft with a ventilation duct that connects to the residences located above each other. One ventilation opening of this duct is located over the bathroom door in the lobby of each residence and one in the actual bathroom.

2.2.3 Preparation of the test site

Before the field experiments were started, modifications were made to the building, both for safety reasons and to keep the conditions during the tests as equal as possible, as well as to minimise the influence of any disruptive factors. This section discusses the main modifications on the first floor. A complete list of all modifications is given in Appendix 5.

The internal corridor on the first floor (corridor 1.2) originally had a double door on one side only, i.e. towards corridor 1.1. There was an open connection between the corridor and corridor 1.3. Since this might give rise to a significant smoke buffer and it might give a distorted view of the conditions during a fire in corridor 1.2, a double door was also installed between corridor 1.2 and corridor 1.3. All the combustible materials were removed from all the first-floor residences in which measurements were conducted. Furthermore, Promatec-100 fire board was installed in several locations in the fire room to protect against heat and radiation and to reduce the risk of glass breaking/failing. As a result of the air and smoke permeability research (see section 2.3.3), major air leaks were sealed in fire room 1.19 and in the partition between fire room 1.21 and corridor 1.2.

2.3 Preliminary research

2.3.1 Simulations

Two simulations were performed with CFAST version 7.4.3 to prepare for the actual tests in the test building. CFAST is a two-zone simulation model for fire growth and smoke propagation from the National Institute of Standards and Technology (NIST). The simulations were performed to get an initial picture of the fire development and smoke propagation that could be expected in the test building.

Two variants of the tests were simulated: one was performed with variant 0 (door open) and one with variant 1 (door closed). The fire service deployment was not considered in either variant. The input parameters, input files and extensive results of the simulations can be found in Appendix 6.

[17] Where referring to 'door open' or 'door closed', this means the front door to the residence.

The results of the simulations can be summarised as follows:

- The fire was hardly ventilation controlled in the simulation with the door open, whereas it was ventilation controlled in the simulation with the door closed.
- During the simulation with the door open, smoke propagated to all the rooms (projected in the simulation) on the first floor, except residence 1.24. Smoke also propagated to the corridors and residences on the other floors. The ventilation ducts played an important role in the smoke propagation through the building.
- During the simulation with the door closed, opening the door from the fire room to corridor 1.1 for 30 seconds was decisive for the smoke propagation to corridor 1.2. On the other floors, the smoke did not propagate beyond the corridors and the residences above or below the fire room. The ventilation ducts also played an important role in the smoke propagation through the building in this simulation.

2.3.2 Pre-test

A pre-test day was held at the Schuylenburcht test site in May 2019 to verify that the fire scenario was realistic, that the measuring equipment and measurement design would provide the right information, and whether any adjustments should be made to the work process. The pre-test consisted of two fire tests: one test in the residence / fire room 1.19 and one test in the residence / fire room 1.21. The research design was fine-tuned and finalised on the basis of the outcomes of this pre-test.

2.3.3 Air and smoke permeability research

On 7 June 2019, the Nieman Raadgevende Ingenieurs consultancy firm conducted air and smoke permeability research in residence 1.19, residence 1.20 and residence 1.21 in order to assess the leak tightness of external and internal partition structures in the building. Table 2.1 provides a summary of the air permeability measurements with natural ventilation (NV) open or closed / taped up. The research report can be found in Appendix 7.

Table 2.1 Results of the air permeability measurements

Residence	Leak with NV open [cm^2]	Leak with NV closed [cm^2]	Difference [cm^2]
1.19	164	61	103
1.20	191	54	137
1.21	227	136	91

The air and smoke permeability research provided the following information about possible smoke propagation routes:

- to the internal corridor via openings in the wall structure between the residence and the corridor.
- to the overhead residences (2.19 or 2.21) via penetrations for the central heating system, a CAI connection and a corner detail of the wall that forms a partition between the floor and the residence.
- via gaps and openings, including in fire boards (both internally and externally).
- to the neighbouring residence 1.20 via the wall sockets in the partition wall between the residences.
- to the outside through openings in the outer wall.

It is concluded that there were considerable differences in the air permeability of the different residences. They were caused by specific differences, especially in the internal partitioning structures. As a result, the internal / external air permeability ratio differed from residence to residence, but the internal leak tightness (inside the building) always exceeded the external leak tightness (to the exterior).

2.4 Field experiments

A total of nineteen tests were conducted for the current research. All tests -– except those for the baseline scenario – lasted 55 minutes and consisted of the following two phases: a 20-minute escape phase and a 35-minute deployment phase. The baseline scenario did not involve a deployment phase during the test: the fire was extinguished after 55 minutes. The baseline situation during the field experiments, the variables in relation to the escape and deployment phases, and the measurement design are discussed below. All the actions that were performed while testing were recorded in protocols (see Appendix 9).

2.4.1 Baseline situation

This section presents the general baseline situations and the baseline situations for the escape and deployment phases. The baseline situation concerns the elements that were identical in every test that was conducted.

General

Residences 1.19 and 1.21 on the floor plan of figure 2.2 were used as the fire rooms during the tests. It was decided to work with two fire rooms since there were two tests per day (with exception of the first day). Changing the fire room prevented the heated partitioning structures, the evaporating gases, and the moisture in the room that had been used, from potentially influencing subsequent tests. Some residences were not suitable for use as a fire room because their ventilation profiles differed (see Appendix 3A). To rule out any differences due to the influence of wind on the outer wall as much as possible, it was decided to only use rooms on one side of the building as the fire rooms. The east side was preferred as this would reduce any nuisance (smoke) in the neighbouring area.

The windows and the door in the outer wall of the fire room were kept closed and the ventilation ducts to the rest of the building, except those in the bathroom, were left open. This ensured that the ventilation profiles in the fire rooms would remain identical as much as possible and the natural ventilation remained intact as much as possible. The fire rooms had no direct open connection to the corridor via ventilation ducts. Residence 1.18, residence 1.20 and residence 1.22 do have a direct open connection to the corridor through a ventilation duct. This is explained in Appendix 3A. The baseline situation for the ventilation profile of the other residences in the residential building, except residence 1.25, was assumed to be a situation where the doors to the residences were closed and the (fictitious) people were still in the residences. The door to residence 1.25 was left open throughout all the tests in order to be able to compare the effect of an opened door in the other residences to that of a closed door. Here, it was assumed that any people present had escaped before the fire service started its deployment.

In the two fire rooms, the fire object was placed in the corner of the living room/bedroom and ignited by means of crib no. 5 (see figure 2.7).[18] A detailed description of the positions and ignition of the fire objects is given in Appendix 8.

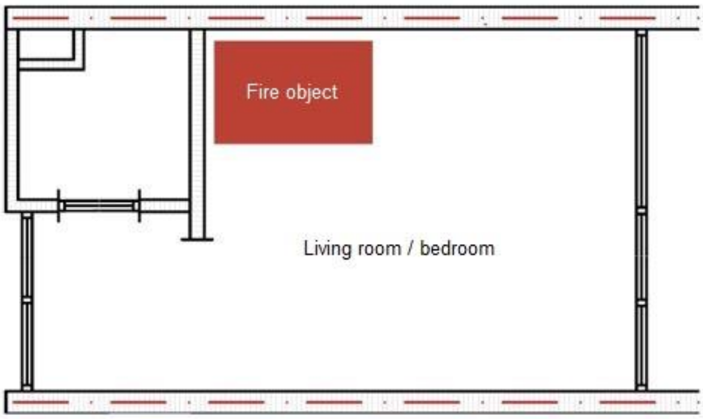


Figure 2.7 Position of the fire object and a photo of crib no. 5

Escape phase

The escape phase concerns the actions and environmental conditions for the people present. This phase runs from the ignition (t = 0 minutes) until the start of the deployment (t = 20 minutes). This phase lasted 20 minutes, assuming the following time frame (see figure 2.8):

> The start of the fire, the alarm of the smoke detector in the residence, and the report of the fire by the occupant (start at t = 0 minutes, end at t = 4 minutes). There was no in-house emergency response organisation in the building.

> The occupant of the residence in which the fire started (the fire room) opens the door in order to escape (t = 5 minutes).

> End of the escape phase (t = 20 minutes).

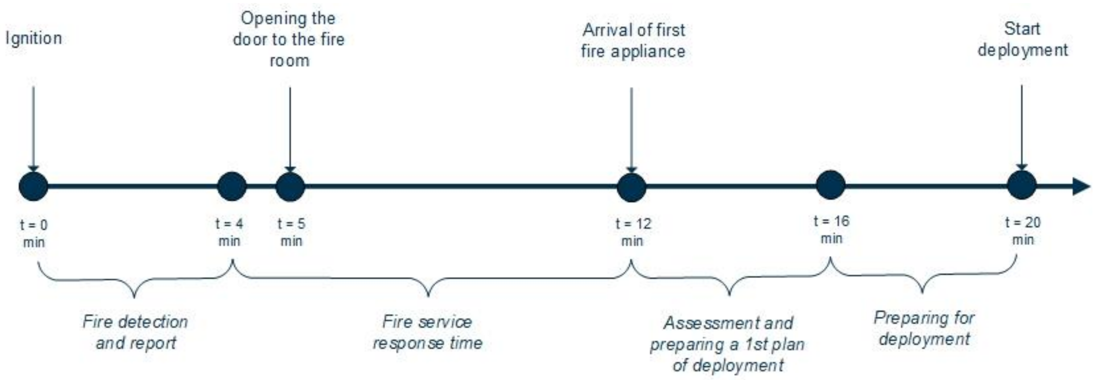


Figure 2.8 The escape phase

With regard to escaping, it was assumed that there was one person in each residence, except in the fire room and in residence 1.25, whose door was open during all the tests. The people living in these latter two rooms were assumed to have already escaped.
Events relating to the fire service's operational time also occurred during the escape phase. The following time frame was assumed for this:

> The fire being reported to the incident control room (t = 4 minutes).

[18] Crib no. 5 was ignited according to the protocol in British standard BS 5852:2006.

> The response time for the first fire appliance from the moment the fire was reported (start at t = 4 minutes, end at t = 12 minutes).
> The assessment by the fire service and preparing a first deployment plan (start at t = 12 minutes, end at t = 16 minutes).
> The fire service preparing for the deployment (start at t = 16 minutes, end at t = 20 minutes).

In total, the operational time of the fire service, i.e. the time between the moment the fire started and the fire service's initial action, was 21.5 minutes. This was because it was assumed that it would take the fire service 1.5 minutes to progress to the fire room through the corridor from the start of its deployment until the actual action could be taken (see figure 2.14 and figure 2.15).

External size-up
An external size-up was performed at 15 minutes after the start of the test – i.e. the moment when the fire service would arrive at the building – to determine whether the fire room could be located from the outside. Both smoke indicators and thermal differences were examined (using a thermal imaging camera, type FLIR E50 TIC).[19]

Deployment phase
The deployment phase, which followed immediately after the escape phase after 20 minutes, is the phase from the moment when the deployment started until the end of the test after 55 minutes. Two different deployment methods were applied during this phase. These methods and their time frames are explained in section 2.4.3.

A standard deployment[20] by a crew of four crew members[21] and a crew commander, together with the possibilities offered by a fire appliance, was assumed.[22] It was decided to use the staircase on the south side of the building which lands in corridor 1.4 on the first floor as the route of deployment (see the red arrow in figure 2.9). From this corridor, the deployment crew progressed towards the fire room from the start of the deployment (t = 20 minutes) via two double doors and corridor 1.3. Door management was applied according to the basic principles in order to limit an unnecessary supply of oxygen when entering the fire room where possible.[23] The fire was extinguished by directly extinguishing the object and, where necessary, it was alternated with gas cooling above the fire. The extinguishing agent was water which was applied by means of a standard high-pressure jet with a flow rate of 100-125 litres per minute at 40 bar pressure from the pump. Because the fire hose needed to be pulled through during the deployment, the two double doors in the fire service's deployment route were always ajar. All the actions of the deployment crew were recorded in a deployment protocol (see Appendixes 9C - 9F).

[19] This external size-up was performed in accordance with the teaching materials from the Crew Member A (Manschap A) course (Brandweeracademie-IFV, 2019b).
[20] In accordance with the teaching materials from the Firefighting module of the Dutch Fire Service Academy's crew member training course.
[21] All crew members who were active during the tests were active in repressive roles in a fire brigade and had at least the Manschap A (Crew Member A) diploma.
[22] This is the minimum potential to be alerted in the event of 'building on fire' in accordance with the national reporting and alerting scheme. In line with the 'Bespoke Turnout' (Uitruk op maat) project, this study did not consider whether the personnel arrived on the scene in one or more vehicles.
[23] It was decided to not apply any special aids such as a smoke stopper since this was not a standard method of the Dutch fire service, or at least not yet. In addition, in order to prevent any damage to door posts and thus negatively affect the possibility of repeating the tests, it was decided not to force any access doors while carrying out the study.

Mechanical ventilation was opted for the ventilation during the deployment phase; this involved installing and running a positive pressure fan in order to create a flow which would dispel the smoke to the outside. Natural ventilation, where windows or balcony doors in a residence, a corridor or room are opened, would have been the alternative.
Two electric fans with capacities of 25,000 cubic metres per hour each were used (figure 2.9 shows the locations of the fans). When the fire was extinguished, the balcony door in the fire room was opened first, followed by the door in the outer wall in corridor 1.3 and the double doors between corridors 1.2 and 1.3 in order to create a flow profile. Subsequently, the fan in corridor 1.3, directed towards corridor 1.2, was switched on. While ventilating, all the doors were blocked by means of wedges in order to prevent them from being blown shut. While ventilating the residences, the door to the bathroom was also opened and blocked. The fan was left running for the rest of the test. After ventilating the ground floor, the second floor and the third floor as well, the second fan in corridor 1.1, directed towards corridor 1.2, was activated. The door in the outer wall of residence 1.29 was opened to create the flow profile.

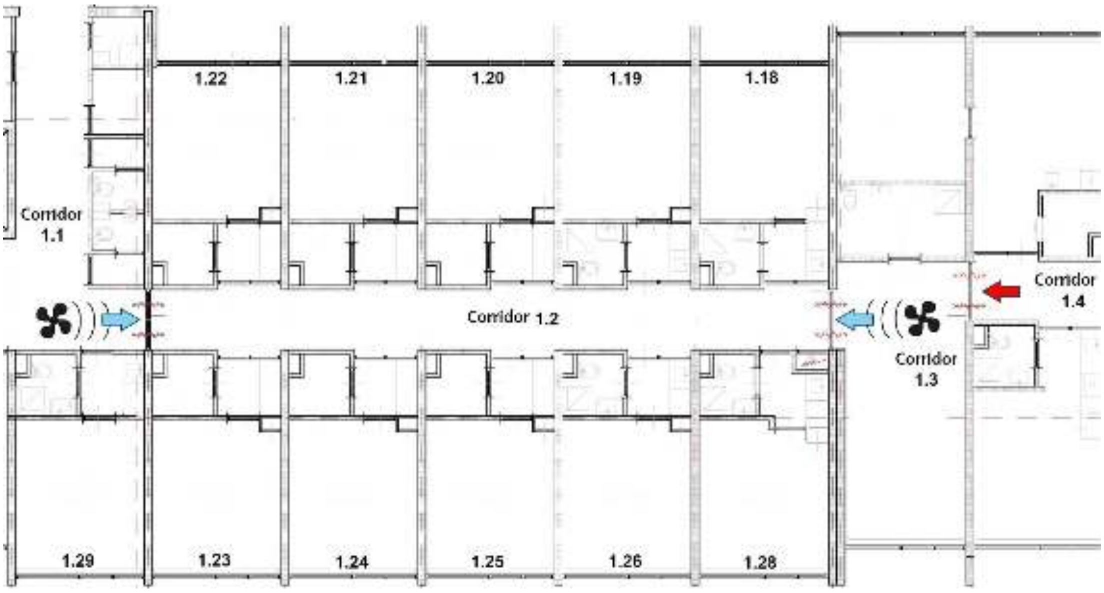


Figure 2.9 Deployment route and fan locations

Post assessment
The deployment crew carried out post assessments following each test. This included carbon monoxide measurements at various locations in the building and at various times (between t = 55 minutes and t = 90 minutes). These measurements were taken to determine whether there was still carbon monoxide in any rooms and whether concentrations had dropped to safe levels to allow people to enter the building again without wearing any protective equipment.

2.4.2 Variables in relation to the escape
This section discusses the variables that influence smoke propagation and the possibility of escape and survivability during the escape phase.

Fire object
Two different types of fire object were used during the tests: a sofa and an organic fire load (see figure 2.10). Seventeen tests were conducted with the best-selling two-seater sofa in the Netherlands which mainly consists of polyurethane foam. Two other tests were conducted with an organic fire load (wood) in order to examine the influence of the source on

smoke propagation. Detailed descriptions of the fire objects can be found in Appendixes 8A and 8B.

Figure 2.10 Fire objects: sofa (on the left) and organic fire load (on the right)

To ignite the sofa, the crib was placed in the corner of the seat, the backrest and the armrest, the closest to the outer wall (see figure 2.11). To ignite the organic fire load, the crib was placed in the same corner, between the first two battens (see figure 2.11).

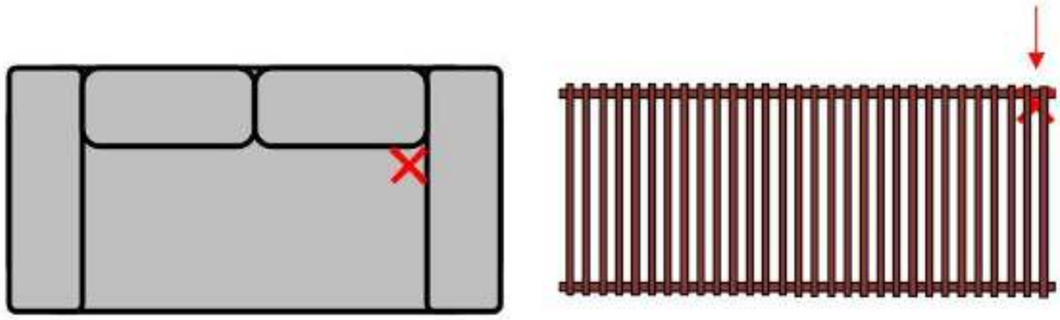


Figure 2.11 Position of the crib on the fire objects

The door to the fire room

Two different positions of the door to the fire room were tested during the field experiments:

> Door open: the occupant of the residence in which the fire started (the fire room) opens the door (t = 5 minutes) and escapes through corridors 1.2 and 1.3 to a safe location outside the residential building (indicated in light blue in figure 2.12). The door to the fire room was open in tests 1, 3, 5, 7, 9, 15, 17, 18 and 19 (see table 2.2).

> Door closed: the occupant of the residence on fire opens the door (t = 5 minutes) and then closes this door (t = 5.5 minutes) before using corridors 1.2 and 1.3 to escape to a safe location outside the residential building (indicated in dark red in figure 2.12). The door to the fire room was closed in tests 2, 4, 6, 8, 10, 11, 12, 13, 14 and 16 (see table 2.2).

The occupants' escape behaviour was taken into account in the above described positions of the door to the fire room.

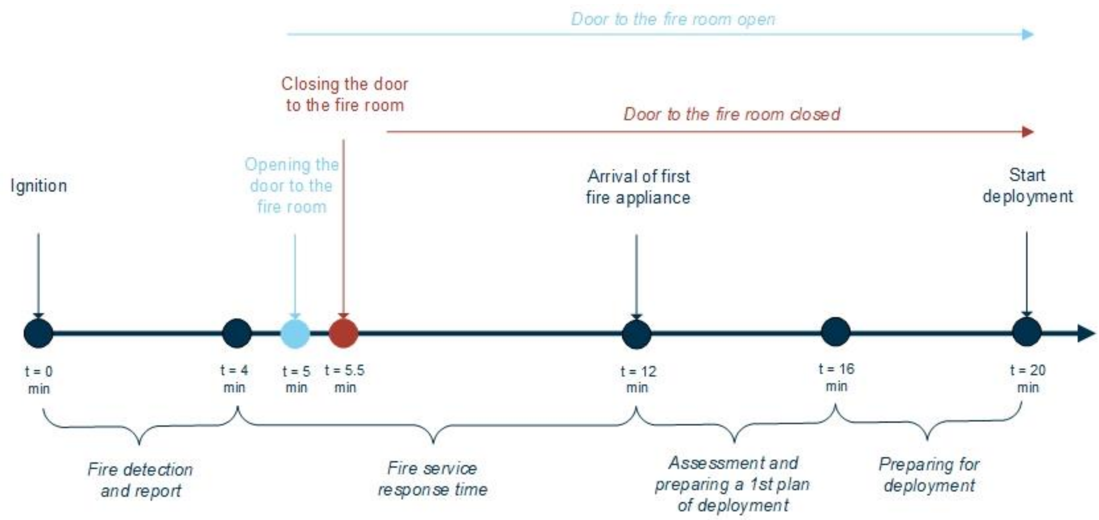


Figure 2.12 Escape phase, including the door open and door closed time frame

The balcony door

Two tests were conducted with both the door to the fire room and the balcony door open (tests 18 and 19, see table 2.2) in order to create a situation with maximum ventilation. These tests were conducted to examine the influence of an open balcony door on the possibility of escape and survivability.

Smoke resistant partitions

Two different smoke resistant partitions were tested during the field experiments:

> Smoke resistant partitions in accordance with the existing situation (existing structure). These smoke resistant partitions were already present in the building. The existing smoke resistant partitions were tested in tests 1 - 9 and in tests 14 - 19 (see table 2.2).

> Smoke resistant partitions in accordance with the new requirements in the future Dutch Building Decree (*BBL*). Smoke resistant doors (S200) were installed in the fire room and in residence 1.24 during these tests (10 - 13, see table 2.2). Furthermore, the gaps and air leaks in both the external and internal partitioning structures of the two rooms were sealed as much as possible and the ventilation duct was closed.

Mobile water mist system

The effect of an automatic fire extinguishing system, i.e. a mobile water mist system, hereinafter 'mobile water mist', in the fire room was examined (tests 6 - 9, see table 2.2). It was decided to use a mobile system, since, contrary to a fixed system, a mobile system is easy to install and remove. The mobile water mist was placed against the wall opposite the fire object (indicated in light blue in figure 2.13); this position is, from the perspective of the side of the sofa, one metre in the direction of the outer wall. The water mist was activated by a multi-sensor fire detector and featured a 130-litre water tank. The tank was empty about fifteen minutes after activation of the system.

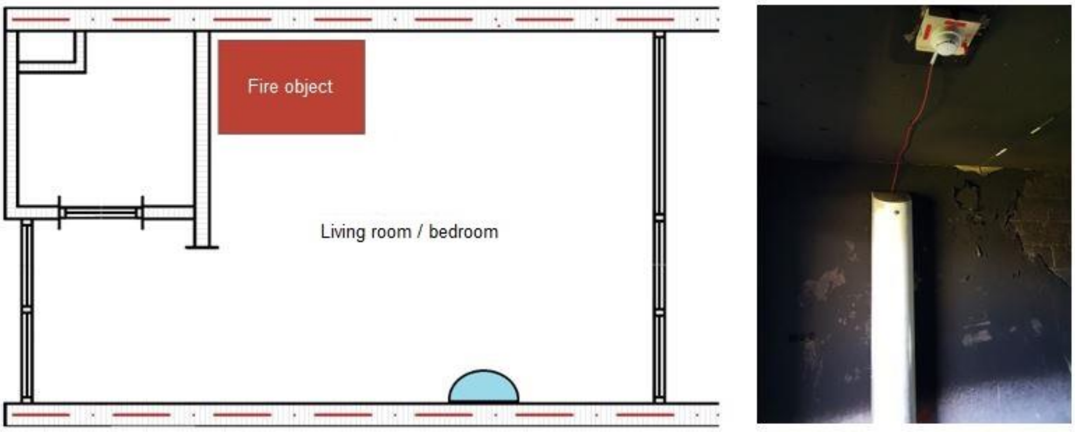


Figure 2.13 Position of the mobile water mist in the fire room and a photo of the mobile water mist

A combination of smoke resistant partitions and mobile water mist
The effect of the combination of the smoke resistant partitions in accordance with the new requirements and the application of the mobile water mist was examined in tests 10 and 11 (see table 2.2).

2.4.3 Variables in relation to the deployment

The variable that influences smoke propagation and the possibility of escape and survivability is the choice of deployment method made by the fire service: no attack, an offensive interior attack, or a defensive interior attack. During the tests without deployment (tests 1 and 17), the fire was not extinguished until the end of the test. The offensive and defensive interior attacks are explained in more detail below.

Offensive interior attack
An offensive interior attack involves the fire to be extinguished before the fire service starts to evacuate people from the building. Here, the actual evacuation was not simulated, but it was assumed that this would take place simultaneously with ventilating the residences. The following time frame was assumed during the offensive interior attack (see figure 2.14):

> The deployment crew progresses towards the fire room from corridor 1.4 and takes position near the door to the fire room (start at t = 20 minutes, end at t = 21.5 minutes).
> The deployment crew enters the fire room and starts extinguishing the fire (t = 21.5 minutes).
> The deployment crew starts ventilating the fire room and the corridor on the first floor (t = 25 minutes).
> The deployment crew starts ventilating the other first-floor residences (t = 27 minutes).
> The deployment crew starts ventilating the rest of the building (t = 36 minutes).
> End of test (t = 55 minutes).

Figure 2.14 Deployment phase: offensive interior attack

An offensive interior attack was performed in tests 2, 5, 6, 9, 10, 12, 15, 16 and 18.

Defensive interior attack

A defensive interior attack consists of the fire service closing the door to the fire room and then first evacuating the occupants from other residences before fighting the fire. Phased evacuation was opted for, with the people in the residences on corridor 1.2 being evacuated first.[24] It was determined that one minute would be needed to get a person out of the residence and beyond the double doors. To simulate this, the deployment team opened the door to the residence for half a minute and then walked through the double doors between corridors 1.2 and 1.3. A two-man crew jointly escorted one (fictitious) occupant to a safe part of the building (corridor 1.3). When in the safe part, the evacuation was fictitiously taken over by other people/relief workers.

The following time frame was assumed during the defensive interior attack (see figure 2.15):

> The deployment crew progresses towards the fire room from corridor 1.4 and takes position near the door to the fire room (start at t = 20 minutes, end at t = 21.5 minutes).
> The deployment crew closes the door to the fire room (t = 21.5 minutes).
> The deployment crew starts evacuating the first floor (t = 22.5 minutes).
> The deployment crew enters the fire room and starts extinguishing the fire (t = 35 minutes).
> The deployment crew starts ventilating the fire room and the corridor on the first floor (t = 38.5 minutes).
> The deployment crew starts ventilating the other first-floor residences (t = 39.5 minutes).
> The deployment crew starts ventilating the rest of the building (t = 43.5 minutes).
> End of test (t = 55 minutes).

[24] The evacuation sequence was recorded in the deployment protocol (see Appendix 9).

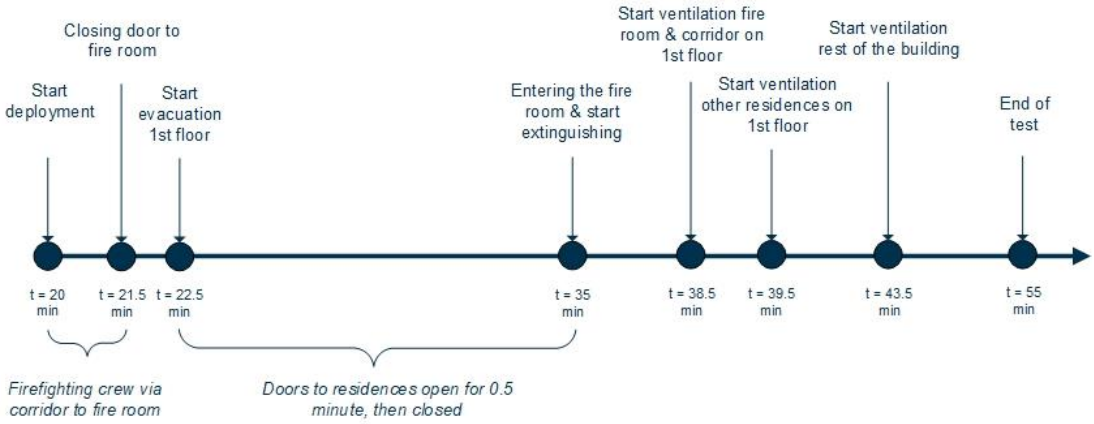


Figure 2.15 Deployment phase: defensive interior attack

A defensive interior attack was performed in tests 3, 4, 7, 8, 11, 13, 14 and 19.

2.4.4 Overview of the tests and variables

Table 2.2 shows an overview of the field experiments conducted and the escape and deployment variables of each test. The tests have been classified into variants. The test numbers and the date numbers indicate the chronology of the tests, while the number of the fire room shows where the test took place. In addition, two variants serve as a basis for comparison with variants with measures for risk management, in order to examine the effect of these measures:

> Variant 0 (door open) forms the basis for comparison with variant 1 (door closed) and variants 2, 6 and 8 (measures for risk management and door open).

> Variant 1 (door closed) forms the basis for comparison with variants 3, 4, 5 and 7 (measures for risk management and door closed).

Table 2.2 Overview of the tests and variables

Test	Date	Fire room	Escape					Deployment
			Fire object	Door to the fire room	Balcony door	Smoke resistant partitions	Mobile water mist	Methods
Variant 0: Door open								
1	240619_1	1.21	Sofa	Open	Closed	Existing	No	None
3	250619_2	1.19	Sofa	Open	Closed	Existing	No	Defensive
5	260619_2	1.19	Sofa	Open	Closed	Existing	No	Offensive
17	040719_2	1.19	Sofa	Open	Closed	Existing	No	None
Variant 1: Door closed								
2	250619_1	1.21	Sofa	Closed	Closed	Existing	No	Offensive
4	260619_1	1.21	Sofa	Closed	Closed	Existing	No	Defensive

16	040719_1	1.21	Sofa	Closed	Closed	Existing	No	Offensive
Variant 2: Mobile water mist and door open								
7	270619_2	1.19	Sofa	Open	Closed	Existing	Yes	Defensive
9	280619_2	1.19	Sofa	Open	Closed	Existing	Yes	Offensive
Variant 3: Mobile water mist and door closed								
6	270619_1	1.21	Sofa	Closed	Closed	Existing	Yes	Offensive
8	280619_1	1.21	Sofa	Closed	Closed	Existing	Yes	Defensive
Variant 4: Mobile water mist, smoke resistant partition, and door closed								
10	010719_1	1.21	Sofa	Closed	Closed	BBL	Yes	Offensive
11	010719_2	1.19	Sofa	Closed	Closed	BBL	Yes	Defensive
Variant 5: Smoke resistant partition and door closed								
12	020719_1	1.21	Sofa	Closed	Closed	BBL	No	Offensive
13	020719_2	1.19	Sofa	Closed	Closed	BBL	No	Defensive
Variant 6: Organic fire load and door open								
15	030719_2	1.19	Wood	Open	Closed	Existing	No	Offensive
Variant 7: Organic fire load and door closed								
14	030719_1	1.21	Wood	Closed	Closed	Existing	No	Defensive
Variant 8: Balcony door open and door open (maximum ventilation)								
18	050719_1	1.19	Sofa	Open	Open	Existing	No	Offensive
19	050719_2	1.19	Sofa	Open	Open	Existing	No	Defensive

2.4.5 Measurement design

In order to be able to establish the details of smoke propagation in a residential building with internal corridors and its effect on the possibility of escape and survivability, several variables were measured during the field experiments. These variables were chosen on the basis of the theoretical framework in chapter 1. The variables and measuring equipment are briefly explained in more detail below. A summary of the measuring equipment used on the first floor and the associated relevant information is given in table 2.3. A further explanation of the measuring equipment, its technical specifications, and the possibility of measurement errors is given in Appendix 10. The measurement locations on the first floor are shown in a floor plan (see figure 2.16).[25] The measurement locations on all floors are shown in Appendix 11.

Temperature
During the tests, the temperature was measured at several measurement locations using 89 thermocouples (type K). A total of 56 thermocouples were placed at different heights on eight different measuring poles (poles B1 - B8 on the floor plan in figure 2.16) on the first floor: 0.3 metre, 0.9 metre, 1.5 metres, 1.8 metres, 2 metres, 2.2 metres and 2.4 metres. In addition, three separate thermocouples were placed on the first floor in three different ventilation ducts in corridor 1.2 (indicated by the light blue circles in figure 2.16). The data from these thermocouples was registered using the LabVIEW system.

Radiation
Two types of radiation meters were used in order to measure the radiation during the tests: five water-cooled heat flux sensors (Schmidt-Boelter) and five plate thermometer heat flux meters (PTHFM). The radiation meters were only placed on the first floor on six different measuring poles (B1 and B4 - B8 on the floor plan in figure 2.16). The water-cooled heat flux sensors were placed at a height of 0.3 metre on measuring poles B4 - B8. The plate thermometer heat flux meters were placed at heights of 0.3 and 1.5 metres on measuring pole B1 and at a height of 1.5 metres on measuring poles B4 - B6. The data of these radiation meters was registered using the LabVIEW system.

Pressure
Twelve differential pressure meters were used to measure the pressure during the tests. Eight differential pressure meters were placed on different measuring poles (B1 - B8 on the floor plan in figure 2.16) at a height of 0.2 metre to measure the pressure difference between the room and the outside air. The data from these differential pressure meters was registered using the LabVIEW system.

Visibility distance
The visibility distance was measured by means of cameras aimed at signs and by means of photovoltaic cells. A total of four cameras were aimed at visibility distance signs installed on a wire secured at a distance of 2 to 9 metres from a camera. Both the cameras and the visibility distance signs were installed at a height of 1.5 metres. The visibility distance was then recorded using the camera images. One camera with visibility distance signs was placed on the first floor. This is indicated by ZL1 (see figure 2.16). In addition, four visibility distance meters were used. They consisted of a light source and a photovoltaic cell that were placed specific distances (from 15 to 25 cm) apart. These visibility distance meters were only installed in corridor 1.2 on the first floor. They were installed at both 0.3 and 1.5 metres high on measuring poles B5 and B6 (see figure 2.16). The data from these meters was registered using the LabVIEW system.

Smoke layer height
The height of the smoke layer was measured by means of a painted batten with height markings from 0 to 2.4 metres. In total 19 battens were installed, 7 of which were on the first floor (RH1 to RH7, see figure 2.16). The smoke layer height was then recorded using camera images.

[25] As measurement location B1 changes along with the fire room (residences 1.19 or 1.21), it is shown in the floor plan twice.

Weight
The weight of the fire object was measured continuously using a weighing scale consisting of three load cells. They were installed in the fire room (residence 1.19 or 1.21) in a triangular arrangement in a fixed position under the fire object (WS1 in figure 2.16). The data from the load cells was registered using the LabVIEW system.

Gas concentrations
The gas concentrations, i.e. the oxygen (O_2), carbon monoxide (CO), carbon dioxide (CO_2) and nitrogen oxides (NO_x) concentrations, were measured using Testo measuring equipment on the first floor and Dräger measuring equipment on the other floors. Gas measurements were conducted in 20 locations, 10 of which on the first floor (G1 - G8 in figure 2.16). All the gas measurements were conducted at a height of 1.5 metres, except the gas measurements at measurement locations G5 and G6 which were conducted at heights of 0.3 and 1.5 metres. The gas measurement data was recorded using the Testo or Dräger systems.

Table 2.3 Overview of the measuring equipment on the first floor

Measuring equipment	Measurement location	Measuring height	Quantity	Recording
Thermocouple type K	B1 - B8 Corridor 1.2	0.3 - 0.9 - 1.5 - 1.8 - 2 - 2.2 - 2.4 2.1	56 3	LabVIEW
Water-cooled heat flux sensor (SB) Plate thermometer heat flux meter (PTHFM)	B4 - B8 B1 B4 - B6	0.3 0.3 and 1.5 1.5	5 2 3	LabVIEW
Differential pressure meter	B1 - B8	0.2	8	LabVIEW
Visibility distance signs	ZL1	1.5	1	Camera
Visibility distance meter	B5 and B6	0.3 and 1.5	4	LabVIEW
Smoke layer height	RH1 - RH7	0 to 2.4	7	Camera image
Weighing scale	WS1	N/A	1	LabVIEW
Gas measurements	G1 - G4, G7, G8 G5 and G6	1.5 0.3 and 1.5	6 4	Testo

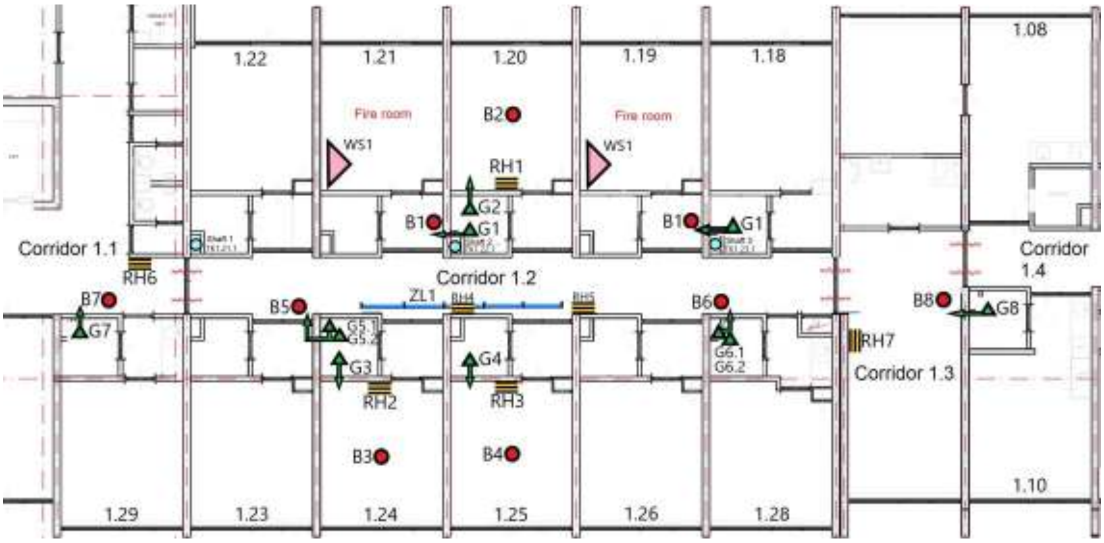


Figure 2.16 Measurement locations on the first floor

Camera images

In order to get a visual image of the smoke propagation, 34 video cameras were used to record the individual field tests. These cameras, as identified above, were also used to obtain a visual image of the visibility distance and the smoke layer height. The cameras were placed on the floor, in a window frame, or at a height of 1.5 metres. The locations of these cameras on the first floor are shown in figure 2.17.[26] The camera locations on all floors are shown in Appendix 11.

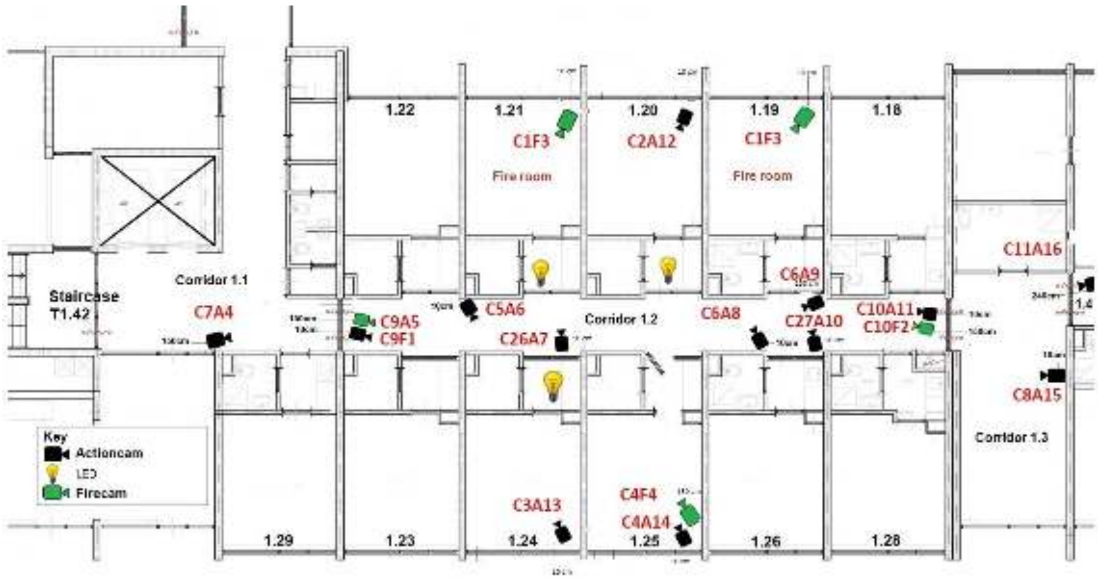


Figure 2.17 Camera locations on the first floor

[26] As camera C1F3 changes along with the fire room (residences 1.19 or 1.21), it is shown in the floor plan twice.

2.5 Data analysis

The data obtained from the measurements was analysed in order to answer the research questions about smoke propagation in real-life situations, the possibility of escape and survivability, measures for risk management, and the fire service's deployment method. This section discusses the data analysis per research question.

2.5.1 Smoke propagation in the residential building

To answer the third research question '*In the event of fire in the residential building, how does the smoke actually propagate in practice and what are the decisive factors for this propagation?'*, two issues were examined:

> smoke propagation routes
> factors that play a role in smoke propagation.

Smoke propagation routes

All the camera images from the escape and deployment phases were examined in order to establish the smoke propagation routes. The escape and deployment phases were examined separately since the fire service actions might have influenced smoke propagation.

The assessment of these images led to the following aspects concerning smoke and smoke propagation for the individual tests and rooms:

> times when smoke was visible in a room
> smoke propagation route: smoke propagation between rooms, both horizontally and vertically
> sub-route: smoke propagation via a part of a partition between rooms (e.g. cracks)
> visibility (in the room while there was smoke) and visibility distance (only for corridor 1.2)
> smoke layer height (in corridor 1.2 and in first-floor residences).

Where the camera images did not show the route or building section along which smoke entered a room, this was noted as 'route unknown' and the smoke propagation route was not linked to a sub-route. Furthermore, the amount of smoke was not examined since this is subjective and not necessary in order to establish the smoke propagation routes.

Smoke is not always visible; it can also consist of invisible particles. The smoke propagation of these invisible particles was established by verifying whether any CO[27] was measured when no smoke was visible. Short, incidental peak measurements of CO (< 20 ppm), measured using Testo equipment or Dräger equipment were not included. The CO concentrations were only included in the smoke propagation routes and not in their sub-routes because gas measurements do not enable the determination of the route along which gases enter a room. This means that the smoke propagation routes were established both on the basis of camera images and CO measurements, while the sub-routes were established solely on the basis of camera images.

Factors that play a role in smoke propagation

In order to establish which factors play a role in smoke propagation, the same aspects as those established for examining the smoke propagation routes were used. In addition, it was

[27] Attention was paid to CO since, among the gases measured, this gas was found to be the gas that propagated the most through the building, as established on the basis of the data measured for the various gases.

assessed which variables (e.g. the door to the fire room being open or closed) were different for certain tests and what these differences meant for the smoke propagation. Based on the similarities and differences in smoke propagation between tests, the factors which played a role in this smoke propagation were established.

A factor is considered to be a 'factor which influenced smoke propagation' if it influenced the smoke propagation in all the tests within the same variant or in several variants (for example if the fire object is a factor). A factor is considered to be a ‘factor which potentially influenced smoke propagation’ based on differences in smoke propagation within one variant.

2.5.2 The possibility of escape and survivability

To answer the research question ‘*What influence does the observed smoke propagation have on the possibility of escape and survivability in the residential building for people with different degrees of vulnerability?*’, the possibility of escape and survivability was established on the basis of:
> three different groups
> the times for the possibility of escape and survivability for these three groups (for the first floor)
> the percentages of the threshold values for certain situations within the possibility of escape and survivability for these three groups at t = 20 minutes (for the first floor)
> the CO concentrations (for the ground floor, second floor and third floor).

The choices made and steps taken for these four aspects are explained below. A detailed explanation is given in Appendix 12.

Three different groups

The effect of the fire conditions on the possibility of escape and survivability differs from person to person. As mentioned in section 1.3.5, certain sub-populations are more vulnerable to these conditions than others and a sensitivity factor (sf) is used to represent this vulnerability. As vulnerability to the conditions differs from person to person, the current research used the sensitivity factor to distinguish between three groups:
> general group, sf = 1
> vulnerable group, sf = 0.3
> highly vulnerable group, sf = 0.1

Combining this sensitivity factor with the threshold values for the individual methods in table 1.2 from section 1.3.5 leads to the method-specific threshold values for the individual groups and situations as presented in table 2.4. These threshold values are used in order to determine the times for the possibility of escape and survivability.

Table 2.4 Overview of the threshold values according to SFPE

Fire condition	Method	Impaired			Life-threatening			Fatal		
		Highly vulnerable	Vulnerable	General	Highly vulnerable	Vulnerable	General	Highly vulnerable	Vulnerable	General
Irritant gases	FIC/FLD	0.1	0.3	1.0	0.5	1.5	5	0.1	0.3	1.0
Asphyxiant gases	FED_{IN}	-	-	-	0.1	0.3	1.0	0.2	0.6	2.0
Heat	FED_{heat}	0.1	0.3	1.0	0.8	2.4	8.0	1.2	3.6	12.0
Visibility	FEC_{smoke}	0.1	0.3	1.0	-	-	-	-	-	-

Times for the possibility of escape and survivability (first floor)
The times for the possibility of escape and survivability for the three groups were calculated using the equations from the SFPE manual described in Appendix 1. The fire conditions measured for the individual tests and rooms (irritant and asphyxiant gases, heat, and visibility distance) served as the input for these equations. The times were calculated for each individual test; where multiple tests of one variant were conducted, the average results were calculated to obtain one time per variant, room, situation and group. The research question was answered by considering the measurement data of the tests of variant 0 (door open), the tests of variant 1 (door closed), and the tests of variant 8 (balcony door open, maximum ventilation).

To analyse the possibility of escape and survivability, the times were rounded to whole minutes to compensate for any uncertainty in the measurements and the calculation method. Furthermore, the analysis only considered the first 20 minutes of the test (the escape phase) since the deployment might influence the smoke propagation and hence the times for the possibility of escape and survivability.

Percentages of threshold values at 20 minutes (first floor)
In addition to the times when the threshold values for the possibility of escape and survivability were exceeded, the percentages of the threshold values at 20 minutes were also considered for those situations where the threshold value had not been exceeded, since this percentage shows whether certain threshold values might *be on the brink* of being exceeded. This provides clarity as to whether staying in a room for more than 20 minutes might still lead to an impaired escape, or a life-threatening or fatal situation.

CO concentrations (ground floor, second floor and third floor)
The CO concentrations measured were considered in order to establish survivability on the ground floor, the second floor and the third floor. Based on the simulation carried out as part of the preliminary research, it was found that no increases in temperatures were to be expected on the ground floor, the second floor and the third floor. The visibility distance was

not measured on these floors, but, given the camera images, it is not expected that escaping would be impaired due to a poor visibility distance as a result of dense smoke. This made the development of the CO concentration the best means of predicting survivability on the ground floor, the second floor and the third floor. A brief analysis of the CO concentrations on these floors was made first. As they were not high enough to exceed the threshold values for a life-threatening or fatal situation during the escape phase (0 tot 20 minutes), the times for the possibility of escape and survivability were not considered for the ground floor, the second floor and the third floor.

The effect of an open balcony door
The effect of an open balcony door on the times for the possibility of escape and survivability was established by comparing the following elements of the tests of variant 8 (balcony door open, maximum ventilation) with those of the tests of variant 0 (door open):

- survivability in the fire room
- the possibility of escape in corridor 1.2
- survivability in corridor 1.2
- survivability in the other first-floor residences for up to 20 minutes
- the percentage of non-exceeded threshold values in the other first-floor residences at 20 minutes
- survivability on the other floors.

Differences between equal tests
Since for some variants several tests were conducted, it was examined whether there were any differences between these tests in terms of the times for the possibility of escape and survivability. This was done in order to assess whether other variables than the tested variables (the variants) played a role in the times for the possibility of escape and survivability. Subsequently, the outcome was included in a comparison of the variants in order to examine whether the difference could be attributed to the tested variables of the variant in question or whether other variables may have had an influence.

2.5.3 Effects of measures for risk management

The research method described in section 2.5.2 was used to answer the research question '*In the event of fire, to what extent are a) current and future smoke resistant partitions, b) a mobile water mist system, and c) an organic fuel effective in improving the possibility of escape and survivability in the residential building for people with different degrees of vulnerability?*' The effect of the measures for risk management for the different groups was established by comparing the variants of a measure to variant 0 (door open) or variant 1 (door closed) (see section 2.4.4 for a summary). It was also examined whether the measure tested led to an improvement or a deterioration for all the components (as described above under 'The effect of an open balcony door') examined together.

2.5.4 The deployment method

To answer the research question '*In the event of fire in the residential building, which deployment method gives the best possibility of escape and survivability?*', the degree to which the different tests and periods of deployment improved or worsened conditions in the room was compared. This was done by using the method for establishing the possibility of escape and survivability described in sections 1.3.5 and 2.5.2.

Since people are not constantly in the same room while escaping and during an evacuation, using the available escape time per room is not possible for the deployment phase, unlike for the escape phase. This is because the available escape time per room is a dose/speed calculation *for the specific room in question.* It was therefore decided that the threshold values for the possibility of escape and survivability would be examined in combination with an analysis of the CO concentration. An assessment was made as to whether the CO concentration increased or decreased (deteriorated or improved) in order to be able to come to a conclusion as to the influence of the deployment on people's possibility of escape and survivability. Since only the improvement or deterioration was examined, averages (between tests) did not need to be used for this analysis. Instead, the influence of the deployment was assessed for every individual test.

The (changes in) CO concentration were established as the main indicators for the improvement or deterioration of conditions in a room. This decision was made for several reasons.

- Previous research showed that CO is a good indicator for other toxic gases.
- Meters that can measure various gases were only placed on the first floor. The meters placed on the other floors mainly measure CO. This is why CO was chosen for the comparison of the fire gas concentrations.
- It is customary for the fire service to measure CO during an incident. That is why CO is a good basis for translating the results into practice.
- The preliminary research (simulations) had shown that other factors, such as the temperature outside the fire room, only played a limited role with regard to the possibility of escape and survivability.

External size-up
For the purpose of the external size-up, the results of the visual inspection at the times recorded in the protocols were compared to the images recorded by the thermal imaging camera. The thermal imaging camera was used to take photos at several different distances and from several different viewing angles, both of the front and the rear of the building. The photos were examined for any difference in temperature that might be visible and the extent of such a difference. It was also checked whether there was any visible smoke propagation in the various residences that were not the fire room.

Situation at the start of the deployment
To begin with, an analysis was made of the possibility of escape and survivability per test, based on the variables measured (as described in section 2.4.5). For every variable, it was examined whether it had changed or remained unchanged during the test. If it had changed, it was examined when this happened and whether this could be tracked back to a specific action by the deployment crew. This was translated into graphs where every fire service action was entered as a vertical line. Corrections were made for any deviations from the deployment protocol. The start of the analysis was set at t = 15 minutes (5 minutes prior to the start of the deployment at t = 20 minutes) in order to be able to include the situation in the residential building before the arrival of the fire service in the analysis. A list of times of actions that are part of the deployment protocol was used in order to be able to analyse the variables measured (see Appendix 9).

Since, in contrast to the situation in the first 20 minutes of the test (the escape phase), the analysis of the ground floor, second floor and third floor prior to the deployment phase was relevant, the existing concentrations on these other floors at the start of the deployment (t = 20 minutes) were taken into account. This analysis was combined with the amount of visible smoke in, for example, corridor 1.2 (see chapter 3).

The influence of the deployment

In order to be able to determine the influence of the deployment on the environmental conditions, changes in the possibility of escape and survivability for the individual rooms on the first floor were first examined. Here, different deployment periods were compared:

- for the offensive attack: prior to the deployment, during the deployment, and after ventilating.
- for the defensive attack: prior to the deployment, during the evacuation, and after ventilating.

Within any of these periods, it was examined whether any changes in the situation compared to the previous period had taken place. The prevailing situation (in terms of the possibility of escape and survivability) within a period was established by determining the situation that was applicable during more than 90% of the time within this period.

Furthermore, differences between the deployment periods distinguished in terms of CO concentration were examined for each room on the first floor. This not only enabled consideration of the dose that would be inhaled by someone who was in the room for an extended period of time, but also the direct influence of the deployment on the conditions in the room. CO readings were converted into an ordinal measurement level in terms of improvement, deterioration, or an unchanged situation compared to the preceding phase. The threshold value for an improvement, deterioration, or an unchanged situation was set at a change of 10 ppm CO. Cross-comparisons were made by filtering by the following variables: open / closed door, deployment methods and measures for risk management.

The analysis of the other quantities (temperature, heat radiation, visibility, oxygen, carbon dioxide, nitrogen oxides, etc.) of the individual tests was also taken into account. These analyses were compared with the various fire service actions. It was then examined which variables changed or remained stable relative to the situation at the time when the deployment started. The deployment actions were also included in these graphs. Next, graphs were made in which several tests within different variants were shown in the same graph so as to find similarities, e.g.: starting the fan caused the smoke to propagate to residence 2.21 within one minute after the fan was started in X cases. This showed which actions (repeatedly) led to a deterioration in the residences and corridors on the various floors.

For each individual test, it was examined whether a specific action was visible as an influence on the conditions (variables measured) in the rooms. Corrections were made for any deviations from the protocol as recorded in the logbook of the control room (see Appendixes 9H and 13). Any traceable effects (effect traceable to a fire service action because no other actions were taken at that time) that occurred with a delay because a measuring point was further from the source were also examined.

Cross-comparisons between specific actions (e.g. extinguishing or ventilating) and CO being propagated were also made for the other floors. Based on the analyses, a cross-comparison between two variables (the position of the door to the fire room and the deployment methods: offensive or defensive) was examined in greater depth. This was done because a literature review showed that these two variables had the most influence. This cross-comparison also considered the current real-life situation where measures for risk management tend to be absent. This can be used to assess the optimum deployment method for a given position of the door to the fire room for variants 0 and 1.

2.6 The quality of the research

The quality of the research is determined to a significant degree by the extent to which attention was paid to uniformity, reliability and validity, both beforehand and while carrying out the research. In order to obtain reliable and valid results, extra attention should be paid to uniformity, specifically when carrying out large-scale field research. Therefore, this section first goes into the uniformity of the test conditions, using guidelines concerning the quality of research from AMC-UvA (2002) as a reference, followed by a discussion of reliability and validity.

2.6.1 Uniformity of test conditions

Attempting to achieve maximum uniformity of test conditions is important in order to rule out, or at least minimise, the influence of (undesirable) variables on the tests. By choosing to conduct field experiments in an actual residential building – as opposed to laboratory tests – concessions to uniformity were made beforehand. However, the benefits of such field experiments for achieving the aim of the research were considered to be of greater importance. Although concessions were made beforehand with regard to uniformity, it was attempted to keep/make conditions as uniform as possible as of that moment.

Concretely, the following measures were taken (in advance) to promote the uniformity of the test conditions.

- Promoting uniform fire growth by:
  - Choosing two almost identical residences as the fire rooms located at equal distances from the ends of the corridor.
  - Sealing the outer wall in order to minimise the influence of wind on fire growth and smoke propagation. Fire-resistant material was applied to the windows in the fire room to prevent them from breaking, which would lead to a unique and therefore incomparable situation.
  - Limiting the number of tests on one day so that the building could be cleared of smoke and the temperature in the fire room could drop sufficiently to ensure an equivalent starting situation for all tests.
  - Using sofas of exactly the same type from one production series as the fire object to rule out the possibility of differences in composition or configuration leading to different fire growth.
  - Placing the sofas in the exact same location in the fire room(s) and having them ignited by the same team member in the same way.
  - Removing or covering all combustible materials in both fire rooms (such as flooring) to prevent the fire load from increasing unintentionally.
- Promoting uniform conditions that enabled smoke to propagate by:
  - Sealing the outer wall (by closing the windows) so as to minimise any possible effect of wind pressure on the smoke propagation. Of course, it was not possible to ensure a uniform wind pressure all around the building.

    - Strictly describing an checking which doors should be closed at the start of the experiment.
- Promoting uniform conditions with regard to the deployment by:
    - Using a protocol describing which actions were to be carried out before, during, and after a test, which equipment should be used, etc.
    - Giving instructions, including written instructions, to the deployment / safety crew prior to the test, and by coordinating the actual actions of the deployment crew during the incident from the control room, including giving exact commands and counting down.
    - Working with the same crew commander on almost all test days.
- Promoting a uniform analysis by using computerised data processing tools.

2.6.2 Reliability

Where the reliability of research is concerned, the question is whether the results would be the same if the research were to be conducted again in exactly the same manner. The assumption is that equal tests lead to equal measurement results. If there is a high correlation between the two measurement moments, the measurement is highly reliable. Low correlation suggests low reliability. It should be noted that a low correlation coefficient does not necessarily mean that the measurements are not reliable: after all, the results may actually be different due to an additional variable.

The reliability of this smoke propagation test was promoted by means of the design and implementation of the tests and the use of the measuring equipment.

- The design and implementation of the tests:
    - The research team that designed the tests also constructed the test design and supervised the implementation. This ensured a high degree of consistency in the various phases of the research.
    - There was a small, compact research team and a fixed team/sub-team was used for every aspect of the research (including mobile measuring equipment, stationary measuring equipment, data collection and analysis), reducing the probability of different interpretations during the tests.
    - A pre-test was conducted in preparation of the actual testing.
    - All test variants, except the tests with an organic fire load, were conducted at least twice for the purpose of repeatability.
    - All test variants were conducted according to clearly defined protocols.
    - A logbook was kept, recording the weather conditions and all crucial moments during a test. Any deviations from the research protocol were also noted. The main deviations are listed in Appendix 9H.
- Measurements and measuring equipment:
    - All measuring equipment was calibrated and checked for correct operation and the proper recording of measurement results prior to each test.
    - Measurements were conducted on all floors in several rooms and at several heights for all the tests.
    - The measurement results were linked to the camera images.
    - Besides our own gas measurements, gas measurements were also conducted by RIVM. This implicitly provided an extra test of the reliability of the measuring equipment.[28]

[28] See Appendix 14.

2.6.3 Internal and external validity

Validity refers to the extent to which a measurement fulfils its purpose (Drenth & Sijtsma, 2006). Simply put, it is about the question as to whether that what is being measured is what should actually be measured. Validity can be divided into internal and external validity.

Internal validity

Internal validity is defined as the extent to which the reasoning part of the research was carried out correctly. In other words: methodological validity. This concerns the extent to which the correct methodology was applied, whether the sample was taken correctly, whether the correct measuring instrument was used, and whether the correct analysis techniques were applied. Reliability (see above) is a prerequisite for internal validity.

The following measures were taken to achieve a high degree of internal validity:

- A comparison of the research results: by using a combination of simulations and field experiments (partly by means of two different measuring systems) and making a comparison with real-life case studies on smoke propagation.
- Searching for any evidence that will disprove the findings from the field experiments: when comparing the findings of the tests with the real-life situation (for fires where smoke propagation played a role), situations were explicitly searched for in which the conclusions from the experiment did *not* match the real-life situation.
- Performing control checks as part of the data analysis: the same analysis was conducted independently by several people to make sure that the outcome was consistent.
- The use of an advisory board to test the research design, the data collection, the analysis method and the findings.
- A review by internal and external scientists to test the data collection, the analysis method, and the findings.

External validity

External validity concerns the extent to which the research results can be generalised to situations other than those in the research. This form of validity consists of the following components:

- Ecological validity: the extent to which the research results correspond to the real-life situation. Ecological validity is tested by explicitly linking the results of the experiments to, and comparing them with, the real-life situation in the chapter on generalisability (chapter 7). It should be noted that in real-life situations no actual measurement results are available in the event of fire in a residential building. This means that the comparison with the real-life situation is based on fire research that took place *after* the fire and on evaluations by the fire services in question.
- Generalisability of the sample: is the sample representative for the population? There are hundreds of thousands of residential buildings in the Netherlands. Because of the reliability and validity requirements and the costs involved in conducting a large-scale field experiment, it was not possible to take a larger sample from these thousands of residential buildings. This means that the sample is too small to automatically consider it to be sufficiently generalisable. Nevertheless, there are reasons to claim that the results of this research are sufficiently well-founded to be able to draw conclusions and make recommendations regarding smoke safety in residential buildings:
  - Although the building where the experiments were conducted has a specific shape and layout, the claim that this type of building is often found in the Netherlands is justified.

- The literature review that was conducted in advance and the comparison made with actual fires in residential buildings were done in order to demonstrate that the results of the experiment do not differ from findings in the real-life situation.

> Validity of meaning: the degree to which a concept measures what should understood by that concept / what the meaning of the concept is (exclusivity of meaning). Validity of meaning can be divided into the following elements:
  - Validity of content: the extent to which the measuring instrument manages to cover the meaning of a concept in all its aspects. This validity was given substance by carrying out an extensive literature review into the relevant variables that influence the possibility of escape and survivability in the event of a fire. These results were used to design the experiment and the measurement method. Although not all factors (and in particular all fire gases) could be measured continuously, the main factors were measured continuously.
  - Validity of construct: the extent to which the sub-aspects of a comprehensive concept cover the entire concept. The theme of this research, smoke propagation, is a comprehensive concept. This aspect of validity was therefore taken into account by (1) establishing, as part of the literature review, which factors should be measured as a minimum requirement, (2) using specific measuring equipment for these different factors, and (3) correlating the results with each other using internationally applied methods for determining the risk of smoke propagation and its effect on the possibility of escape and survivability over time.

3 Smoke propagation: routes and factors

3.1 Introduction

In order to get a good impression of the smoke propagation in the building, the smoke propagation routes were mapped using camera images (video and audio) of the field experiments. These routes were used to identify the factors that play a role in the smoke propagation. In addition to the images, measurements (of gas concentrations, visibility distance, temperature, etc.) were used for a number of situations. A more detailed analysis of the measurements and the resulting effect on the possibility of escape and survivability can be found in chapters 4, 5 and 6. These subsequent chapters are based on the smoke propagation routes and decisive factors established in this chapter.

This chapter starts with a guide as to how to interpret the results. This is followed by a summary of the identified smoke propagation routes and a more in-depth discussion of these routes for the individual floors. The smoke propagation based on the camera images is compared with the propagation of fire gases (CO measurements) in order to map both visible and non-visible smoke propagation. And finally, the factors which play a role in the smoke propagation during the tests are described.

3.2 How to interpret the results

The nineteen tests were divided into eight variants. These variants and the corresponding tests are shown in table 3.1. A full summary of all tests is given in section 2.4.4 (see table 2.2).

Table 3.1 Overview of the variants and corresponding tests

Variant no.	Variant name	Number of tests	Test no.	Date no.	Fire room
0	Door open	4	1 3 5 17	240619_1 250619_2 260619_2 040719_2	1.21 1.19 1.19 1.19
1	Door closed	3	2 4 16	250619_1 260619_1 040719_1	1.21 1.21 1.21
2	Mobile water mist and door open	2	7 9	270619_2 280619_2	1.19 1.19
3	Mobile water mist and door closed	2	6 8	270619_1 280619_1	1.21 1.21
4	Mobile water mist, smoke-resistant partition, and door closed	2	10 11	010719_1 010719_2	1.21 1.19
5	Smoke-resistant partition and door closed	2	12 13	020719_1 020719_2	1.21 1.19
6	Organic fire load and door open	1	15	030719_2	1.19
7	Organic fire load and door closed	1	14	030719_1	1.21
8	Balcony door open and door open (maximum ventilation)	2	18 19	050719_1 050719_2	1.19 1.19

3.2.1 Key to the results

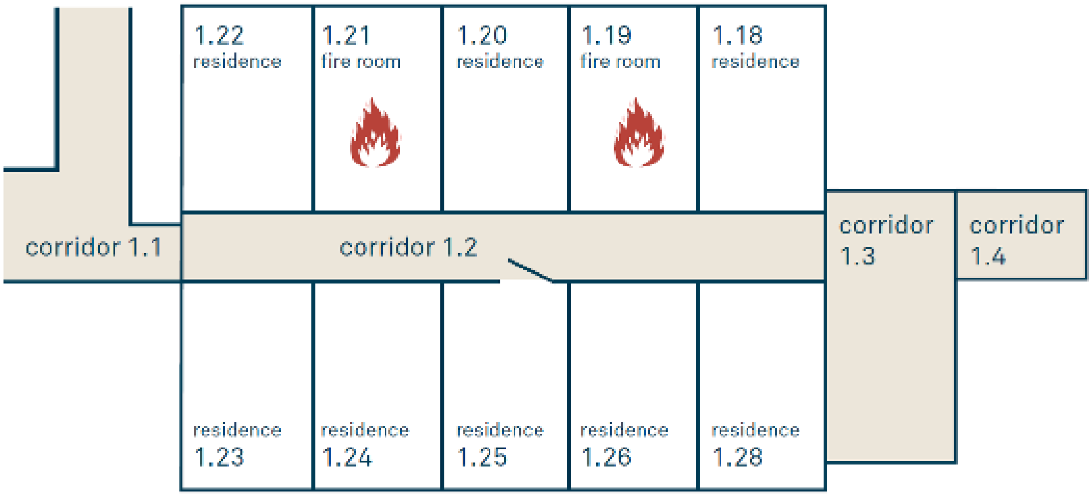


Figure 3.1 Schematic floor plan of the first floor

Abbreviations
> Fire room [BR]
> Residence 1.25 [W1.25], this notation also applies to the other residences
> Corridor 1.2 [G1.2], including camera height (m). The same notation applies to the other corridors
> CAI: central TV antenna installation

Variants
> Tests of variant 0 (door open)
> Tests of variant 1 (door closed)
> Tests of variant 2 (mobile water mist, door open)
> Tests of variant 3 (mobile water mist, door closed)
> Tests of variant 4 (mobile water mist and smoke-resistant partition, door closed)
> Tests of variant 5 (smoke-resistant partition, door closed)
> Test of variant 6 (organic fire load, door open)
> Test of variant 7 (organic fire load, door closed)
> Tests of variant 8 (balcony door open and door open, maximum ventilation)

Colours and explanation of the tables for visible and non-visible smoke
Visible smoke propagation was compared to the CO concentration measured at room level; this is shown in the tables by means of three different colours (see figure 3.2).
> Dark grey: both visible smoke and CO were measured.
> Blue: no visible smoke and no CO were measured.
> Light grey: either visible smoke or CO was measured. The cell indicates whether it concerns smoke or CO.

Visible smoke and CO measured
No visible smoke and CO measured
Either visible smoke or CO measured

Figure 3.2 Colour scale tables for visible and non-visible smoke

3.2.2 Explanation of the presentation of the results

The results of the tests of the different variants are presented as follows:

> If smoke is visible in a room, this refers to the visible, solid and liquid particles in the smoke, unless otherwise indicated. In order to make the text easier to read, this chapter will use the term 'visible smoke'.

> A smoke propagation route describes the smoke propagation from one room to another. A route can consist of several sub-routes. Sub-routes can go via different openings, such as gaps, cracks, seams, penetrations or ducts. Where there is a further division into sub-routes, this has been indicated. These routes are shown in maps / figures and indicated with capital letters. Furthermore, screenshots were taken of the camera images to illustrate the smoke propagation routes.

> The tables show the variant numbers as well as the individual test numbers. The results refer to individual tests because a spread in smoke propagation was found when testing the same variant. The actual variant is mentioned here. The table is set up according to the colour scale from figure 3.2.

The results discussed in this chapter are a summary of extensive analyses. The appendixes listed below form the basis for the results and analyses of this third chapter.

> Appendix 15: overview photographs of the rooms on the first floor at fixed times per test, both for the escape phase and the deployment phase. These photographs give more information about the visible smoke in a room, which can range from a small amount of local smoke with low optical density to smoke with high optical density that fills almost the entire room.

> Appendix 16: the graphs showing the measured CO values per test. Spot measurements were conducted to measure the maximum CO concentration in a room and establish the presence of CO. The maximum CO concentration was the starting point for the escape and deployment phases. The graphs give more information about the CO values measured, and any fluctuations, during the entire test.

> Appendix 17: an overview of visibility distances and smoke layer heights per test and per room.

> Appendix 18: an overview of the moments when visible smoke propagation to rooms took place, for the individual floors.

> Appendix 19: an overview for the individual floors of the smoke propagation routes and sub-routes along which smoke visibly propagated.

> Appendix 20: the full analysis of the factors that play a role in smoke propagation.

3.3 An overview of the smoke propagation routes

The figures below show an overview of the horizontal (see figure 3.3) and vertical (see figure 3.4) smoke propagation routes in the residential building.

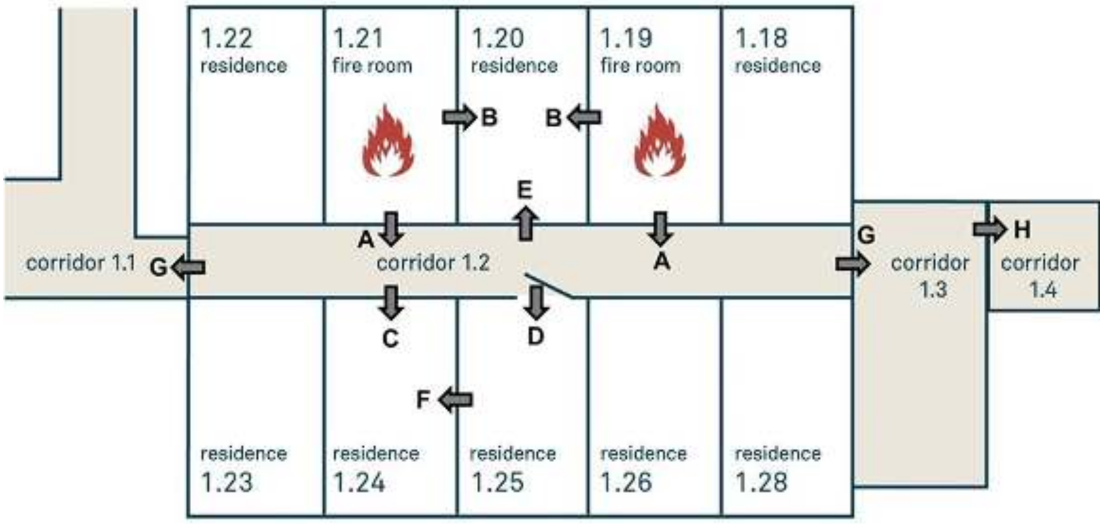


Figure 3.3 Horizontal smoke propagation routes on the first floor

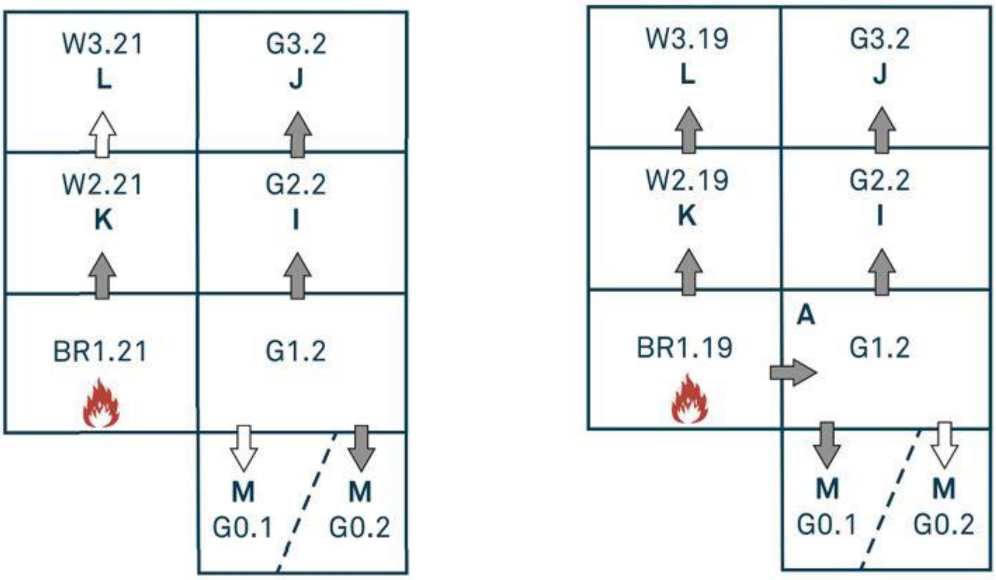


Figure 3.4 Vertical smoke propagation routes from the fire rooms 1.21 and 1.19

Description of the smoke propagation routes

Route A	From the fire room to corridor 1.2
Route B	From the fire room to residence 1.20
Route C	From corridor 1.2 to residence 1.24
Route D	From corridor 1.2 to residence 1.25
Route E	From corridor 1.2 to residence 1.20
Route F	From residence 1.25 to residence 1.24
Route G	From corridor 1.2 to corridors 1.3 and 1.1
Route H	From corridor 1.3 to corridor 1.4
Route I	From corridor 1.2 to a corridor on a higher floor (corridor 2.2)
Route J	From corridor 1.2 to a corridor on a higher floor (corridor 3.2)
Route K	From the fire room to a residence on the second floor (2.19 / 2.21)
Route L	From the fire room to a residence on the third floor (3.19)
Route M	From the first floor to the ground floor (corridors 0.1 and 0.2 (ventilation duct), both included as separate routes).

The camera images also showed smoke propagation of which the route is unknown, possibly because these route or sub-routes were beyond the camera range. Such routes are not included in the overview.

The different routes are described in more detail in the sections below. Horizontal smoke propagation on the first floor will be discussed first, followed by the vertical smoke propagation routes to the other floors. The sub-routes along which smoke propagated to a residence or corridor are shown at the individual room level.

3.4 Smoke propagation on the first floor

The horizontal smoke propagation routes on the first floor are routes A to H. Further explanations of these routes are provided below.

3.4.1 Smoke propagation route A

Figure 3.5 shows route A on the floor plan and the corresponding sub-routes in the fire room.

Figure 3.5 Route A and sub-routes A1 and A2

Smoke propagated to corridor 1.2 via gaps and seams around the closed door (A1) of the fire room or through the opened door to the fire room (A2). Where the door was closed, the smoke propagated via the gap/seam between the door and the frame, and also via the gap between the door and the floor construction. It did not take long for this smoke propagation to start: 2 to 2.5 minutes after ignition. The amount of smoke that flowed into the corridor before the door to the fire room was opened did not reduce the visibility distance to less than 5 metres. Figure 3.6 shows the smoke propagation to corridor 1.2 just before and after the door to the fire room was opened (camera positioned at 1.5 metres high).

Figure 3.6 Smoke propagation to corridor 1.2 just before and after the door to the fire room was opened during test 1 of variant 0

When the door to the fire room was opened (t = 5 minutes), the smoke in the fire room flowed into the corridor, past the lintel over the door frame. The smoke flowed directly from the door opening into the corridor in both longitudinal directions. It only took the smoke 10 seconds to propagate along the full length of the corridor. After this propagation, the smoke layer height and volume increased, moving the smoke downward to the floor. In the majority of the tests with the door open, the visibility distance decreased within a few minutes; this continued until the end of the escape phase. In some tests, the visibility distance did not decrease or only decreased temporarily. Appendix 17 shows an overview of the visibility distance in corridor 1.2 for each test.

3.4.2 Smoke propagation routes B and E

Figure 3.7 shows routes B and E on the floor plan and the corresponding sub-routes to residence 1.20.

Figure 3.7 Routes B and E, and sub-routes B1, B2, E1, E2, E3 and E4

The sub-routes for smoke propagation to residence 1.20 were the wall sockets (B1 and B2), gaps and seams around the door (E1 to E3), or the opened door (E4) (during the deployment phase). Smoke mainly propagated via the wall socket in the wall adjacent to the fire room during the escape phase. Depending on the test situation, this smoke propagation took place 2.5 to 3 minutes after ignition or at the moment when the door to the fire room was opened (t = 5 minutes). Some tests where the door to the fire room was closed at t = 5.5 minutes showed smoke entering residence 1.20 through the wall socket at an accelerated speed. Figure 3.8 shows the smoke propagation via this route.

Figure 3.8 Smoke from a wall socket in the wall of residence 1.20 during test 16 of variant 1

Smoke propagated to the residence via the top and sides of the door during the escape phase. During the deployment phase, smoke mainly propagated along the underside of the door. Opening the door caused smoke from the corridor to enter the residence.

3.4.3 Smoke propagation routes C and F

Figure 3.9 shows routes C and F on the floor plan and the sub-routes to residence 1.24.

Figure 3.9 Routes C and F, and sub-routes C1, C2, C3, C4 and F1

Smoke propagated to residence 1.24 along the same routes and sub-routes taken by the smoke propagation to residence 1.20: via the wall socket (F1), the gaps and seams around the closed door (C1 to C3), or the opened door (C4). The smoke along the ceiling and the walls in figure 3.10 shows that, during the escape phase, smoke also came through the gaps / seams around the door and from the wall socket (red arrow).

Figure 3.10 Smoke propagation to residence 1.24 during test 3 of variant 0

The smoke via sub-route F1 seems to have cooled down so much that it 'fell' from the wall socket, contrary to the smoke that entered residence 1.20 along the same sub-route and that did not drop down immediately. During the escape phase, smoke mainly propagated via the gaps and seams along the top of the door, whereas, during the deployment phase, smoke propagated through the gaps and seams on the long sides or the undersides of the door or through the opened door.

3.4.4 Smoke propagation route D

Figure 3.11 shows route D on the floor plan and the sub-route to residence 1.25.

Figure 3.11 Route D and sub-route D1

Visible smoke propagation to residence 1.25 took place via the door opening of the open door (D1). The smoke flowed into the residence from corridor 1.2, after which the layer of smoke in the residence grew and became optically denser. The smoke along the ceiling in figure 3.12 shows how this entered the residence from corridor 1.2.

Figure 3.12 Smoke propagation to residence 1.25 after the door to the fire room was opened during test 1 of variant 0

Appendix 17 features a graph with the smoke propagation to residence 1.25, including the visibility distance and the smoke layer height.

3.4.5 Smoke propagation routes G and H

Figure 3.13 shows routes G and H on the floor plan and the sub-routes to corridors 1.1, 1.3 and 1.4.

Figure 3.13 Routes G and H, and sub-routes G1 to G8 and H1 to H3

Smoke propagated to the corridors 1.1, 1.3 and 1.4 through the double doors that separate the different corridors. The smoke propagated to these corridors through gaps and seams around the closed doors (G1, G2, G3, G5, G6, G7, H1 and H2) or through the opening of the fully or partially opened doors (G4, G8 and H3). Smoke propagation to corridor 1.1 took place during both the escape and the deployment phases.

Smoke propagated through the double doors from corridor 1.2 and into corridor 1.3 in two ways. During the escape phase, the first smoke propagation route was through the gaps and seams of the closed double door (G5 to G7). The second route was via the door opening of the opened double door (G8). This was opened during the escape phase and during the deployment phase. During the escape phase, the double door was opened at approx. t = 5.5 to 6 minutes. This caused a small amount of smoke to propagate from corridor 1.2 to 1.3. The door was opened during the deployment phase to enable the deployment crew to enter corridor 1.2. The double door was no longer fully closed once the deployment started, because of the hose the deployment crew was using. The door was fully opened when ventilating during the deployment phase (after extinguishing). The left-hand photograph in figure 3.14 shows smoke near the double door of corridor 1.3 during the escape phase; the right-hand photograph shows smoke near the double door to corridor 1.3 during the start of the deployment.

Figure 3.14 Smoke during the escape phase (t = 7 minutes) and the start of the deployment (t = 20 minutes) during test 3 of variant 0

3.4.6 Propagation of visible and non-visible smoke

The routes described are based on visible smoke varying from dense black smoke to barely perceptible light smoke. In addition, CO was measured to assess the smoke propagation in the form of invisible gases. In this context, it should be noted that a spot measurement was conducted in the centre of the room. This means that smoke first had to reach that spot for the sensor to measure CO.

The visual observations were compared to the CO measurements. A distinction was made between the escape phase (0-20 minutes) and the deployment phase (≥ 20 minutes). For the visible smoke propagation in the deployment phase, it was established whether there was still smoke in the room and/or whether new smoke was supplied. In respect of the CO measurements, the presence of CO was established for both phases, see Appendix 16. This is a broad comparison; a more in-depth analysis of the CO measurements can be found in chapters 4, 5 and 6.

Overviews of the propagation of visible and non-visible smoke to the residences and corridors on the first floor are given in table 3.2 and table 3.3. Appendix 18 lists the moments when visible smoke propagated to rooms for all floors. A list of the CO measurements of all tests is given in Appendix 16.

Table 3.2 Smoke propagation to the first-floor residences

Variant no.	Variant name	Test no.	W1.20		W1.24		W1.25	
			0-20 min.	≥ 20 min.	0-20 min.	≥ 20 min.	0-20 min.	≥ 20 min.
0	DO	1						
		3						
		5						
		17						
1	DD	2					Smoke	
		4			Smoke			
		16						
2	MWM and DO	7						
		9						
3	MWM and DD	6	CO	CO	CO	CO		
		8	CO	CO				
4	MWM, RW and DD	10		CO		CO	Smoke	
		11	CO	CO		CO		
5	RW and DD	12			CO			
		13			CO			
6	OV and DO	15	CO					
7	OV and DD	14	CO				Smoke	
8	MV	18						
		19						

Note. DO = door open, DD = door closed, MWM = mobile water mist, RW = smoke resistant partition, OV = organic fire load and MV = maximum ventilation

Table 3.2 shows that no smoke was observed in some tests, but that CO was measured in those tests in the first-floor residences.

Table 3.3 Smoke propagation to the first-floor corridors

Variant no.	Variant name	Test no.	G1.1		G1.2		G1.3	
			0-20 min.	≥ 20 min.	0-20 min.	≥ 20 min.	0-20 min.	≥ 20 min.
0	DO	1	Smoke*	Smoke*				
		3						
		5						
		17						
1	DD	2	Smoke				Smoke	
		4	Smoke				Smoke	
		16					Smoke	
2	MWM and DO	7					Smoke	
		9					Smoke	
3	MWM and DD	6	Smoke					CO
		8	Smoke					X
4	MWM, RW and DD	10						CO
		11		CO				X
5	RW and DD	12	Smoke				Smoke	
		13	Smoke				Smoke	Smoke
6	OV and DO	15	Smoke					
7	OV and DD	14						
8	MV	18						
		19						

Note. DO = door open, DD = door closed, MWM = mobile water mist, RW = smoke resistant partition, OV = organic fire load and MV = maximum ventilation
*Test 1 of variant 0 (door open) has no CO measurement in corridor 1.1, because the measuring equipment for the sensor in question did not work.

Table 3.3 shows that smoke was observed in corridors 1.1 and 1.3 during the escape phase in several tests, but no CO was measured.

3.4.7 Summary

Smoke propagated to corridor 1.2 and to other first-floor residences via several routes and sub-routes. This mainly concerned routes through gaps and seams around doors and routes through wall sockets. This type of smoke propagation occurred at an early stage during the escape phase (2 to 3 minutes after ignition). The smoke propagation around the doors was mainly through the gaps and seams at the top and the long sides of the door. In time, when the smoke layer had moved downward to the floor, smoke also propagated via the bottom of the doors. Smoke propagation via wall sockets not only happened from the fire room to residence 1.20, but also from residence 1.25 to residence 1.24.

Smoke propagation to corridors 1.1 and 1.3 was visible after the door to the fire room was opened. The smoke layer that built up in corridor 1.2 after the door to the fire room had been opened caused smoke to propagate to the adjoining corridors through gaps and seams around the double doors. Smoke propagation to corridor 1.4 was not observed in all tests and was only observed in the deployment phase.

The combination of visible smoke and CO was often measured on the first floor. CO was measured in residences 1.20 and 1.24 in a number of tests without visible smoke propagation being observed. This was true for both the escape and deployment phases. Visible smoke was observed during some tests in corridors 1.1 and 1.3 without any measured CO, particularly during the escape phase,

3.5 Smoke propagation to the other floors

Vertical smoke propagation to the other floors was via routes I to M. Further information about these routes is given below.

3.5.1 Smoke propagation routes I and J

Figure 3.15 shows routes I and J on the floor plan and the sub-routes in corridor 1.24.

Figure 3.15 Route I and sub-routes I1, I2 and I3

Smoke propagation to corridor 2.2 (located over corridor 1.2) took place via ventilation ducts with ventilation openings in this corridor (I1, I2 and I3). These ventilation ducts connect to the other floors. Figure 3.16 shows the smoke propagation via one of the three ventilation openings in corridor 2.2.

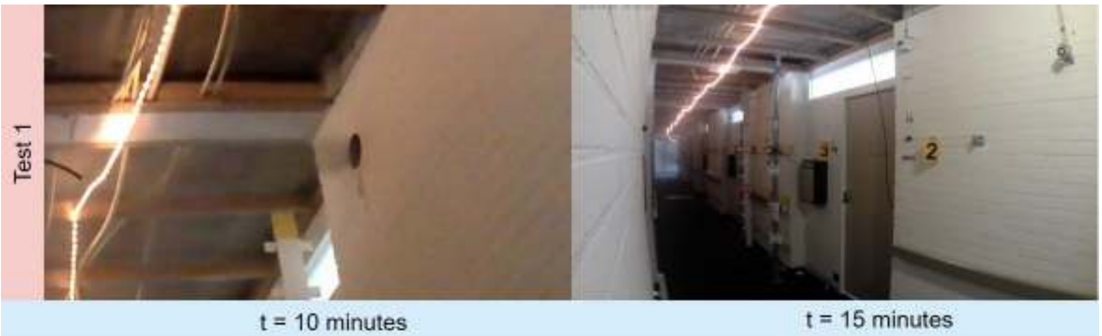


Figure 3.16 Smoke from the opening of a ventilation duct in corridor 2.2 during test 1 of variant 0

Figure 3.17 shows routes I and J on the floor plan and the sub-routes in corridor 3.2 alongside them.

Figure 3.17 Route J and sub-routes J1, J2 and J3

Smoke propagated to the corridor on the third floor in the same way as to corridor 2.2, via one or several ventilation opening(s) in the corridor (J1, J2, and J3). Smoke was found to propagate on the third floor in more tests than on the second floor.

3.5.2 Smoke propagation routes K and L

Figure 3.18 shows route K on the floor plan and the sub-routes to residences 2.19 and 2.21.

Figure 3.18 Routes K and L, and sub-routes K1 and K2

Smoke propagated to residence 2.19 via three sub-routes: from a wall-integrated wall socket / central antenna connection (K1), from a ventilation opening over the bathroom door in the lobby of the residence (K2) and from a ventilation opening in the bathroom (K2). Smoke propagated via the wall socket during the escape phase. Smoke propagated via the two ventilation openings simultaneously, and both during the escape phase and the deployment phase. The underlying residence (1.10) was the fire room in all the three tests in which smoke propagated to residence 2.19.

During the four tests in fire room 1.21, visible smoke was observed in (the overhead) residence 2.21. This smoke entered the residence via the wall socket / central antenna connection. Unlike residence 2.19, no smoke propagation from the existing ventilation openings was observed.

Figure 3.19 shows route L on the floor plan and the sub-route to residence 3.19.

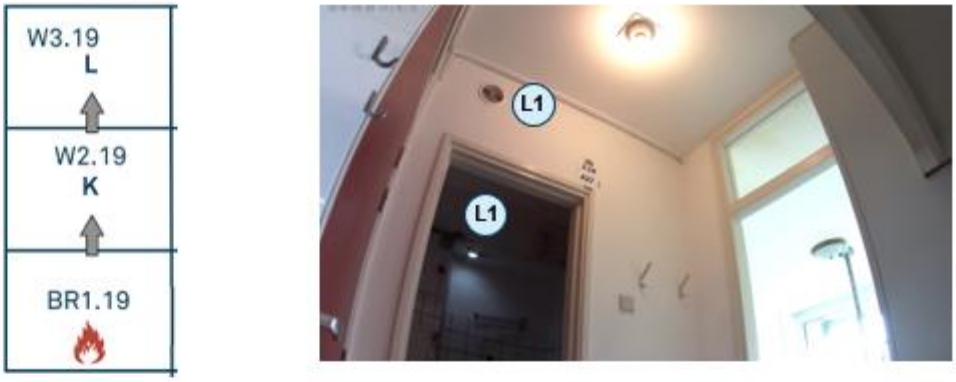


Figure 3.19 Route L and sub-route L1

Smoke propagation to residence 3.19 was observed during two tests. In both cases, the fire was in room 1.19. The smoke came from the ventilation opening in the bathroom and the ventilation opening over the bathroom door in the lobby (L1). No smoke propagated to residence 3.21 in any test.

Figure 3.20 shows the smoke propagation during test 3 of variant 0 (door open) via the ventilation opening in the bathroom and the ventilation opening over the bathroom door in the lobby.

Figure 3.20 Smoke propagation to residence 3.19 via the ventilation ducts during test 3 of variant 0

3.5.3 Smoke propagation route M

Figure 3.21 shows route M and the sub-route to the ground floor.

Figure 3.21 Route M and sub-route M1

Smoke propagation to the ground floor took place during two tests. Smoke, which had entered via an unknown route in the partition structure, was observed in the cloakroom (corridor 0.1, M1) during the escape phase of test 3 of variant 0 (door open). Smoke was also observed from an opening in a ventilation duct in corridor 0.2 (M1): at the end of the escape phase and the start of the deployment phase during test 1 of variant 0 (door open) and in the deployment phase during test 3 of variant 0 (door open). Figure 3.22 shows the smoke propagation during test 3 of variant 0 (door open) in the two corridors.

Figure 3.22 Smoke propagation to the ground floor during test 3 of variant 0

3.5.4 Propagation of visible and non-visible smoke

The visual observations were compared to the CO measurements. A distinction was made between the escape phase (0 to 20 minutes) and the deployment phase (≥20 minutes), where it was established whether, for the visible smoke propagation in the deployment phase, there was still smoke in the room or whether new smoke was supplied. The presence of CO was determined in both phases for the CO measurements. This is a broad comparison; a more in-depth analysis of the CO measurements can be found in chapters 4, 5 and 6.

Overviews of the propagation of visible and non-visible smoke to the residences and corridors on the second and third floors are shown in table 3.4 to table 3.6. Appendix 18 lists the moments when visible smoke propagated to rooms for all floors. A list of the CO measurements of all tests is given in Appendix 16.

Table 3.4 Smoke propagation to the corridors on the second and third floors

Variant no.	Variant name	Test no.	G2.2		G2.3	
			0-20 min.	≥ 20 min.	0-20 min.	≥ 20 min.
0	DO	1				
		3				
		5		CO	Smoke	Smoke
		17		CO*		Smoke
1	DD	2	Smoke			
		4				
		16			Smoke	Smoke
2	MWM and DO	7		CO	Smoke	
		9			Smoke	
3	MWM and DD	6				
		8				
4	MWM, RW and DD	10				
		11				
5	RW and DD	12		CO		CO
		13				CO
6	OV and DO	15				
7	OV and DD	14		CO		
8	MV	18				
		19			Smoke	Smoke

Note. DO = door open, DD = door closed, MWM = mobile water mist, RW = smoke resistant partition, OV = organic fire load and MV = maximum ventilation
*Only measured at sensor G12

Table 3.5 Smoke propagation to the second and third-floor residences

Variant no.	Variant name	Test no.	W2.19 / 2.21		W3.19[29] / 3.21	
			0-20 min.	≥ 20 min.	0-20 min.	≥ 20 min.
0	DO	1		CO		
		3	Smoke			
		5				CO
		17	Smoke			CO
1	DD	2	Smoke			
		4	Smoke			
		16	Smoke			
2	MWM and DO	7				CO
		9				CO
3	MWM and DD	6				
		8				
4	MWM, RW and DD	10				
		11				CO
5	RW and DD	12	Smoke	CO		
		13	Smoke	CO		
6	OV and DO	15				
7	OV and DD	14				
8	MV	18		CO		CO
		19				

Note. DO = door open, DD = door closed, MWM = mobile water mist, RW = smoke resistant partition, OV = organic fire load and MV = maximum ventilation

Table 3.6 Smoke propagation to the ground floor

Variant no.	Variant name	Test no.	G0.1		G0.2	
			0-20 min.	≥ 20 min.	0-20 min.	≥ 20 min.
0	DO	1				
		3	Smoke			
		5				
		17				
1	DD	2				CO
		4				
		16				

Note. DO = door open, DD = door closed
Since visible smoke propagation was observed only in variant 0 and variant 1, only the smoke propagation during the tests of these variants is shown in the table

[29] There was no visible smoke propagation to residence 3.21 during any test.

3.5.5 Summary

Smoke propagated to the second *and* the third-floor corridors in less than half of the tests. In these situations, smoke propagation to the corridor on the third floor was more common than smoke propagation to the corridor on the second floor. The extent to which smoke propagated varied not only per variant, but also per test within one variant.

Smoke propagated to the second-floor corridor via the ventilation ducts, and to the second-floor residences via the wall sockets with central antenna connections and the ventilation openings. Smoke only propagated to the third floor via the ventilation ducts. Where smoke propagated to the second and third-floor residences, this was always to the residences located directly above the fire room.

Visible smoke propagation to the ground floor only occurred in two tests of variant 0 (door open); this occurred after smoke propagation to the other floors.

Smoke propagation to other floors was not always observed visually or by measurements. In many cases there was either visible smoke observed or CO measured.

3.6 Factors that play a role in smoke propagation

3.6.1 Introduction

An analysis of the camera images and other research data revealed factors that played a role in the smoke propagation in the residential building. These factors and their influence on smoke propagation are discussed in more detail in the following sections.

3.6.2 The fire object

One of the factors that plays an important role in smoke propagation is the type of fire object. Seventeen tests had a sofa as the fire object and two tests featured an organic fire load (wood). An analysis of the camera images showed that there were differences between the smoke production and smoke propagation during the tests with an organic fire load and those with a sofa as the fire object. It was found that the organic fire load produced less visible smoke than the sofa. During the tests with the sofa, the amount of smoke in the fire room was such that visibility in the room at floor level had been reduced to zero within 8 minutes. The fire remained visible longer during the tests with the organic fire load. To visualise this, figure 3.23 shows two comparisons between tests with a sofa (synthetic fire load) and tests with an organic fire load.

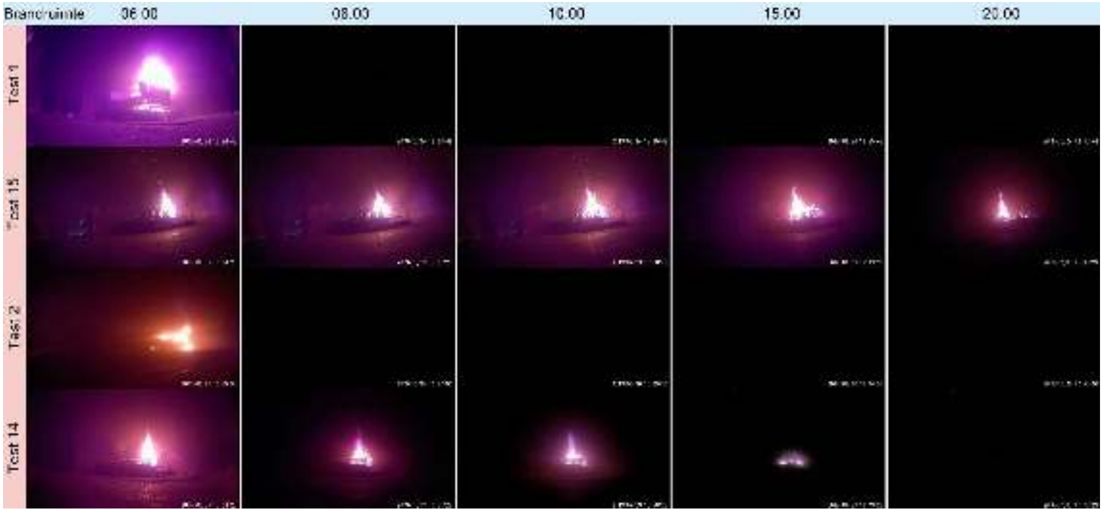


Figure 3.23 Images from the fire room during the escape phase of test 1 of variant 0, test 14 of variant 6, test 2 of variant 1, and test 15 of variant 7

The amount of smoke produced by the fire object influences the smoke propagation in the residential building. Differences between the tests with the sofa and the organic fire load were visible particularly on the first floor, in corridors 2.2 and 3.2; this concerned both the tests with the door open and the tests with the door closed (without any other measures for risk management being applied; see Appendix 20).

3.6.3 Opening and closing doors

Another factor that influences smoke propagation is opening and closing doors. The tests varied in the opening and closing of the door to the fire room (open or closed). Based on the camera images, smoke propagation via both the door to the fire room and via other doors was analysed in more detail.

The door to the fire room

Both during the tests of variant 0 (door open) and during the tests of variant 1 (door closed), the smoke propagated to all the residences on corridor 1.2 and to the corridors (1.1, 1.2 and 1.3) on the first floor. In the escape phase, smoke was supplied to the corridors and the residences from the fire room during the tests of variant 0 (door open) for a long time. However, the period in which the smoke entered the corridors or residences tended to be short in the tests of variant 1 (door closed). Smoke was also supplied to the second and third-floor corridors for a long time during the tests of variant 0 (door open). During the tests of variant 1 (door closed), no smoke tended to be visible in these corridors. Smoke was only observed on the ground floor during the tests of variant 0 (door open).

Figure 3.24 shows the difference in smoke propagation in residence 1.24 between a test with the door to the fire room open (test 1) and a test where this door is closed (test 4).

Figure 3.24 Smoke in residence 1.24 during test 1 of variant 0 and test 4 of variant 1

Figure 3.25 shows the difference in smoke propagation in corridor 1.3 between a test with the door to the fire room open (test 17) and a test with the door closed (test 4).

Figure 3.25 Smoke in corridor 1.3 during test 17 of variant 0 and test 4 of variant 1

During the two tests of variant 8, both the door to the fire room and the balcony door were open. A comparison with the tests of variant 0 (door open) shows hardly any difference in smoke propagation on the first floor. However, contrary to the tests of variant 0 (door open), no visible smoke was observed on the second floor.

The doors of the other residences

The door of residence 1.25 was open throughout all tests. The door to the neighbouring residence (residence 1.24) was closed during the escape phase in all tests. The difference in smoke propagation in residence 1.24 and in residence 1.25 is shown in figure 3.26 and figure 3.27.

Figure 3.26 Smoke in residence 1.24 and 1.25 during test 1 of variant 0

Figure 3.27 Smoke in residence 1.24 and 1.25 during test 4 of variant 1

The camera images of these two residences clearly show that an open or closed door to the residence influences the smoke propagation. This applies to both the tests with the door to the fire room open and those where it was closed.

3.6.4 Mobile water mist and smoke-resistant partition

To determine if, and the extent to which, a mobile water mist and a smoke partition influence smoke propagation, the following variants have been compared with variant 0 (door open) or variant 1 (door closed):

> variant 2 (mobile water mist and door open)

> variant 3 (mobile water mist and door closed)

> variant 5 (smoke-resistant partition and door closed)

> variant 4 (mobile water mist, smoke-resistant partition, and door closed)

An overview of the comparison of the tests can be found in Appendix 20.

Variant 2 (mobile water mist and door open)

During the tests of variant 2 (mobile water mist and door open), the smoke did not propagate beyond the first and third floors, whereas smoke propagated to all the floors during the tests of variant 0 (door open).

Furthermore, residences 1.20 and 1.24 were free from visible smoke during the tests of variant 2 (mobile water mist and door open) for a longer time than during the tests of variant

0 (door open). Corridor 3.2 was also free from visible smoke longer. Figure 3.28 shows a graph that visualises this. The graphs of all tests can be found in Appendix 17.

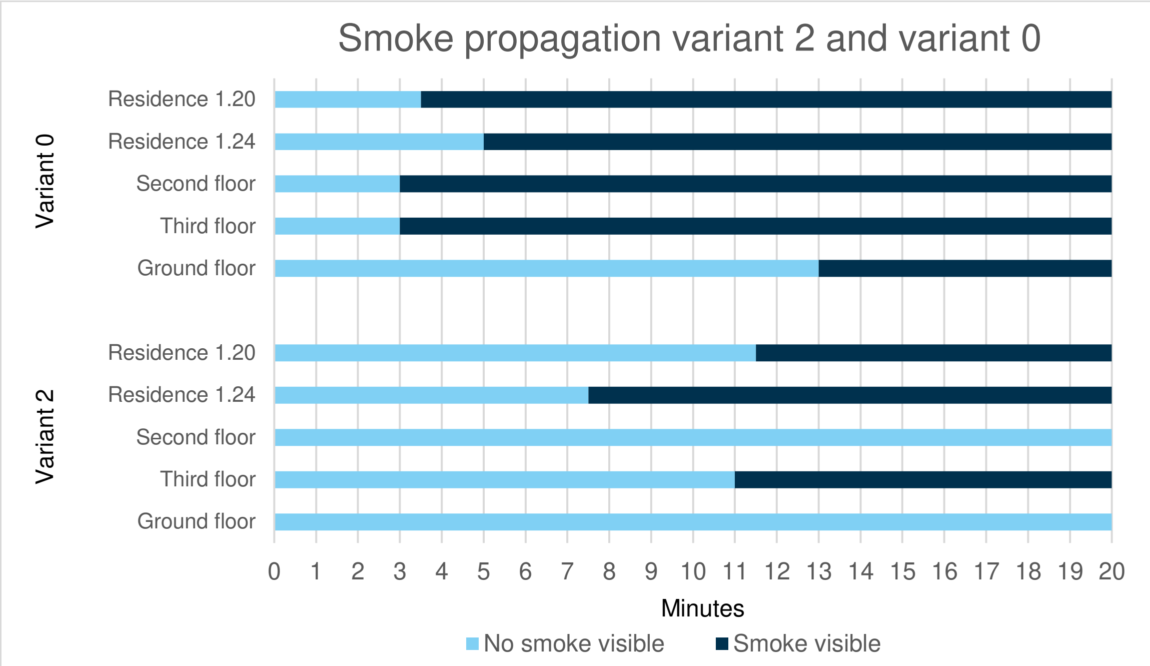


Figure 3.28 Smoke propagation in tests of variant 2 and variant 0

Variant 3 (mobile water mist and door closed)
In the tests of variant 2 (mobile water mist and door closed), the smoke did not propagate beyond the first floor; residence 1.20 and corridor 1.3 were actually clear of visible smoke during the escape phase. However, smoke propagated to all the floors except the ground floor during the tests of variant 1 (door closed).

Variant 5 (smoke resistant partition)
During the two tests of variant 5, both the fire room and residence 1.24 were fitted with smoke resistant partitions that complied with future smoke resistance requirements. The greatest effect of the smoke resistant partition was visible in residence 1.24 which stayed clear of visible smoke during the escape phase, contrary to the tests of variant 1 (door closed). In these tests, the smoke entered the residence via the gaps and seams around the door after 5 minutes.

Another difference is the smoke propagation to the second and third floors. During the tests of variant 5 (smoke resistant partition), corridor 2.2 on the second floor and corridor 3.2 on the third floor remained clear of visible smoke. During the tests of variant 1 (door closed), smoke propagated to the second and third floors for a short period.

Variant 4 (mobile water mist, smoke resistant partition, and door closed)
The two tests of variant 4 were conducted with a combination of a mobile water mist and a smoke resistant partition. Contrary to the tests of variant 1 (door closed), smoke propagation was limited to corridors 1.1, 1.2 and residence 1.25 during these variant 4 tests. All other rooms on the first floor and all other storeys stayed clear of visible smoke during the escape phase.

A comparison between the tests of variant 5 (smoke resistant partition and door closed) and the tests of variant 4 (mobile water mist, smoke resistant partition, and door closed) is shown in figure 3.29 for corridor 1.2.

Figure 3.29 Corridor 1.2 during tests 12 and 13 of variant 5 and tests 10 and 11 of variant 4

Figure 3.29 shows that the combination of a mobile water mist and a smoke resistant partition further reduced the smoke propagation to corridor 1.2. The same applied to the smoke propagation to other rooms. Contrary to the tests of variant 5 (smoke resistant partition and door closed), no visible smoke was observed in residence 1.20, in corridor 1.3, and on the second floor during the tests of variant 4 (mobile water mist, smoke resistant partition, and door closed).

Finally, the tests of variant 4 (mobile water mist, smoke resistant partition, and door closed) were also compared to the tests of variant 3 (mobile water mist and door closed). The results are quite similar, although minor differences were observed in some rooms on the first floor. They are discussed in more detail in Appendix 20.

3.6.5 The location of the fire room

As indicated before, two residences were used as the fire room during the tests, i.e. residence 1.19 and residence 1.21. The analysis of the camera images showed that the location of the fire room influences the smoke propagation, both on the first floor (horizontal propagation) and to the floors above (vertical propagation). On the first floor, the location of the fire room specifically influenced the time when smoke propagation was observed in residences 1.24 and 1.25. In some tests, smoke was observed in residence 1.24 before it was observed in residence 1.25; this was the case where the fire room (1.21) was located directly opposite residence 1.24. The smoke propagation to the other floors also depended on the location of the fire room. Smoke mainly propagated to the corridors and the residences above the fire room. When residence 1.19 was the fire room, it was observed that the smoke propagated to residence 2.19 and to residence 3.19. When residence 1.21 was the fire room, the smoke was found to propagate only to residence 2.21. A detailed explanation is given in Appendix 20.

3.6.6 The fire service deployment

Another factor that influences the smoke propagation in residential buildings is the fire service deployment. An analysis of the camera images showed that almost every fire service action led to other or further smoke propagation in the building. Chapter 6 addresses the influence of the deployment on the smoke propagation in more detail.

Extinguish before rescue

When the fire service opened the door to the fire room, there was an increase in visible smoke in the corridors and the residences, mainly on the first floor. The use of fans also caused an increase in smoke to the residences and corridors, sometimes also to spots where there was no smoke before.

After the door to the fire room was opened, the fan forced the smoke in corridor 1.2 under the doors into the other residences. Because the doors between corridors 1.2 and 1.3 were open for the purpose of using the fan, smoke also flowed from corridor 1.2 to corridor 1.3.

Figure 3.30 shows an example of the smoke propagation as a consequence of the deployment. It shows that little smoke was visible in residence 1.20 at the moment when the offensive attack started (t = 20 minutes). Images of six minutes after the start of the deployment (t = 26 minutes) show black smoke coming into the residence from under the door.

Figure 3.30 Supply of visible smoke in residence 1.20 as a consequence of the deployment during test 5 of variant 0

Rescue first and then extinguish

During the tests with the defensive attack, smoke propagation was mainly observed at the moment when the door to a residence was opened to simulate an evacuation; part of the smoke still present in corridor 1.2 flowed into the residence. An example is shown in figure 3.31.

Figure 3.31 Smoke propagation to residence 1.24 in the event of a simulated evacuation during the deployment during test 3 of variant 0

3.6.7 Openings

The openings between rooms are a determining factor for smoke propagation. Horizontal and vertical smoke propagation took place during the tests via large and small openings, such as open doors, ducts, gaps and seams between rooms. Routes were observed:

- which the smoke flowed through as soon as the layer of smoke had come down to the top of an opening,
- in which the smoke was forced through openings if there were differences in pressure between rooms, for example due to pressure build-up in the fire room,
- where the smoke propagated through openings, under the influence of forced air flows.

Visibly more smoke propagated through the larger openings, such as opened doors, the gap under a closed door, and the ventilation ducts than through the smaller openings. However, different tests gave differences in the speed at which the smoke passed through the same openings. Besides the differences in speed, there were also visible differences in optical density (see Appendix 17).

Opening and closing doors also influenced the smoke propagation through other openings than the door opening. Where a door was opened, smoke mainly propagated via the actual door opening, but many tests showed that closing the door led to smoke propagation to neighbouring rooms via other openings (gaps and seams, wall sockets, etc.).

3.6.8 Penetrations

Penetrations for building installations between rooms also played a role in both horizontal and vertical smoke propagation. These penetrations include ventilation ducts, electric facilities (wall sockets) and other connections (central antenna). Smoke propagated to other floors, the ground floor, and outside the building via the ventilation ducts in the residences and via the ventilation ducts in the corridor. A detailed explanation is given in Appendix 20.

Smoke propagating between rooms via the wall sockets for the electricity supply was observed on the first floor. This was smoke that propagated from the fire room to the neighbouring residence (1.20) and from residence 1.25 to residence 1.24. This smoke propagation did not occur continuously. A detailed explanation is given in Appendix 20. Furthermore, smoke propagation between the fire room and the overhead residence on the second floor via the wall sockets with central antenna connections was observed in some tests (see figure 3.32).

Figure 3.32 Smoke propagation via a wall socket with a central antenna connection in residence 2.19 during test 13 of variant 5

3.6.9 Other factors

Two other factors that may influence smoke propagation in residential buildings are differences in fire growth and the weather conditions.

The same fire objects (sofa and organic fire load) were used during the tests; these objects were placed in the same location in the fire room and ignited in the same way. A comparison based on the camera images and the measurements showed that there were major similarities in fire growth and smoke development between tests with the same measures for risk management. However, in some tests with the same measures for risk management, minor differences in fire growth were also observed, e.g. because part of a sofa cushion had fallen on the floor while the sofa was burning. These minor differences may have influenced smoke production and smoke development in the fire room. These minor differences in fire growth possibly also had a limited influence on the smoke propagation in the building. This is explained in more detail in Appendix 20.

Another factor that may have influenced the smoke propagation in the building is the weather conditions. Appendix 16 shows an overview of the weather conditions in the individual tests. Temperature differences and differences in wind speeds and wind directions may have influenced horizontal and vertical smoke propagation, and an analysis of the data suggests that this was indeed the case during a number of tests. However, given the number of other factors that may also have had an influence, this cannot be established with sufficient certainty. This analysis is explained in more detail in Appendix 20.

3.7 Summary

Smoke propagation routes

This chapter shows that the smoke propagated via several different routes and sub-routes during the tests, both directly from the fire room to corridor 1.2 and to adjoining residences. With regard to the smoke propagation to rooms further away, the propagation from the fire room through the door to corridor 1.2 is particularly relevant. After the door to the fire room was opened, the corridor quickly filled with smoke. This smoke propagated further through the building via various routes. This involved both horizontal and vertical smoke propagation to different rooms. More smoke propagated horizontally than vertically.

On closer examination, the smoke propagation routes were mainly routes via doors, wall sockets and ventilation ducts. During the escape phase, smoke propagated horizontally via wall sockets and gaps and seams around closed doors. This was not only observed as quickly as within 2 to 3 minutes after ignition, even before the door to the fire room was opened, but also later during the escape phase. In time, smoke also propagated via the bottoms of closed doors. Most smoke propagation was visible via open doors or when doors were opened, both during the escape and the deployment phases.

Vertical smoke propagation occurred via ventilation ducts and wall sockets with a central antenna connection. The smoke propagated via the ventilation ducts into the residences and corridors on the ground, second, and third floors. Smoke propagation to the second-floor residence over the fire room via the wall sockets with a central antenna connection was also observed. The number of tests where vertical smoke propagation was observed was the greatest for the third and second floors; smoke propagation on the ground floor was only observed in two tests. The vertical smoke propagation was less consistent than the horizontal smoke propagation and the differences between tests were greater.

The smoke propagation during the deployment phase was more erratic than during the escape phase. In contrast to the escape phase, the moments when smoke propagated during the deployment were sometimes random. It seems that, in addition to the deployment by the fire service, more variables and factors influenced the smoke propagation.

The analysis also showed that there was a difference between visible smoke and the measurement of CO. In the majority of tests on the first floor, visible smoke was observed and CO was measured. However, there were situations where no smoke was observed, but CO was measured. This was the case in some tests, particularly in residences 1.20 and 1.24. Conversely, visible smoke was observed without CO being measured in some situations. This was the case with several tests in corridors 1.1 and 1.3. Where smoke propagated to the other floors, visible smoke was observed *or* CO measured in the majority of the tests, but not both.

Factors influencing smoke propagation
The analysis revealed factors that influenced smoke propagation during the tests. Factors with a clearly visible influence on smoke propagation were the fire object and the opening or closing of doors. The organic fire load produced less smoke and caused less smoke propagation. Closing the door to the fire room reduced the extent of smoke propagation. This also applies to keeping the doors of the other residences closed. Opening a door quickly increased the visible smoke propagation to the room behind the door. Besides the opening of doors, other openings and penetrations (such as ventilation ducts, gaps and seams) also played a role in the smoke propagation through the residential building. Smoke could propagate both horizontally and vertically through these other openings and penetrations, but the propagation speeds differed significantly.

The location of the fire room influenced possible propagation routes. Visible smoke propagation to residences on the second and third floors was only to residences directly over the fire room.

Facilities also seem to have been factors that reduced the visibly observed smoke propagation. The mobile water mist, the smoke resistant partition, and the combination of the two seem to have reduced the smoke propagation; the test variants with the mobile water mist showed the greatest reducing effect. It should be noted here that no visible smoke was observed in many of these tests, while CO was measured.

The fire service deployment also influences the smoke propagation. Opening doors and using fans increased smoke propagation through the building, also to rooms where there was no smoke during the escape phase.

Two other factors that may have influenced the smoke propagation in the residential building in different tests are minor differences in fire growth and the weather conditions. However, given the number of other variables and factors that may also have had an influence, this cannot be established with sufficient certainty.


5
4
3
2

4. The possibility of escape and survivability

4.1 Introduction

Measurement results (of gas concentrations, visibility distance, temperature and radiation) can be used as the basis for determining times for the possibility of escape and survivability. This was determined using the criteria listed in sections 1.3.5 and 2.5.2, and by differentiating between four situations (see figure 4.2, left) and three groups (see figure 4.2, right). This chapter discusses the results of the tests of variant 0 (door open), variant 1 (door closed), and variant 8 (balcony door open and door open, maximum ventilation). In addition, variant 0 (door open) and variant 1 (door closed) also serve as the basis for the comparison with the variants where measures for risk management were applied. The results of the tests with measures for risk management and the effect of these measures on the possibility of escape and survivability are described in chapter 5.

Variant 1 (door closed) also serves as a variant with a measure for risk management since keeping the door closed is a measure on its own. Therefore, the tests of variant 1 (door closed) are not only discussed in chapter 4, but also in chapter 5 where they are compared with the tests of variant 0 (door open).

This chapter starts with an explanation of how to interpret the results. After this, the results of the tests of variant 0 (door open) and variant 1 (door closed) are presented in the form of times for the possibility of escape and survivability. This chapter ends with the results of the tests of variant 8 (balcony door open and door open, maximum ventilation). These latter tests, apart from the opened balcony door, were conducted in the same way as the tests of variant 0 (door open). The tests of variant 8 (balcony door open and door open, maximum ventilation) are compared with the tests of variant 0 (door open) in order to assess the influence of an open balcony door.

The times for the possibility of escape and survivability on the first floor are presented in this chapter (4) and in chapter 5. For the other floors, only the relevant results are presented. The results in these chapters concern the first 20 minutes (the escape phase) of the tests. The deployment phase (the fire service deployment) starts after these first 20 minutes. As this deployment might influence the smoke propagation, and thus the times for the possibility of escape and survivability, chapters 4 and 5 only present the times for the possibility of escape and survivability during the first 20 minutes of the test. The influence of the deployment on the possibility of escape and survivability is described in more detail in chapter 6.

4.2 How to interpret the results

The explanation below of how to interpret the results starts with a key – including a floor plan with the names of the rooms – which is useful to refer to when reading the results. This is followed by an explanation of how the specific results are presented in chapter 4 and chapter 5. This explanation of how to interpret the results ends with a description of the differences found between equal tests of one variant. Here, the spread in times for the possibility of escape and survivability between these equal tests is discussed. This is important for the correct interpretation of the results.

4.2.1 Key to the results

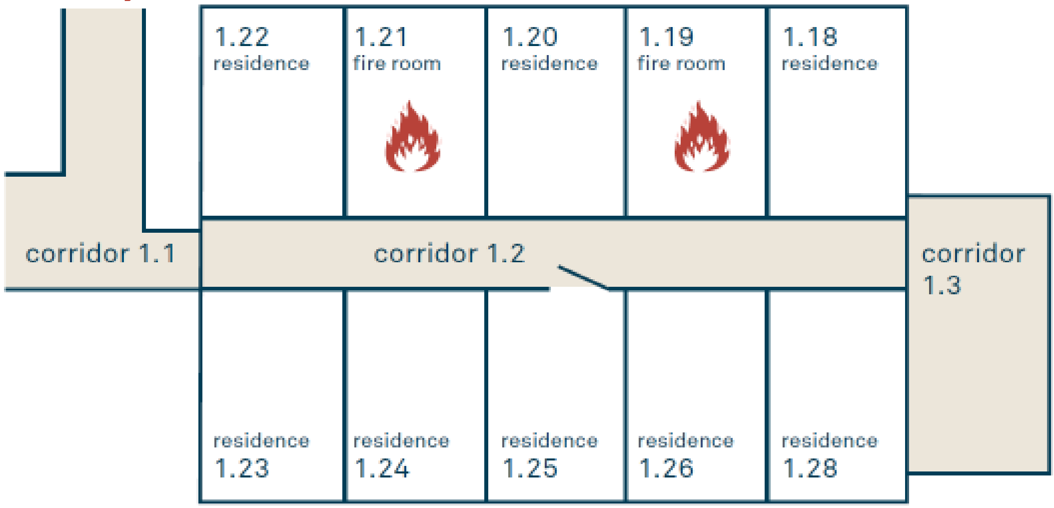


Figure 4.1 Schematic floor plan of the first floor

Abbreviations
> Fire room [BR]
> Residence 1.25 [W1.25], this notation also applies to the other residences
> Corridor 1.2 at a height of x m [G1.2 (x m)]
> Corridor 1.1 [G1.1], this notation also applies to corridor 1.3

Variants
> Tests of variant 0 (door open)
> Tests of variant 1 (door closed)
> Tests of variant 2 (mobile water mist, door open)
> Tests of variant 3 (mobile water mist, door closed)
> Tests of variant 4 (mobile water mist and smoke resistant partition, door closed)
> Tests of variant 5 (smoke resistant partition, door closed)
> Test of variant 6 (organic fire load, door open)
> Test of variant 7 (organic fire load, door closed)
> Tests of variant 8 (balcony door open and door open, maximum ventilation)

Symbols, icons and colours in the tables with the results of the times for the possibility of escape and survivability

	Safe escape
	Impaired escape
	Life-threatening situation
	Fatal situation

	Highly vulnerable
	Vulnerable
	General

Figure 4.2 Symbols for four situations (left) and icons of three groups (right)

Time [min]	0 - 5	5 - 8	8 - 11	11 - 14	14 - 17	17 - 20
Colour						

Figure 4.3 Colour scale in the tables with the results of the times for the possibility of escape and survivability

4.2.2 Explanation of the presentation of the results

Tests of variant 0 and variant 1

The results of the tests of variant 0 (door open) and variant 1 (door closed) are presented as follows:

- A table which shows the times for the different situations (safe escape, impaired escape, life-threatening situation and fatal situation) for each room and each group. The times are shown in minutes and rounded to whole minutes.
  - The times in the table were calculated according to the method described in section 1.3.5 and Appendix 1, and indicate when a certain situation occurred. The room numbers correspond to those in the floor plan of figure 4.1.
  - The table contains symbols for the four different situations. Figure 4.2 shows which situation is represented by each specific symbol. The various different situations are explained in more detail in section 1.3.5.
  - The table contains icons for the three different groups. Figure 4.2 shows which group is represented by each specific icon. The grouping is explained in more detail in section 2.5.2. In this research those are groups with a certain degree of sensitivity to asphyxiant and irritant gases, heat, and smoke-obstructed visibility.
  - The table is set up according to the colour scale from figure 4.3. This colour scale only indicates the available safe escape times and thus helps to give a quicker insight in these times.
- A stacked bar containing the times for the different situations, presented per room and per group. The times in stacked bars are shown in minutes and rounded to one decimal place.
- A table showing the maximum CO concentration measured in the first 20 minutes of the test on the ground floor, the second floor, and the third floor. This concentration is stated because it reflects smoke propagation to the other floors. This table is only shown for variant 0 (door open) because it was only during the tests of this variant that CO was measured on the other floors.

The results discussed in this chapter are a summary of extensive analyses. The following appendixes provide the basis for the results and analyses in chapters 4 and 5:

- Appendix 16: the graphs showing the values measured for the individual sensors and tests. This appendix also identifies any noteworthy aspects found from the measurement data up to 20 minutes, with an indication of whether these findings are expected to have influenced the possibility of escape and survivability.
- Appendix 21: the overview stating the calculated times for the possibility of escape and survivability for the different methods (FIC, FLD, FED_{in}, FED_{heat}, FEC_{smoke}) for each measurement location and test.
- Appendix 22: the tables with the percentages of the threshold values at 20 minutes. The section on 'non-exceeded threshold values' in the analysis of elements is based on these tables. If a threshold value for a situation has not been exceeded, these tables answer the question of whether the threshold values for an impaired escape, a life-threatening situation, or a fatal situation might be *about* to be exceeded.
- Appendix 23: the plots of the spread in times for the possibility of escape and survivability for every variant that was tested more than once.

Tests of variant 8 and variants with measures for risk management

The results of the tests of variant 8 (balcony door open and door open, maximum ventilation) and the tests of the variants with measures for risk management are presented in the same way. In addition to the analysis of the tests of the actual variant, each of these variants is also compared to variant 0 (door open) or variant 1 (door closed). Consequently, the tables with the times and the stacked bars for these variants list both the actual variant and the variant which these variants were compared to.

A table is also given for the comparison referred to above, presenting a textual description of whether there was a equal situation, a (slight) improvement, or a (slight) deterioration for each of the following elements:

> survivability in the fire room
> the possibility of escape and survivability in corridor 1.2
> survivability in the other first-floor residences up to t = 20 minutes
> the percentage of non-exceeded threshold values of the other first-floor residences at t = 20 minutes
> survivability on the ground, second, and third floors
> the effect of the measure for risk management for different groups.

This table is followed by a description of any noteworthy aspects observed when comparing variants. A further explanation of the elements in this table and the substantiation for the classification of equal, (slight) improvement, or (slight) deterioration is given in Appendix 12. Section 5.7 summarises the comparisons for the various variants with measures for risk management in a table with the same elements as those described above. Here, the textual description has been replaced by symbols: 0 (equal), + (slight improvement), ++ (improvement) and - (slight deterioration).

4.2.3 Differences between ‘equal’ tests

Large-scale fire tests are often conducted with one test per variant. In this research, some tests were conducted four times for a similar variant. This increases the reliability of the results; however, it also shows that there are uncertainties with regard to the results of large-scale fire tests. Since not every variable can be controlled perfectly, two 'equal' tests do not always give fully matching results. This section gives a general representation of the spread in times at which the threshold values for the ‘impaired’, ‘life-threatening’, and ‘fatal’ situations were exceeded for variants that were tested more than once. These threshold values differ for the general, vulnerable, and highly vulnerable groups. Appendix 23 shows plots of the spread for the different variants. This appendix also gives a further description of the spread for the tests (in one variant) which were conducted more than once.

In general, the following can be noted about the spread in the times when the threshold values were exceeded:

> The lower the concentrations of asphyxiant and irritant gases measured, the greater the spread. In most cases this was due to a longer distance or a greater number of barriers that could stop the gases between the fire room and the measuring point.
> The spread was greater for the general group than for the highly vulnerable group, and greater in the ‘fatal’ situation than in the ‘impaired’ situation. This is because the threshold value was higher in these cases. A minor difference in measured values gave a larger difference in the times calculated for higher threshold values.
> The spread in the fire room was less than 1 minute in more than 90% of all cases. The spread in all rooms on the first floor was less than 5 minutes in more than 85% of the cases. The largest spread in time measured for equal tests (within one variant) was 12

minutes. When establishing this, only the cases in which a time was exceeded in the first 20 minutes of the test were considered.

> The spread can be greater than a few minutes for lower concentrations. If the spread within one variant was greater than the differences in average times between two variants, it is not certain that the difference can be explained by the extra measure that was applied. Therefore, no conclusions can be drawn from any minor differences between variants in these locations.

There are many influencing factors in fire tests on a real-life scale whose exact influence on smoke propagation has not been fully established yet and will probably never be quantifiable. The following might have influenced the spread in times within one variant to some extent:

> Whether a test was conducted in fire room 1.19 or in fire room 1.21. Both fire rooms can differ slightly in terms of airtightness and in their position relative to the measuring equipment. For example, the gas sampling sensor in residence 1.20 was closer to fire room 1.21 than to 1.19.
> Differences in how the sofa burnt, for example by fragments that fell from the sofa and that were burning or were not burning.
> Making the fire rooms and the wall between corridor 1.2 and residence 1.24 airtight for the tests with the smoke resistant partition on 1 and 2 July. Measures taken to achieve this airtightness included sealing gaps and seams using mastic sealant. After the tests on 1 and 2 July, these measures to achieve airtightness were removed again as far as possible. This may have influenced the airtightness of the fire rooms and of residence 1.24 compared to the situation of before 1 July.
> The weather outside: the wind and the temperature difference between inside and outside influence the natural ventilation in the building.

4.3 Tests of variant 0 (door open) and variant 1 (door closed)

This section shows the results of the tests of variant 0 (door open) and variant 1 (door closed).

During the tests of variant 0 (door open), the door to the fire room was opened after 5 minutes and kept in its maximum open position for the first 20 minutes. During the tests of variant 1 (door closed), the door to the fire room was opened after 5 minutes, ikept open for 30 seconds and closed again after 5.5 minutes. Afterwards, the door was kept closed until at least t = 20 minutes. Table 4.1 lists the relevant data of the tests of variant 0 (door open) and variant 1 (door closed).

Table 4.1 Data of the tests of variant 0 and variant 1

Variant no.	Variant name	Number of tests	Test no.	Date no.	Fire room
0	Door open	4	1 3 5 17	240619_1 250619_2 260619_2 040719_2	1.21 1.19 1.19 1.19
1	Door closed	3	2 4 16	250619_1 260619_1 040719_1	1.21 1.21 1.21

4.3.1 Results of variant 0 (door open)

The results of the times for the possibility of escape and survivability of variant 0 (door open) are shown below both as numbers in a table (see table 4.2) and visually (see figure 4.4), by means of the stacked bars, per room, per group, and per situation.

Table 4.2 Times for the possibility of escape and survivability (in minutes) of variant 0

	Fire room			Corridor 1.2 1.5 m			Corridor 1.2 0.3 m			Residence 1.25			Residence 1.20			Residence 1.24		
	< 3	< 3	< 4	< 5	< 5	< 5	< 6	< 8	< 9	< 6	< 6	< 8	< 9	< 12	< 18	12	< 16	-
	3	3	4	5	5	5	6	8	9	6	6	8	9	12	18	12	16	-
	4	5	6	6	6	7	9	10	13	7	7	8	9	12	18	12	16	-
	4	5	7	6	7	7	9	11	16	7	8	8	11	15	-	15	-	-

Note. For the yellow, orange and red smileys, a – in the table means that the threshold value for the group and situation in question was not reached within 20 minutes. For the green smiley, a – means that safe escape was possible for the first 20 minutes.

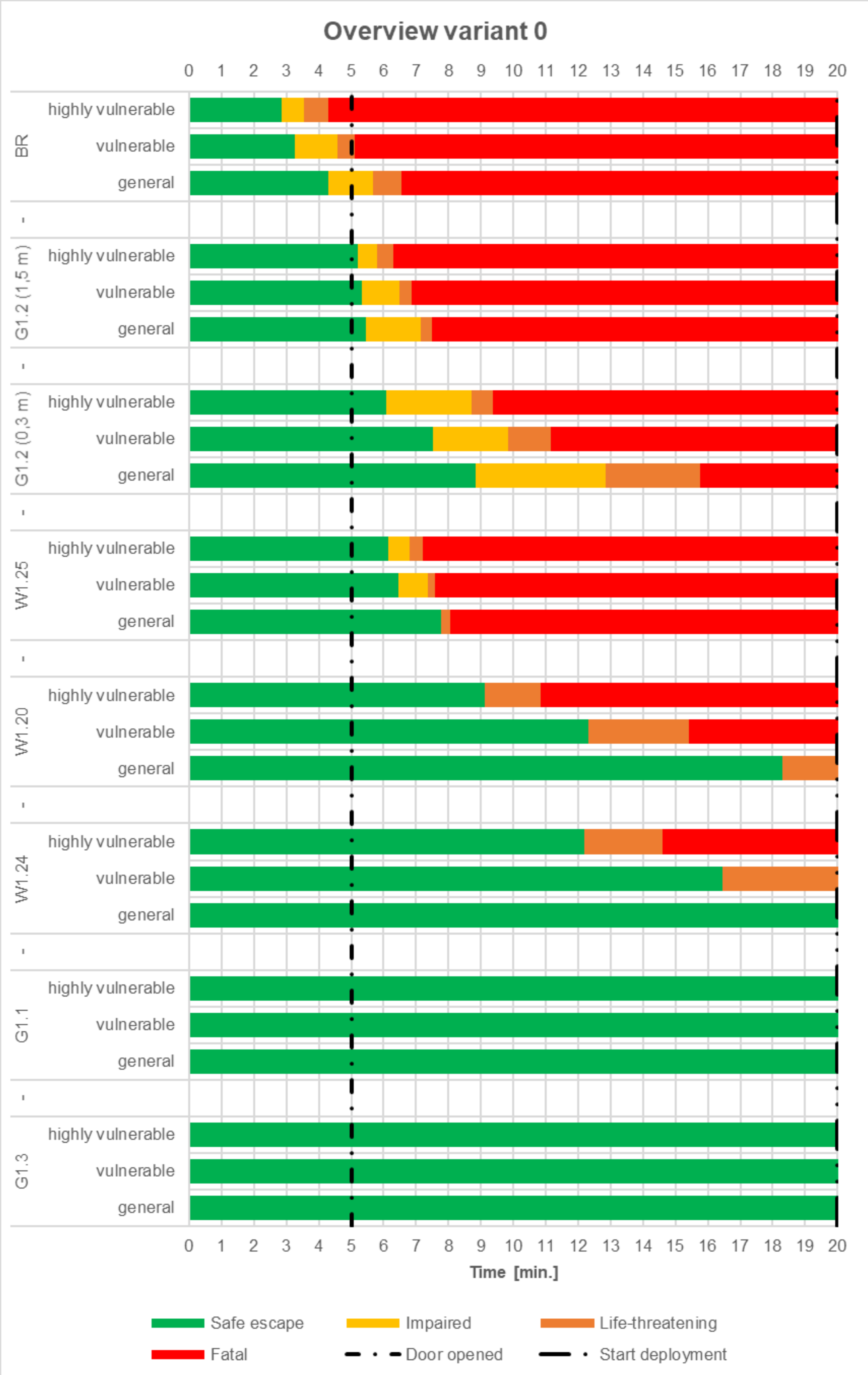


Figure 4.4 Times for the possibility of escape and survivability of variant 0

Other floors

Table 4.3 lists the maximum CO concentrations measured on the ground floor, the second floor, and the third floor for the four tests of variant 0 (door open). The development of the CO concentrations on these floors is shown in Appendix 24.

Table 4.3 Maximum CO concentrations on the ground floor, second floor, and third floor during variant 0

Room (sensor)	Test 1 [ppm]	Test 3 [ppm]	Test 5 [ppm]	Test 17 [ppm]
Corridor 0.1 (G17)	0	0	0	0
Corridor 0.2 (G18)	215	0	0	0
Residence 2.19 or 2.21 (G9)	0	0	0	0
Residence 2.24 (G10)	0	0	0	0
Corridor 2.2 (G11)	90	40	0	0
Corridor 2.2 (G12)	110	145	0	0
Residence 3.19 or 3.21 (G13)	0	55	0	0
Residence 3.24 (G14)	0	0	0	0
Corridor 3.2 (G15)	65	235	10	30
Corridor 3.2 (G16)	45	30	0	0

No temperature increases were measured on the other floors. Minor temperature variations of a few degrees Celsius were measured in the ventilation ducts on these floors.

4.3.2 Analysis of variant 0 (door open)

The main findings from the results of the tests of variant 0 (door open) are discussed below:

> **Fire room**: there was a life-threatening situation in the fire room after approx. 4 to 6 minutes (depending on the group). About 1 minute after the life-threatening situation, the situation became fatal for each group.

> **Corridor 1.2**: at a height of 1.5 metres in corridor 1.2, there was an impaired escape situation for each group after approx. 5 minutes; this was the case almost immediately after the door between the fire room and corridor 1.2 was opened. The impaired situation at 1.5 metres became fatal quickly: after about 2 minutes. If someone had then tried to escape through the smoke, this could have quickly become fatal. An impaired situation occurred at a height of 0.3 metre after 6 to 9 minutes (depending on the group). At this height, the impaired situation became fatal (depending on the group in question) after approx. 3 to 7 minutes.

> **Other first-floor residences**: **a** fatal situation was reached in all groups in residence 1.25 after approx. 7 to 8 minutes.
> The spread in time when threshold values were exceeded was greater for the different groups in residences 1.20 and 1.24.

In residence 1.20, there was a life-threatening situation in the fire room after approx. 9 to 18 minutes (depending on the group). The situation in residence 1.20 became fatal for the highly vulnerable and vulnerable groups after approx. 11 to 15 minutes. The situation did not become fatal for the general group during the first 20 minutes.
The situation in residence 1.24 did not become fatal for the vulnerable group during the first 20 minutes. For the general group, no life-threatening situation was reached in residence 1.24 within the first 20 minutes.
The times for survivability in the other first-floor residences were the shortest in residence 1.25. This was due to the open door between residence 1.25 and corridor 1.2. The times for survivability were shorter in residence 1.20 than in residence 1.24. Smoke could propagate to residence 1.20 via the shared wall with the fire room or the shared ventilation duct with corridor 1.2. Smoke propagation to residence 1.24 was only possible through the wall with a door and a door frame between residence 1.24 and corridor 1.2.

- **Corridors 1.1 and 1.3**: safe escape through corridors 1.1 and 1.3 was possible for the first 20 minutes. Camera images showed a slight amount of smoke in these corridors in the first 20 minutes.
- **Other floors**: CO was measured on at least one floor in all the tests on the ground floor, the second floor, and the third floor. The highest concentration measured was 235 ppm. A 20-minute stay in such a concentration could be life-threatening for the highly vulnerable group. It should be noted here that CO was mainly measured in the corridors on these floors, and only once in one residence on the third floor. The maximum concentration measured in this residence was 55 ppm. Camera images showed smoke in the residence on the second floor over the fire room in two tests, but no CO was measured.
  Differences were found between the CO concentration measured in the different tests on the ground floor, the second floor, and the third floor. The exact cause of these differences cannot be identified yet.

Non-exceeded threshold values

In situations where the threshold values were not exceeded within the first 20 minutes, they might have been *nearly* exceeded. The situation in residence 1.20 did not become fatal for the general group, but 73% of the threshold value for a fatal situation was reached here after 20 minutes. 62% of the threshold value for a life-threatening situation for the general group was reached in residence 1.24. Although not all the threshold values were exceeded in residences 1.20 and 1.24, it is plausible that this would happen if people stayed in their residences for longer than 20 minutes.

Decisive conditions

The asphyxiant gases were the first factor that caused the threshold values for life-threatening and fatal situations to be exceeded in the fire room. The irritant gases were the first factor that caused the threshold value for a life-threatening situation to be exceeded for the highly vulnerable group. This means that heat was not decisive for survivability in the fire room, although it could in itself cause a fatal situation shortly after the asphyxiant gases had led to a fatal situation. Temperature and radiation were measured in the lobby of the fire room at some distance from the fire object. If measurements had taken place at a shorter distance from the fire object, the heat might have been the first cause of the threshold value for a life-threatening or fatal situation in the fire room being exceeded.

Visibility was the first factor which impaired escape in corridor 1.2. Shortly after this, irritant gases also impaired escape for the vulnerable and highly vulnerable groups. The temperature could also have become so high at a height of 1.5 metres in corridor 1.2 that this might have influenced the possibility of safe escape or survivability. The asphyxiant gases caused the threshold value for a life-threatening and fatal situation to be exceeded in corridor 1.2. With regard to the highly vulnerable group, the irritant gases also caused the threshold value for a life-threatening situation in corridor 1.2 to be exceeded.
Where the threshold values for a life-threatening and fatal situation were exceeded in the other residences, this was caused by the asphyxiant gases. Furthermore, the irritant gases influenced the possibility of escape or survivability for the highly vulnerable and vulnerable groups in residence 1.25.

Summary
In summary, it can be stated that one fire object caused a fatal situation in the fire room within just a couple of minutes. Opening the door to the corridor almost immediately led to an impaired escape situation in corridor 1.2. Within a few minutes after opening the door, the situation at a height of 1.5 metres in corridor 1.2 then became fatal, which means that an attempt to escape through the smoke would soon be fatal. The concentrations of asphyxiant gases also became so high in residences 1.20 and 1.24 that a life-threatening or fatal situation occurred. For the general group, the threshold values were not always exceeded within 20 minutes, but they were likely to be exceeded if people stayed in the residence longer. CO was also measured to a certain extent in the tests on the ground floor, second floor, and third floor. Its peak concentration might reach a level that would be life-threatening for the highly vulnerable group after 20 minutes.

4.3.3 Results of variant 1 (door closed)

The results of the times for the possibility of escape and survivability for variant 1 (door closed) are presented below, both numerically in a table (see table 4.4) and visually (see figure 4.5) by means of the stacked bars per room and per group.

Table 4.4 Times for the possibility of escape and survivability (in minutes) of variant 1

	Fire room			Corridor 1.2 1.5 m			Corridor 1.2 0.3 m			Residence 1.25			Residence 1.20			Residence 1.24		
	< 3	< 3	< 4	< 5	< 5	< 5	< 6	< 9	-	< 6	< 16	-	< 10	< 14	-	-	-	-
	3	3	4	5	5	5	6	9	-	6	16	-	10	14	-	-	-	-
	4	5	6	7	13	-	14	-	-	9	16	-	10	14	-	-	-	-
	4	5	6	11	-	-	19	-	-	12	-	-	12	19	-	-	-	-

Note. For the yellow, orange and red smileys, a – in the table means that the threshold value for the group and situation in question was not reached within 20 minutes. For the green smileys, a – means that safe escape was possible for the first 20 minutes.

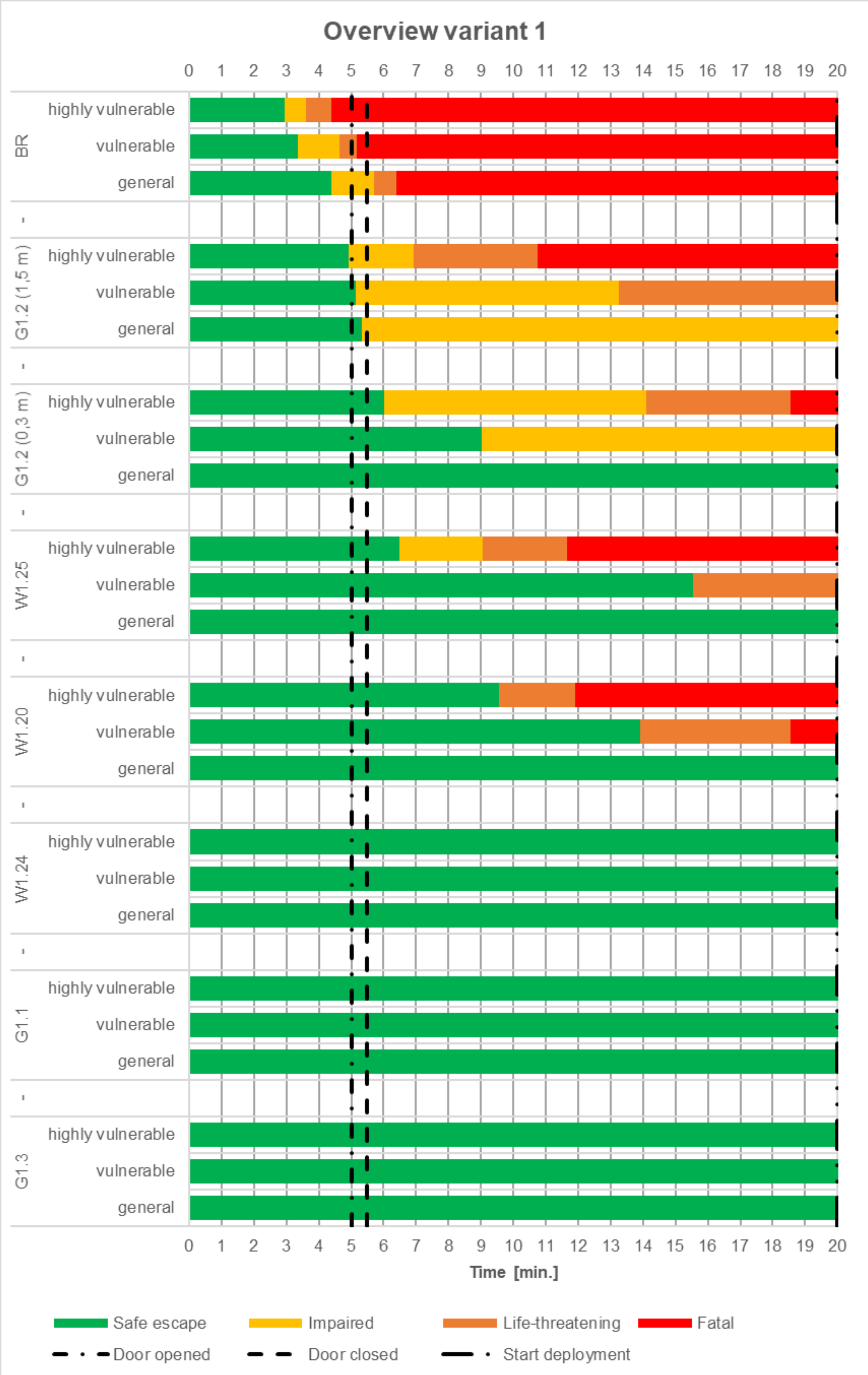


Figure 4.5 Times for the possibility of escape and survivability of variant 1

Other floors

No increased CO concentrations were measured in on the ground floor, the second floor, and the third floor during the first 20 minutes of the test. Camera images did show smoke in corridor 2.2, corridor 3.2, and in residence 2.21 (over the fire room on the second floor). No increased temperatures were measured. Minor temperature variations of a few degrees Celsius were measured in the ventilation ducts on the other floors.

4.3.4 Analysis of variant 1 (door closed)

The results of the tests of variant 1 (door closed) enable the following conclusions to be drawn:

> **Fire room**: There was a life-threatening and fatal situation in the fire room after approx. 4 to 6 minutes (depending on the group).

> **Corridor 1.2**: At a height of 1.5 metres in corridor 1.2, there was an impaired escape situation for each group after 5 minutes; this was the case almost immediately after the door between the fire room and corridor 1.2 was opened. After the door between the fire room and corridor 1.2 was closed, the visibility distance and the concentration of irritant gases improved again slightly. During the period from 6 to 20 minutes, in which the possibility of escape was impaired, there may have been certain moments where there was a safe escape situation for the general group in corridor 1.2. This is not reflected in the stacked bars because once a threshold value has been exceeded, this can no longer be reversed in the calculation method selected underlying the figures with the stacked bars. However, these moments can be recognised in how the decisive conditions for the impaired escape in corridor 1.2 developed (see Appendix 21): the visibility distance (FEC_{smoke}) and the concentration of irritant gases (FIC). Furthermore, camera images show that visibility in corridor 1.2 improved slightly at 1.5 metres high but was still limited. The situation at 1.5 metres high in corridor 1.2 did not become life-threatening for the general group, contrary to the highly vulnerable and vulnerable groups where this occurred after 2 and 8 minutes respectively. The possibility of escape was impaired for the highly vulnerable and vulnerable groups at 0.3 metres high after 6 to 9 minutes. Safe escape was possible at the height of 0.3 metres for the general group for the first 20 minutes.

> **Other first-floor residences**: Safe escape remained possible for all groups in residence 1.24 for the first 20 minutes. This also applied to residences 1.20 and 1.25 for the general group.
The situation in residence 1.20 became life-threatening for the highly vulnerable group after 10 minutes; for the vulnerable group this took 14 minutes. A fatal situation for the highly vulnerable group was reached in residence 1.20 after 12 minutes and for the vulnerable group this was reached after 19 minutes.
In residence 1.25, the situation became fatal for the highly vulnerable group after 12 minutes. The situation did not become fatal for the vulnerable group during the first 20 minutes. The situation in residence 1.25 became life-threatening for this group after 16 minutes.
With regard to the other first-floor residences, the times for survivability were the shortest in residences 1.20 and 1.25. This was because of the open door between residence 1.25 and corridor 1.2 and the shared wall between residence 1.20 and the fire room. This enabled the smoke to propagate to these residences more quickly than to residence 1.24, where two dividing walls between residences had to be passed.

- **Corridors 1.1 and 1.3**: Safe escape through corridors 1.1 and 1.3 was possible for the first 20 minutes. Camera images showed only light smoke in corridors 1.1 and 1.3 during the first 20 minutes.
- **Other floors**: Measurements did not measure any CO on the ground floor, the second floor, and the third floor. Camera images showed smoke on the second floor in corridor 2.2 and residence 2.21 (over the fire room) in one or more tests.

Non-exceeded threshold values

In situations where the threshold values were not exceeded within the first 20 minutes, they might still have been *nearly* exceeded. For example, 80% of the threshold value for a fatal situation was reached for the vulnerable group in residence 1.25 and 72% of the threshold value for a life-threatening situation was reached for the general group in residence 1.20. The highest percentage in residence 1.24 was 26%. Therefore, a stay of more than 20 minutes in residences 1.25 and 1.20 might still lead to life-threatening or fatal situations in some cases, whereas this situation was less likely to occur in residence 1.24.

Decisive conditions

The asphyxiant gases were the first factor that caused the threshold values for life-threatening and fatal situations to be exceeded in the fire room. The irritant gases and the asphyxiant gases almost simultaneously caused the threshold value for a life-threatening situation to be exceeded for the highly vulnerable group. This means that the heat is not the first factor that is decisive for survivability in the fire room, although, in itself, heat might cause life-threatening and fatal situations for the vulnerable or highly vulnerable groups. The temperature and radiation were measured in the lobby of the fire room, at some distance from the fire object. If measurements had taken place at a shorter distance from the fire object, the heat might have been the first cause of the threshold value for a life-threatening or fatal situation in the fire room being exceeded.
Visibility was the first factor impairing escape in corridor 1.2. Shortly after this, irritant gases would also impair escape for the vulnerable and highly vulnerable groups. The asphyxiant gases in corridor 1.2 caused the threshold value for a life-threatening and fatal situation to be exceeded for the vulnerable and highly vulnerable groups. Where the threshold value for a life-threatening and fatal situation was exceeded in the other residences, this was caused by the asphyxiant gases.

Summary

In summary, it can be stated that one fire object caused a fatal situation in the fire room within just a couple of minutes. Briefly (30 seconds) opening the door to the corridor almost immediately led to an impaired escape situation in corridor 1.2. The concentrations of asphyxiant gases increased in residences 1.20 and 1.25 to such an extent that a life-threatening or fatal situation occurred for the vulnerable and highly vulnerable groups. This was not the case for the general group during the first 20 minutes of the test. A longer stay might have led to a life-threatening situation, particularly in residence 1.20. However, in residence 1.24, the situation remained survivable for all groups. Even if a stay in residence 1.24 was somewhat longer than 20 minutes, it is not expected that the threshold values in residence 1.24 would be exceeded. In this case, the two closed partition walls between the residences would stop the smoke sufficiently for more than 20 minutes. No CO was measured in the tests on the ground floor, the second floor, and the third floor.

4.4 Tests of variant 8 (balcony door open and door open, maximum ventilation)

This section gives the results of the tests of variant 8 (balcony door open and door open, maximum ventilation) and the comparison with the tests of variant 0 (door open). The tests of variant 8 were conducted to find out whether an open balcony door had a major influence on the times for the possibility of escape and survivability.

During the tests of variant 8 (balcony door open and door open, maximum ventilation), the door to the fire room was opened after 5 minutes and it was blocked in its maximum open position for the first 20 minutes. In addition, the balcony door was blocked in its maximum open position during the entire escape phase. Table 4.5 shows the relevant data of the tests of variant 8 (balcony door open and door open, maximum ventilation) and variant 0 (door open).

Table 4.5 Data of the tests of variant 8 and variant 0

Variant no.	Variant name	Number of tests	Test no.	Date no.	Fire room
0	Door open	4	1 3 5 17	240619_1 250619_2 260619_2 040719_2	1.21 1.19 1.19 1.19
8	Balcony door open and door open (maximum ventilation)	2	18 19	050719_1 050719_2	1.19 1.19

4.4.1 Results of variant 8 (balcony door open and door open, maximum ventilation) and the comparison with variant 0 (door open)

The results of the times for the possibility of escape and survivability for both variant 8 (balcony door open and door open, maximum ventilation) and for variant 0 (door open) are presented below, numerically in a table (see table 4.6) and visually (see figure 4.6), by means of the stacked bars, per room and per group. This enables a quick comparison between the times of these two variants.

Table 4.6 Times of the possibility of escape and survivability (in minutes) of variant 8 and variant 0

		Fire room			Corridor 1.2 1.5 m			Corridor 1.2 0.3 m			Residence 1.25			Residence 1.20			Residence 1.24		
0		< 3	< 3	< 4	< 5	< 5	< 5	< 6	< 8	< 9	< 6	< 6	< 8	< 9	< 12	< 18	< 12	< 16	-
		3	3	4	5	5	5	6	8	9	6	6	8	9	12	18	12	16	-
		4	5	6	6	6	7	9	10	13	7	7	8	9	12	18	12	16	-
		4	5	7	6	7	7	9	11	16	7	8	8	11	15	-	15	-	-
8		< 3	< 3	< 5	< 5	< 5	< 5	< 6	< 6	< 7	< 6	< 7	< 9	< 10	< 11	< 15	< 17	-	-
		3	3	5	5	5	5	6	6	7	6	7	9	10	11	15	17	-	-
		4	5	6	6	7	8	9	10	11	7	8	9	10	11	15	17	-	-
		4	6	8	7	7	9	9	10	13	8	8	10	11	13	20	-	-	-

Note. For the yellow, orange and red smileys, a – in the table means that the threshold value for the group and situation in question was not reached within 20 minutes. For the green smileys, a – means that safe escape was possible for the first 20 minutes.

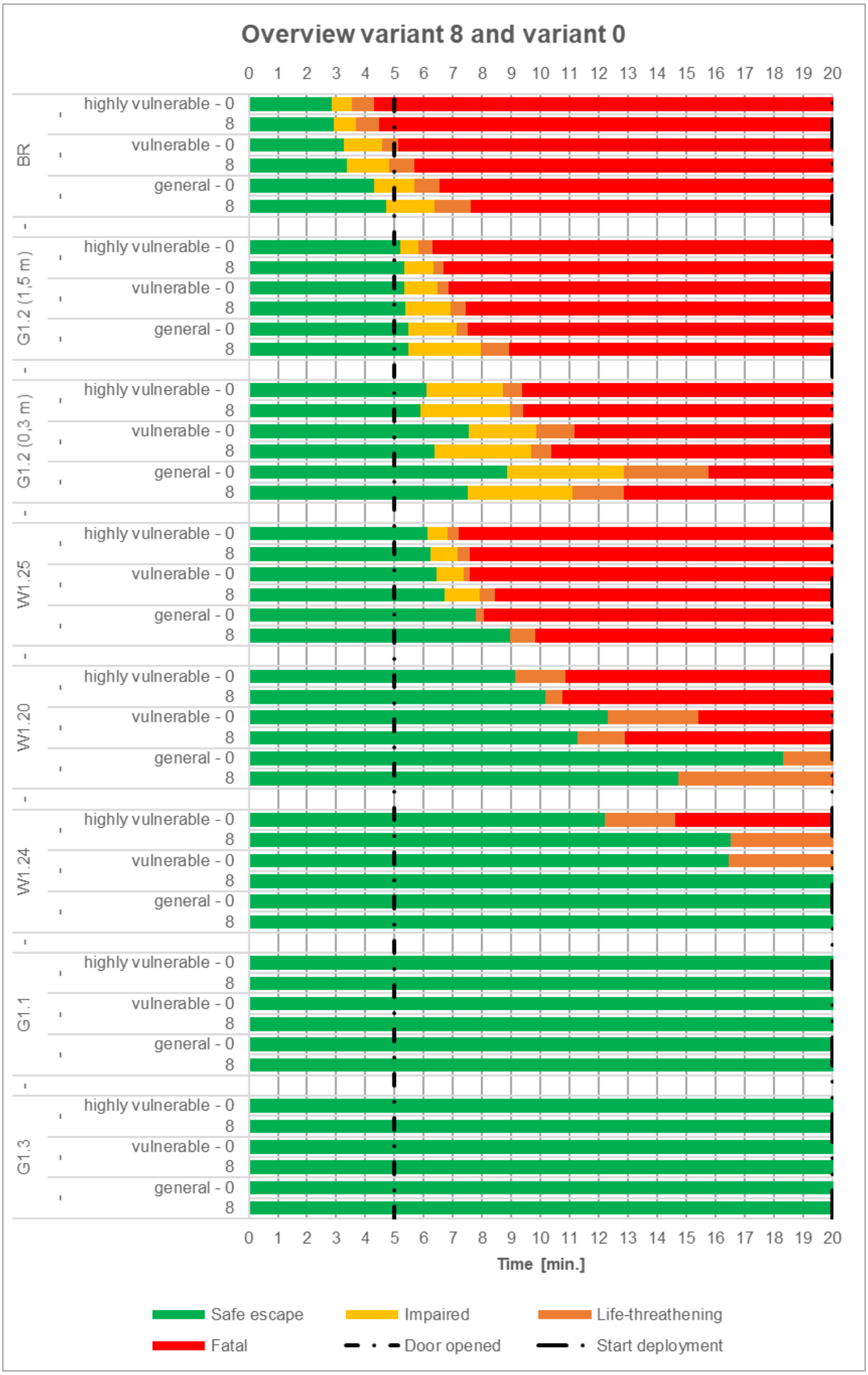


Figure 4.6 Times of the possibility of escape and survivability of variant 8 and variant 0

4.4.2 Analysis of variant 8 (balcony door open and door open, maximum ventilation)

The results of the tests of variant 8 (balcony door open and door open, maximum ventilation) enable the following conclusions to be drawn:

> **Fire room**: the situation in the fire room became life-threatening after approx. 4 to 6 minutes (depending on the group). The situation had become a fatal situation about 2 minutes after a life-threatening situation occurred.

> **Corridor 1.2**: the situation at 1.5 metres high in corridor 1.2 was such that the possibility of escape was impaired for all groups after 5 minutes. This was the case almost immediately after the door between the fire room and corridor 1.2 was opened. After about 2 to 4 minutes, the situation at 1.5 metres high in corridor 1.2 changed from impaired to fatal. Any attempt to escape through the smoke would soon be fatal. At 0.3 metre high, the possibility of escape was impaired after 6 to 9 minutes, depending on the group. At a height of 0.3 metre there was more time between the transition from a situation where the possibility of escape was impaired to a fatal situation than was the case at a height of 1.5 metres.

> **Other first-floor residences**: the situation in residence 1.25 was fatal for all groups after approx. 8 to 10 minutes. The spread in the time it took for the threshold values to be exceeded was greater for the different groups in residences 1.20 and 1.24. The situation in residence 1.20 had become life-threatening after approx. 10 to 15 minutes and fatal after approx. 11 to 20 minutes. The situation in residence 1.24 did not become life-threatening or fatal for the vulnerable and general groups.
> The times for survivability in the other first-floor residences were the shortest in residence 1.25. This was due to the open door between residence 1.25 and corridor 1.2. The times for survivability in residence 1.20 were shorter than in residence 1.24. Whereas the smoke could only propagate to residence 1.24 through the wall with a door and a door frame between residence 1.24 and corridor 1.2, smoke propagation to residence 1.20 could also occur via the shared wall with the fire room or the ventilation duct shared with corridor 1.2.

> C**orridors 1.1 and 1.3**: Safe escape through corridors 1.1 and 1.3 was possible for the first 20 minutes. One test in corridor 1.3 showed quite a lot of smoke on the camera images.

> **Other floors**: Measurements did not measure any CO on the ground floor, the second floor, and the third floor. Camera images do show visible smoke in corridor 3.2.

Non-exceeded threshold values

In situations where the threshold values were not exceeded within the first 20 minutes, they might still have been *nearly* exceeded. The situation in residence 1.24 did not become fatal for the highly vulnerable group within 20 minutes, but 104% of the threshold value for a fatal situation was reached here *after* these 20 minutes. 69% of the threshold value for a life-threatening situation for the vulnerable group was reached in residence 1.24. Although not all threshold values were exceeded in residence 1.24, it is likely that a fatal situation would have occurred for the highly vulnerable group or a life-threatening situation for the vulnerable group if they had stayed in the residence for more than 20 minutes.

Decisive conditions

The asphyxiant gases were mostly the first factor that caused the threshold values for life-threatening and fatal situations to be exceeded in the fire room. However, for the highly vulnerable groups, the irritant gases were the first factor that caused the threshold value for

a life-threatening situation to be exceeded and, for the general group, the heat was the first factor that caused the threshold value for a fatal situation to be exceeded. The heat was not the first decisive condition for the possibility of the highly vulnerable or vulnerable groups to survive in the fire room, but shortly after a fatal situation had been created by the asphyxiant gases, the heat would also have caused a fatal situation for this group. The temperature and radiation were measured in the lobby of the fire room at some distance from the fire object. If measurements had been taken closer to the fire object, the heat might have been found to have been the first factor that caused the threshold value for a life-threatening of fatal situation in the fire room to be exceeded.
Visibility distance was the first factor impairing escape in corridor 1.2. Shortly after this, irritant gases would also impair escape for the vulnerable and highly vulnerable groups. The heat might also become so high at a height of 1.5 metres in corridor 1.2 that this might have influenced the possibility of escape or survivability for the highly vulnerable group. The asphyxiant gases in corridor 1.2 caused the threshold values for a life-threatening and fatal situation to be exceeded. The irritant gases were also the factor that caused the threshold value for a life-threatening situation to be exceeded for the highly vulnerable group in corridor 1.2.
Where the threshold values for a life-threatening and fatal situation were exceeded in the other residences, this was caused by the asphyxiant gases. For the highly vulnerable or vulnerable groups, both the heat and the irritant gases influenced their possibility of escape and survivability in residence 1.25.

4.4.3 Analysis of the comparison of variant 8 with variant 0

Table 4.7 compares the tests of variant 8 (balcony door open and door open, maximum ventilation) with the tests of variant 0 (door open) for the individual elements.

Table 4.7 Comparison between variant 8 and variant 0

Element	Comparison to variant 0 (door open)
Survivability in the fire room	Identical
The possibility of escape and survivability in corridor 1.2	Identical
Survivability in the other first-floor residences up to 20 minutes	Residences 1.25 and 1.20 identical Residence 1.24 improvement
The percentage of non-exceeded threshold values in the other first-floor residences at 20 minutes	Residence 1.24 improvement Otherwise identical
Survivability on the other floors	Improvement
The effect of an open balcony door for the different groups	Residence 1.24 showed an improvement for all groups Otherwise identical

The decrease in mass of the sofa leads to the conclusion that a greater share of the sofa was burnt in the tests of variant 8 (balcony door open and door open, maximum ventilation) compared to the tests of variant 0 (door open). This is probably due to the supply of extra oxygen to the fire via the open balcony door. However, the influence of the open balcony door on the times for the possibility of escape and survivability is slight in the fire room, in corridor 1.2, and in residences 1.20 and 1.25. The situation in residence 1.24 and on the other floors is better. This is probably because more smoke could flow out, resulting in less smoke being propagated in the building.

4.5 Overall analysis

The main findings from the tests of variant 0 and 1 (door open and door closed) and the tests of variant 8 (balcony door open and door open, maximum ventilation) are as follows:

> One burning sofa can lead to a fatal situation in the fire room within a matter of minutes. The burning sofa caused both horizontal and vertical smoke propagation outside the residence in which the sofa was located.

> Briefly opening the door to the fire room to the corridor almost immediately created an impaired escape route in the corridor due to limited visibility and sometimes due to an excess of irritant gases.

> The possibility of escape was impaired in corridor 1.2 after the door to the fire room had been opened. This would cause people in the other residences to be 'stuck' in their residences if they tried to escape after the person in the fire room had escaped.

> The smoke can propagate from the smoke-filled corridor (corridor 1.2) to other corridors on the same floor (corridor 1.1 and corridor 1.3). However, the smoke propagation to corridor 1.1 and corridor 1.3 was limited during the tests. This is probably because the doors between corridor 1.2 and corridor 1.1 and 1.3 were closed for almost the entire first 20 minutes.

> Fatal situations can also occur in residences where there is no fire. Survivability was worse in the residence next to the fire room (1.20) than in the residence opposite whose door was closed (1.24). Survivability was the worst in the residence with an open door to the corridor (1.25).

> If the person in the house where the fire originated closed their front door after escaping, there would be a survivable situation for more than 20 minutes for all groups in the residence opposite whose door was closed (1.24).

> Smoke also propagated to other floors. CO was only measured on these floors during the tests of variant 0 (door open). The extent to which smoke propagated, and the rooms to which it propagated on the other floors, differs from test to test. Peak concentrations of CO were measured on other floors. These concentrations might be life-threatening for the very vulnerable group if they stayed in these areas for 20 minutes.

> The influence of the open balcony door on the times for the possibility of escape and survivability is slight in the fire room, in corridor 1.2, and in residences 1.20 and 1.25 (compared to variant 0 with only the door open). The possibility of escape and survivability improved compared to the tests of variant 0 (door open) in residence 1.24 and on the other floors than the floor where the fire room was located. This is probably because more smoke could flow to the outside air, resulting in less smoke being propagated inside the building.

5 Measures for risk management

5.1 Introduction

Before reading this chapter, please refer to section 4.2 with instructions on how to interpret the results.

This chapter shows the effect of the tested measures for risk management on the possibility of escape and survivability. This starts with a presentation of the times for the possibility of escape and survivability for the tests conducted in combination with measures. Subsequently, these times are compared to the times of the tests where no measures were taken. A comparison is made first between the tests of variant 1 (door closed) and the tests of variant 0 (door open). Next, the tests of the variants with measures for risk management and an open door are compared to the tests of variant 0 (door open), and then the tests of variants with these measures and a closed door are compared to the tests of variant 1 (door closed). This means that only one variable differs in each comparison, in order to show clearly which measure caused the differences.

Section 5.7 summarizes the effects of the different measures relative to the outcome of the tests of variant 0 (door open) or variant 1 (door closed). Section 5.8 compares all the different variants to each other in order to see which measures for risk management result in the greatest improvement in the possibility of escape and survivability.

5.2 Tests of variant 1 (door closed)

This section presents the comparison of the results of the tests of variant 0 (door open) with the tests of variant 1 (door closed). This shows the added value of a door to the fire room being closed most of the time. Since the results of the tests of variant 1 (door closed) were already discussed in section 4.3.3, we will only discuss the comparison here.

During the tests of variant 1 (door closed), the door to the fire room was opened after 5 minutes, it was kept open for 30 seconds and closed again after 5.5 minutes. After this, the door was kept closed until at least t = 20 minutes. Table 5.1 lists the relevant data of the tests of variant 1 (door closed) and variant 0 (door open).

Table 5.1 Data of the tests of variant 1 and variant 0

Variant no.	Variant name	Number of tests	Test no.	Date no.	Fire room
0	Door open	4	1 3 5 17	240619_1 250619_2 260619_2 040719_2	1.21 1.19 1.19 1.19
1	Door closed	3	2 4 16	250619_1 260619_1 040719_1	1.21 1.21 1.21

5.2.1 Results of variant 1 (door closed) and the comparison with variant 0 (door open)

The results of the times for the possibility of escape and survivability of both variant 1 (door closed) and variant 0 (door open) are presented below, both numerically in a table (see table 5.2) and visually (see figure 5.1) by means of the stacked bars, per room and per group. This enables a quick comparison between the times of these two variants.

Table 5.2 Times of the possibility of escape and survivability (in minutes) of variant 1 and variant 0

		Fire room			Corridor 1.2 1.5 m			Corridor 1.2 0.3 m			Residence 1.25			Residence 1.20			Residence 1.24		
0		< 3	< 3	< 4	< 5	< 5	< 5	< 6	< 8	< 9	< 6	< 6	< 8	< 9	< 12	< 18	< 12	< 16	-
		3	3	4	5	5	5	6	8	9	6	6	8	9	12	18	12	16	-
		4	5	6	6	6	7	9	10	13	7	7	8	9	12	18	12	16	-
		4	5	7	6	7	7	9	11	16	7	8	8	11	15	-	15	-	-
1		< 3	< 3	< 4	< 5	< 5	< 5	< 6	< 9	-	< 6	< 16	-	< 10	< 14	-	-	-	-
		3	3	4	5	5	5	6	9	-	6	16	-	10	14	-	-	-	-
		4	5	6	7	13	-	14	-	-	9	16	-	10	14	-	-	-	-
		4	5	6	11	-	-	19	-	-	12	-	-	12	19	-	-	-	-

Note. For the yellow, orange and red smileys, a – in the table means that the threshold value for the group and situation in question was not reached within 20 minutes. For the green smileys, a – means that safe escape was possible for the first 20 minutes.

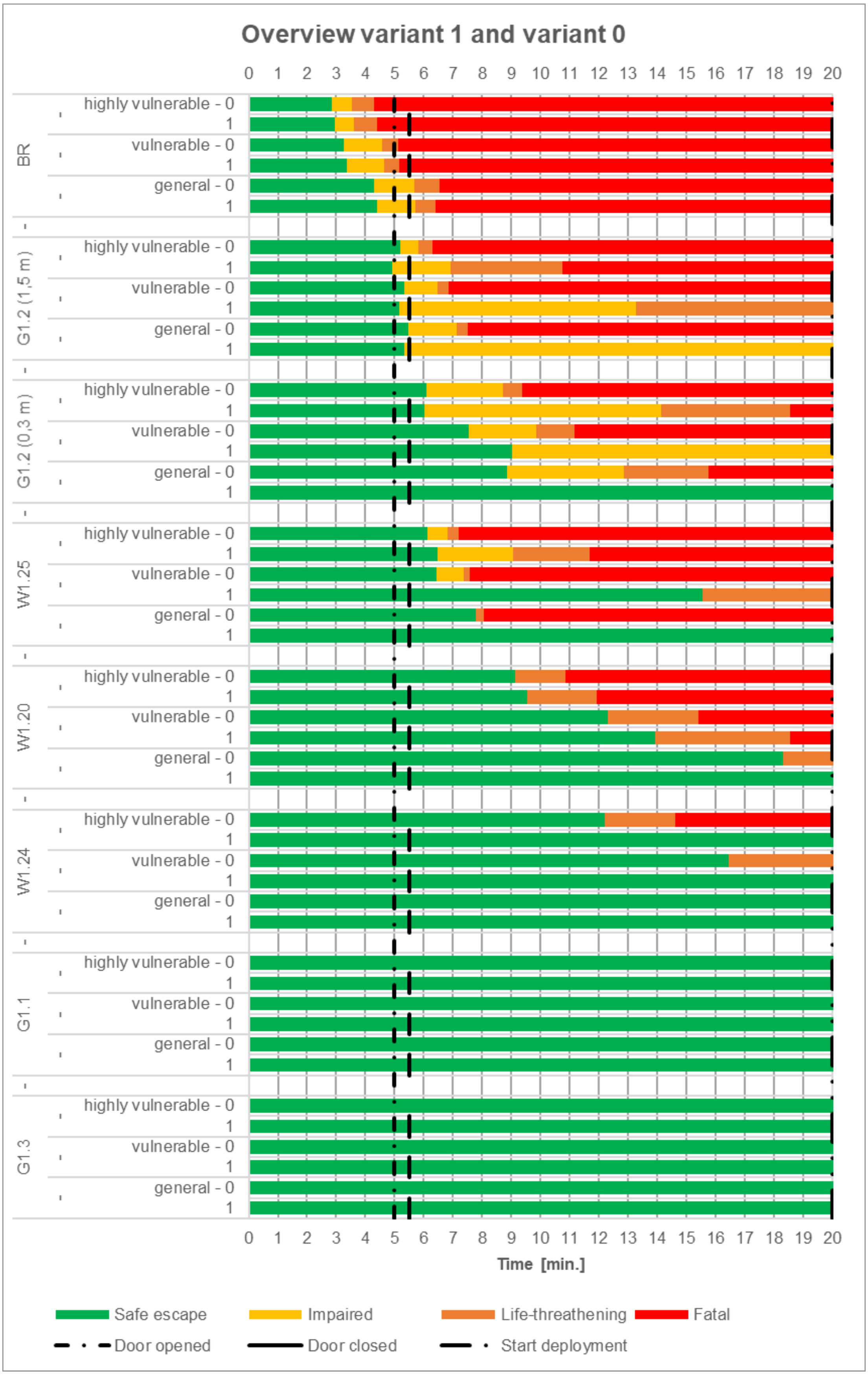


Figure 5.1 Times of the possibility of escape and survivability of variant 1 and variant 0

5.2.2 Analysis of the comparison between variant 1 and variant 0

Table 5.3 lists the results of the comparison between variant 1 (door closed) and variant 0 (door open).

Table 5.3 Comparison between variant 1 and variant 0

Element	Comparison with variant 0 (door open)
Survivability in the fire room	Unchanged
The possibility of escape in corridor 1.2	Unchanged shortly after the door was opened A slight improvement for the general group between 6 and 20 minutes Otherwise unchanged
Survivability in corridor 1.2	Improvement
Survivability in the other residences on the first floor for up to 20 minutes	The situation in residence 1.20 was unchanged for the highly vulnerable group There was a slight improvement in residence 1.20 for the general group The situation in residence 1.24 was unchanged for the general group Furthermore, there was an improvement for all residences and groups
The percentage of non-exceeded threshold values in the other residences on the first floor at 20 minutes	Improvement
Survivability on the other floors	Improvement
The effect of a closed door for the different groups	There was mainly an improvement in survivability for the general and vulnerable groups in residences 1.20 and 1.25 There was no major improvement for the highly vulnerable group in residences 1.20 and 1.25 Survivability improved for all groups in residence 1.24

Escape through corridor 1.2 was impaired quickly after the door to the fire room was opened, even if it was only opened briefly. The visibility distance improved again in corridor 1.2 after some time and the concentration of irritant gases decreased. This led to a slight improvement in the possibility of escape for the general group. There was a survivable situation in all rooms for quite some time, except in the fire room and expect for the highly vulnerable group in residence 1.20. The door to the fire room being kept closed or being open as briefly as possible is important for the possibility of escape and survivability outside the fire room.

5.3 Tests of variant 5 (smoke resistant partition and door closed)

This section presents the times of the tests of variant 5 (smoke resistant partition and door closed) and compares them with the times of the tests of variant 1 (door closed), to give insight in the added value of the smoke resistant partition.

The following modifications were made to the two fire rooms for the tests of variant 5 (smoke resistant partition and door closed):
> Installation of a smoke resistant door (S200).
> The external and internal structure were made as airtight as possible by sealing gaps and seams.
> The ventilation opening in the hall of the residence leading to the ventilation duct was sealed.

The following modifications were made to residence 1.24:
> Installation of a smoke resistant door (S200).
> The external and internal structure were made as airtight as possible by sealing gaps and seams.

The above modifications were implemented in order to simulate an airtight situation as in a new structure.

During the tests of variant 5 (smoke resistant partition and door closed), the door to the fire room was opened after 5 minutes and closed again after 5.5 minutes. This means that it was open for 30 seconds. Afterwards, the door was kept closed until at least t = 20 minutes. Table 5.4 lists the relevant data of the tests of variant 5 (smoke resistant partition and door closed) and variant 1 (door closed).

Table 5.4 Data of the tests of variant 5 and variant 1

Variant no.	Variant name	Number of tests	Test no.	Date no.	Fire room
1	Door closed	3	2 4 16	250619_1 260619_1 040719_1	1.21 1.21 1.21
5	Smoke resistant partition and door closed	2	12 13	020719_1 020719_2	1.21 1.19

5.3.1 Results of variant 5 (smoke resistant partition and door closed) and the comparison with variant 1 (door closed)

The results of the times for the possibility of escape and survivability of both variant 5 (smoke resistant partition and door closed) and variant 1 (door closed) are presented below, both numerically in a table (see table 5.5) and visually (see figure 5.2) by means of the stacked bars, per room and per group. This enables a quick comparison between the times of these two variants.

Table 5.5 Times of the possibility of escape and survivability (in minutes) of variant 5 and variant 1

		Fire room			Corridor 1.2 1.5 m			Corridor 1.2 0.3 m			Residence 1.25			Residence 1.20			Residence 1.24		
1		< 3	< 3	< 4	< 5	< 5	< 5	< 6	< 9	-	< 6	< 16	-	< 10	< 14	-	-	-	-
		3	3	4	5	5	5	6	9	-	6	16	-	10	14	-	-	-	-
		4	5	6	7	13	-	14	-	-	9	16	-	10	14	-	-	-	-
		4	5	6	11	-	-	19	-	-	12	-	-	12	19	-	-	-	-
5		< 3	< 3	< 4	< 5	< 5	< 5	< 6	< 10	-	< 7	< 13	-	< 14	-	-	-	-	-
		3	3	4	5	5	5	6	10	-	7	13	-	14	-	-	-	-	-
		4	5	6	6	13	-	13	-	-	9	13	-	14	-	-	-	-	-
		4	5	6	10	19	-	17	-	-	11	-	-	18	-	-	-	-	-

Note. For the yellow, orange and red smileys, a – in the table means that the threshold value for the group and situation in question was not reached within 20 minutes. For the green smileys, a – means that safe escape was possible for the first 20 minutes.

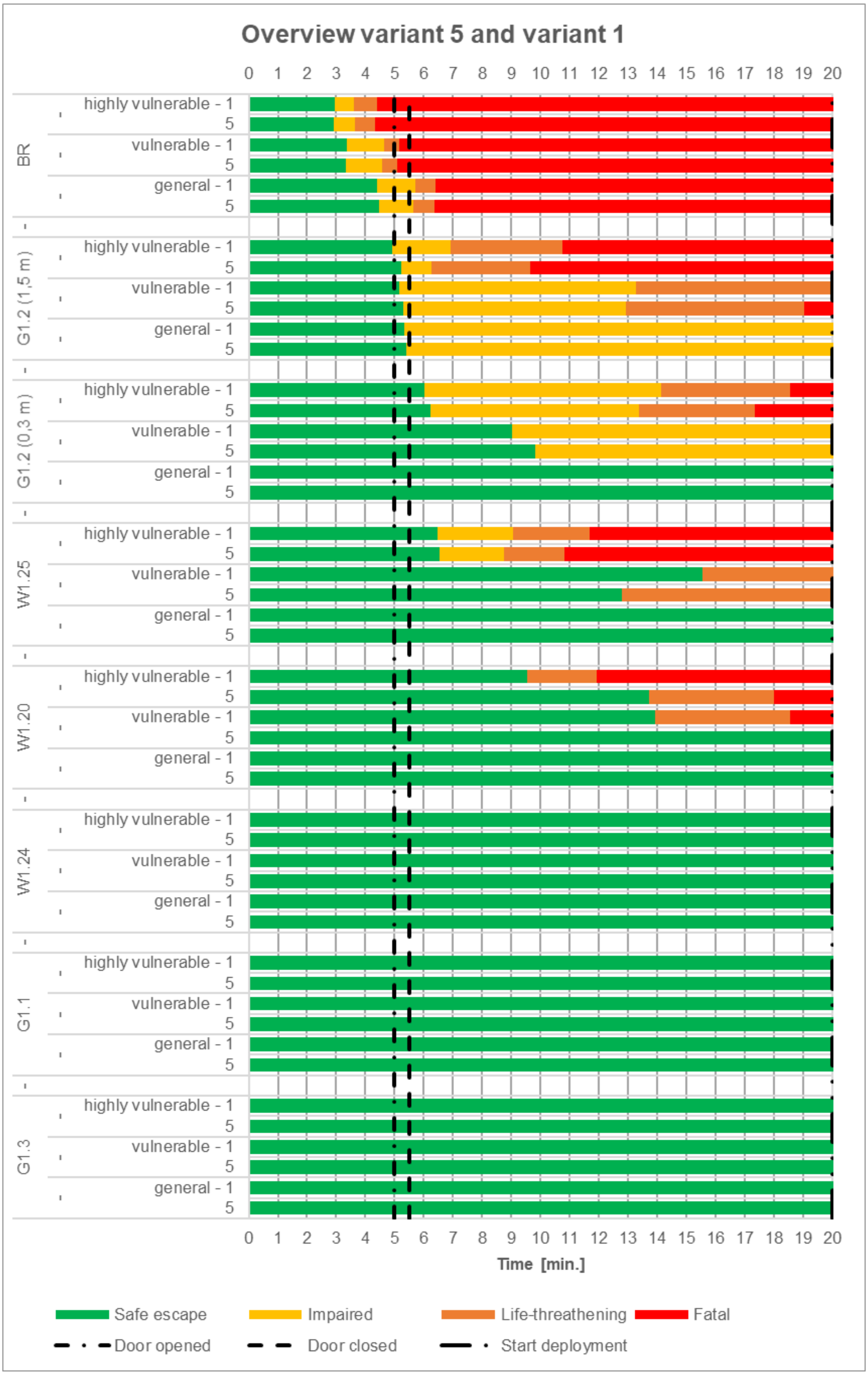


Figure 5.2 Times of the possibility of escape and survivability of variant 5 and variant 1

5.3.2 Analysis of variant 5 (smoke resistant partition and door closed)

The results of the tests of variant 5 (smoke resistant partition and door closed) enable the following conclusions to be drawn.

> **Fire room**: there was a life-threatening and fatal situation in the fire room after approx. 4 to 6 minutes (depending on the group).

> **Corridor 1.2**: the situation at 1.5 metres high in corridor 1.2 was such that the possibility of escape was impaired for all groups after 5 minutes. This was the case almost immediately after the door between the fire room and corridor 1.2 was opened. After this door was closed, the visibility distance and the concentration of irritant gases improved again slightly. During the period from 9 to 20 minutes, there may have been certain moments and locations where there was a safe escape situation for the general group in corridor 1.2. This is not reflected in the stacked bars because once a threshold value has been exceeded this can no longer be reversed in the calculation method selected which underlies the figures with the stacked bars. However, these moments can be recognised in how the decisive conditions for the impaired escape in corridor 1.2 developed (see Appendix 21): the visibility distance (FEC_{smoke}) and the concentration of irritant gases (FIC). Furthermore, camera images show that visibility in corridor 1.2 improved slightly at 1.5 metres high but was still limited.
> The situation became life-threatening for the highly vulnerable group at a height of 1.5 metres after approx. 1 minute. For the vulnerable group, this took about 8 minutes. The situation became fatal for the highly vulnerable group after 10 minutes; for the vulnerable group this took 19 minutes. The situation in corridor 1.2 did not become fatal for the general group during the first 20 minutes. Escape was impaired for the highly vulnerable and vulnerable groups at 0.3 metres high after 6 to 10 minutes. safe escape was possible at the height of 0.3 metres for the general group for the first 20 minutes.

> **Other first floor residences**: safe escape from residence 1.24 remained possible for all groups for the first 20 minutes. This also applied to residence 1.20 for the general and vulnerable groups. Furthermore, safe escape from residence 1.25 was possible for the general group for the first 20 minutes. The situation in residence 1.20 became life-threatening for the highly vulnerable group after 14 minutes and it became fatal after 18 minutes.
> The situation in residence 1.25 was fatal for the highly vulnerable group after 11 minutes. The situation did not become fatal for the vulnerable group during the first 20 minutes. The situation in residence 1.25 became life-threatening for the vulnerable group after 13 minutes.
> The times for survivability in residences 1.20, 1.24 and 1.25 were the shortest in residence 1.25; this was because of the open door between residence 1.25 and corridor 1.2. After residence 1.25, the times for survivability were the shortest in residence 1.20. There were three routes by which smoke could propagate to this residence: via the shared wall with the fire room, via the shared ventilation duct with the corridor, and via the wall between corridor 1.2 and the residence. To propagate to residence 1.24, the smoke had to pass two walls that separate the residences.

> **Corridors 1.1 and 1.3**: safe escape through corridors 1.1 and 1.3 was possible for the first 20 minutes. Camera images showed only light smoke in corridors 1.1 and 1.3 during the first 20 minutes.

> **Other floors**: measurements did not measure any CO on the ground floor, the second floor, and the third floor. Camera images showed some smoke on the second floor in the residence above the fire room (2.19 / 2.21).

Non-exceeded threshold values
In situations where the threshold values were not exceeded within the first 20 minutes, they might still have been *nearly* exceeded. For example, 95% of the threshold value for a fatal situation was reached for the vulnerable group in residence 1.25 and 58% in residence 1.20. The highest percentage in residence 1.24 was 26%. Therefore, a stay of more than 20 minutes in residences 1.25 and 1.20 might still lead to life-threatening or fatal situations in some cases, whereas this situation was less likely to occur in residence 1.24.

Decisive conditions
The asphyxiant gases were the first factor that caused the threshold values for life-threatening and fatal situations to be exceeded in the fire room. The irritant gases were the first factor that caused the threshold value for a life-threatening situation to be exceeded for the highly vulnerable group. The heat is not directly decisive for survivability in the fire room, but, in case of the highly vulnerable group, the thresholds for life-threatening and fatal situations were exceeded. The temperature and radiation were measured in the lobby of the fire room at some distance from the fire object. If measurements had been conducted at a shorter distance from the fire object, the heat might have been the first cause of the threshold value for a life-threatening or fatal situation in the fire room being exceeded.
The visibility distance was the first factor that impaired escape in corridor 1.2; briefly after this, irritant gases also impaired the possibility of escape for the vulnerable and highly vulnerable groups. The asphyxiant gases caused the threshold value for life-threatening and fatal situations to be exceeded for the vulnerable and highly vulnerable groups in corridor 1.2.
Where the threshold value for life-threatening and fatal situations was exceeded in the other residences, this was also caused by the asphyxiant gases.

5.3.3 Analysis of the comparison between variant 5 and variant 1

Table 5.6 shows the results of the comparison between variant 5 (smoke resistant partition and door closed) and variant 1 (door closed).

Table 5.6 Comparison between variant 5 and variant 1

Element	Comparison to variant 1 (door closed)
Survivability in the fire room	Unchanged
The possibility of escape in corridor 1.2	Unchanged
Survivability in corridor 1.2	Unchanged
Survivability in the other residences on the first floor for up to 20 minutes	A slight deterioration for the vulnerable group in residence 1.25 Otherwise unchanged[30]

[30] The table with times for the possibility of escape and survivability shows an improvement for residence 1.20. This is probably due to the use of a different fire room in one of the two tests of variant 5. This is because one test of variant 5 (test 13) was conducted in a different fire room. This showed a clearly different CO concentration in residence 1.20 compared to the other test of variant 5 (test 12) and the tests of variant 1. The average values of these tests showed an improvement for residence 1.20 for the variant 5 tests. The development of the CO concentration for the different tests can be found in Appendix 16.

The percentage of non-exceeded threshold values in the other residences on the first floor at 20 minutes	Unchanged[31]
Survivability on the other floors	Unchanged
The effect of a smoke resistant partition for the different groups	The effect is almost identical to that of a closed door No significant improvement or deterioration for any specific group

The difference with the tests of variant 1 (door closed) is minor. Although the smoke resistant partition may be better at stopping smoke, opening the door to the fire room for 30 seconds was found to be decisive for the smoke propagation from the fire room to corridor 1.2. If this had happened at an earlier or later moment during the fire scenario, or if the door had been open for a longer or shorter time than 30 seconds, the results might have differed. The CO concentrations in residence 1.24 are relatively low, both for the tests of variant 1 (door closed) and the tests of variant 5 (smoke resistant partition and door closed). Since there is also spread in the results of the different tests, no conclusion can be drawn as to whether the smoke resistant partition in residence 1.24 had a positive effect. These field experiments do not justify any conclusion as to the added value of this partition in residence 1.24 where the door to the fire room was left open; this is a question that would be worthy of further research.

The pressures in the fire room were considerably higher than during the tests of variant 1 (door closed). For the tests of variant 1 (door closed), the peak pressure in the fire room was 60 to 170 Pa; for the tests of variant 5 (smoke resistant partition and door closed), this was 340 to 1010 Pa. The amount of air/smoke that passes through a gap or seam depends on the size and the passage coefficient of the gap or seam, and on the pressure difference between the rooms. A higher pressure difference can mean that the same amount of air or even more air is displaced even though the gap is smaller. Although the pressures measured during the tests of variant 5 (smoke resistant partition and door closed) were short peak pressures, they were substantially higher than the highest pressure of 50 Pa for which the parts of the smoke resistant partition should be tested according to NEN 6075:2020.

5.4 Tests of variant 2 (mobile water mist and door open) and variant 3 (mobile water mist and door closed)

This section presents the times of the tests with mobile water mist (variants 2 and 3). This section also compares the tests of variant 2 (mobile water mist and door open) to the tests of variant 0 (door open), and it compares the tests of variant 3 (mobile water mist and door closed) to the tests of variant 1 (door closed). This gives insight in the added value of the mobile water mist.

[31] The table with percentages of the threshold values for the possibility of escape and survivability shows an improvement for residence 1.20. This difference is probably due to the use of a different fire room in one of the two tests of variant 5. This is because one test of variant 5 (test 13) was carried out in a different fire room. This showed a clearly different CO concentration in residence 1.20 compared to the other test of variant 5 (test 12) and the tests of variant 1. The average values of these tests showed an improvement for residence 1.20 for the tests of variant 5. The development of the CO concentration for the different tests can be found in Appendix 16.

The fire room was provided with a mobile water mist system for the tests with a mobile water mist (variants 2 and 3). These tests were conducted with an open door (variant 2; the door between the fire room and corridor 1.2 was opened after 5 minutes and it was kept in its maximum open position for the first 20 minutes) and with a closed door (variant 3; the door between the fire room and corridor 1.2 was opened after 5 minutes and closed again after 5.5 minutes until at least t = 20 minutes). Table 5.7 shows the relevant data of the tests of variant 2 (mobile water mist and door open) and variant 0 (door open), and of the tests of variant 3 (mobile water mist and door closed) and variant 1 (door closed).

Table 5.7 Data of the tests of variants 2 and 0, and of variants 3 and 1

Variant no.	Variant name	Number of tests	Test no.	Date no.	Fire room
0	Door open	4	1 3 5 17	240619_1 250619_2 260619_2 040719_2	1.21 1.19 1.19 1.19
1	Door closed	3	2 4 16	250619_1 260619_1 040719_1	1.21 1.21 1.21
2	Mobile water mist and door open	2	7 9	270619_2 280619_2	1.19 1.19
3	Mobile water mist and door closed	2	6 8	270619_1 280619_1	1.21 1.21

5.4.1 Results of variant 2 (mobile water mist and door open) and the comparison with variant 0 (door open)

The results of the times for the possibility of escape and survivability of both variant 2 (mobile water mist and door open) and variant 0 (door open) are presented below, both numerically in a table (see table 5.8) and visually (see figure 5.3) by means of the stacked bars, per room and per group. This enables a quick comparison between the times of these two variants.

Table 5.8 Times of the possibility of escape and survivability (in minutes) of variant 2 and variant 0

		Fire room			Corridor 1.2 1.5 m			Corridor 1.2 0.3 m			Residence 1.25			Residence 1.20			Residence 1.24		
0		< 3	< 3	< 4	< 5	< 5	< 5	< 6	< 8	< 9	< 6	< 6	< 8	< 9	< 12	< 18	< 12	< 16	-
		3	3	4	5	5	5	6	8	9	6	6	8	9	12	18	12	16	-
		4	5	6	6	6	7	9	10	13	7	7	8	9	12	18	12	16	-
		4	5	7	6	7	7	9	11	16	7	8	8	11	15	-	15	-	-
2		< 3	< 4	< 11	< 5	< 6	< 7	< 7	< 10	< 13	< 7	< 12	< 16	-	-	-	< 16	-	-
		3	4	11	5	6	7	7	10	13	7	12	16	-	-	-	16	-	-
		4	6	11	7	9	13	11	14	19	9	12	16	-	-	-	16	-	-
		5	8	17	8	11	17	13	17	-	11	14	19	-	-	-	19	-	-

Note. For the yellow, orange and red smileys, a – in the table means that the threshold value for the group and situation in question was not reached within 20 minutes. For the green smileys, a – means that safe escape was possible for the first 20 minutes.

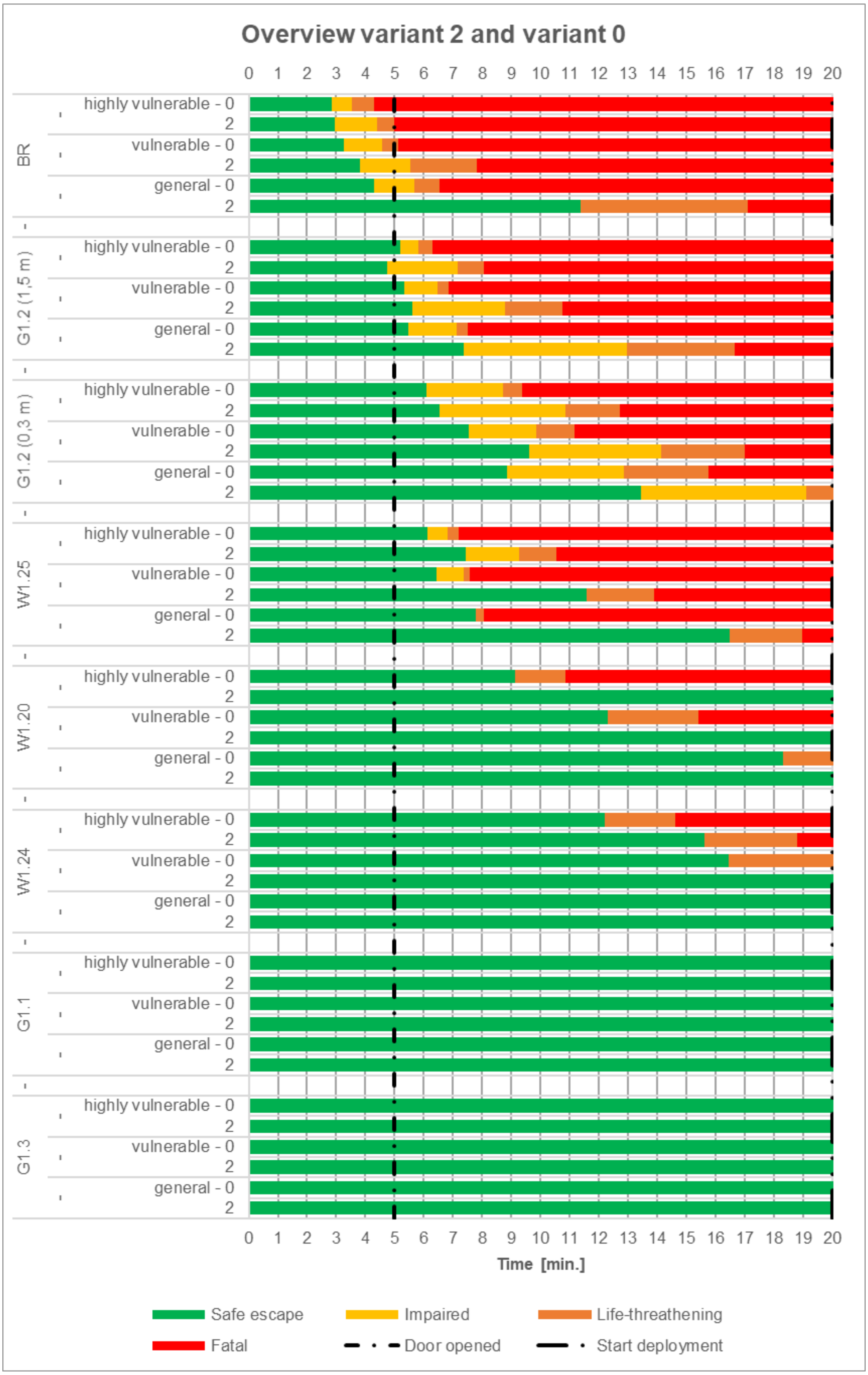


Figure 5.3 Times of the possibility of escape and survivability of variant 2 and variant 0

5.4.2 Analysis of variant 2 (mobile water mist and door open)

The main findings from the results of the tests of variant 2 (mobile water mist and door open) are discussed below.

> **Fire room**: the situation in the fire room took approx. 4 minutes to become life-threatening for the highly vulnerable group, 6 minutes for the vulnerable group, and 11 minutes for the general group. The situation became fatal for the highly vulnerable group within 1 minute after the situation had become a life-threatening situation. This took 2 minutes for the vulnerable group and 6 minutes for the general group.
> **Corridor 1.2**: the possibility of escape was impaired at a height of 1.5 metres in corridor 1.2 after 5 to 7 minutes, depending on the group. This was the case quickly after the door between the fire room and corridor 1.2 was opened. The impaired situation at 1.5 metres became a fatal situation for the vulnerable and highly vulnerable groups as quickly as after about 2 to 3 minutes. It took 5 minutes for the situation to become life-threatening for the general group. An impaired situation occurred at 0.3 metres high after 7 to 13 minutes (depending on the group). The time it took for this situation to become fatal at 0.3 metres for the highly vulnerable group was 6 minutes; for the vulnerable group this took 7 minutes. The situation was not fatal for the general group in the first 20 minutes.
> **Other first floor residences**: in residence 1.25, there was a fatal situation in the fire room after approx. 11 to 19 minutes, depending on the group. The situation in residence 1.20 was such that all groups could escape safely during the first 20 minutes. This also applied to the general and vulnerable groups in residence 1.24, but the highly vulnerable group was faced with a life-threatening situation in that residence after 16 minutes, which turned fatal after 19 minutes.
The survivability times in residences 1.20, 1.24 and 1.25 were the shortest in residence 1.25; this was because of the open door between residence 1.25 and corridor 1.2. The survivability times were shorter in residence 1.24 than in residence 1.20. This is special, since there were three routes by which smoke could propagate to residence 1.20: via the shared wall with the fire room, via the shared ventilation duct with the corridor, and via the wall between corridor 1.2 and the residence. However, smoke could only propagate to residence 1.24 via the wall between corridor 1.2 and the residence.
> **Corridors 1.1 and 1.3**: safe escape through corridors 1.1 and 1.3 was possible for the first 20 minutes. Camera images only showed light smoke in these corridors in the first 20 minutes.
> **Other floors**: measurements did not measure any CO on the ground floor, the second floor, and the third floor. Camera images showed visible smoke in corridor 3.2.

Non-exceeded threshold values

In situations where the threshold values were not exceeded within the first 20 minutes, they might still have been *nearly* exceeded. The situation in residence 1.20 did not become fatal for the highly vulnerable group, but 59% of the threshold value was reached here after 20 minutes. 50% of the threshold value for a fatal situation for the vulnerable group was reached in residence 1.24. Although not all the threshold values were exceeded in residences 1.20 and 1.24, it is plausible to assume that they would be exceeded for the highly vulnerable group in residence 1.20 and for the vulnerable group in residence 1.24 if people had stayed in those residences for more than 20 minutes. The percentages of the threshold value for a life-threatening situation for the general group were 12% (in residence 1.20) and 30% (in residence 1.24). This means that, for these cases, if people stayed in the residences for more than 20 minutes, no life-threatening situation would arise in the short term.

Decisive conditions
The asphyxiant gases were the first factor that caused the threshold values for life-threatening and fatal situations to be exceeded in the fire room. The irritant gases also caused the threshold value for a life-threatening situation to be exceeded for the highly vulnerable group. Heat was not decisive for survivability, not even in the fire room. But since the temperature and radiation were measured in the lobby of the fire room at some distance from the fire object, heat might be decisive for survivability in the direct vicinity of the fire in the fire room.

The visibility distance was the first factor which impaired the possibility of escape in corridor 1.2; briefly after this, the irritant gases also impaired the possibility of escape for the vulnerable and highly vulnerable groups. The heat might also become so high at a height of 1.5 metres in corridor 1.2 that this might have influenced the possibility of safe escape for the highly vulnerable group. The asphyxiant gases caused the threshold values for a life-threatening and fatal situation to be exceeded in corridor 1.2.
Where the threshold values for a life-threatening and fatal situation were exceeded in the other residences, this was caused by the asphyxiant gases.

5.4.3 Analysis of the comparison between variant 2 and variant 0

Table 5.9 shows the results of the comparison between variant 2 (mobile water mist and door open) and variant 0 (door open).

Table 5.9 Comparison between variant 2 and variant 0

Element	Comparison to variant 0 (door open)
Survivability in the fire room	Unchanged for the highly vulnerable group Slight improvement for the vulnerable group Improvement for the general group
The possibility of escape in corridor 1.2	There was a slight improvement for the general group at a height of 1.5 m Unchanged for the vulnerable and highly vulnerable groups at a height of 1.5 m The improvement in the possibility of escape is greater at a height of 0.3 m The improvement in the possibility of escape at a height of 0.3 m was the most significant for the general group
Survivability in corridor 1.2	There was a slight improvement for the highly vulnerable group (at 0.3 m high) or an improvement (at 1.5 m high) There was an improvement for the vulnerable and general groups
Survivability in the other residences on the first floor for up to 20 minutes	The situation remained unchanged for the general group in residence 1.24 and it showed a slight improvement in residence 1.20

	Further improvement
The percentage of non-exceeded threshold values in the other residences on the first floor at 20 minutes	A slight improvement for the general group in residence 1.24 Further improvement
Survivability on the other floors	Improvement
The effect of a mobile water mist and the door being open for the different groups	The improvements were minor, particularly for the highly vulnerable group As far as the vulnerable group is concerned, the improvement was limited in the fire room and in corridor 1.2 at a height of 1.5 metres

The combination of a mobile water mist and an open door mainly brought an improvement for the general group. Only slight improvements were measured for the vulnerable group. With regard to the highly vulnerable group, the times for the possibility of escape and survivability were almost identical to those of the tests of variant 0 (door open). In these tests, the peak CO concentration in the fire room was 15,000 to 30,000 ppm after 400 to 500 seconds. The CO concentration between 400 and 500 seconds was 800 to 1,800 ppm in the tests with the mobile water mist and the door open. This is much lower, but it is still too high for the vulnerable and highly vulnerable groups. The situation in the fire room became fatal for the highly vulnerable group after 5 minutes. During the first 6 minutes, the development of the CO concentration in the fire room was almost identical to that of the tests of variant 2 (mobile water mist and door open) and the tests of variant 0 (door open). It was only after 6 minutes that the effect of the mobile water mist resulted in lower CO concentrations in the fire room.

The tank of the mobile water mist system contained enough water to last approx. 15 minutes. Once this water had been used up, the fire flared up again. There were two moments in the period between the moment when the door to the fire room was opened and the water ran out (between 5 and 17 minutes) where one test showed the temperature to increase again for a short time.
When the water in the mobile water mist tank had run out, the temperature in the fire room increased from around 70 °C at the top of the room to between 170 and 230 °C. The CO concentration also increased then. The fire flaring up means that the mobile water mist did not extinguish the fire.

5.4.4 Results of variant 3 (mobile water mist and door closed) and the comparison to variant 1 (door closed)

The results of the times for the possibility of escape and survivability of both variant 3 (mobile water mist and door closed) and variant 1 (door closed) are presented below, both numerically in a table (see table 5.10) and visually (see figure 5.4) by means of the stacked bars, per room and per group. This enables a quick comparison between the times of these two variants.

Table 5.10 Times of the possibility of escape and survivability (in minutes) of variant 3 and variant 1

		fire room			Corridor 1.2 1.5 m			Corridor 1.2 0.3 m			Residence 1.25			Residence 1.20			Residence 1.24		
1	green	< 3	< 3	< 4	< 5	< 5	< 5	< 6	< 9	-	< 6	< 16	-	< 10	< 14	-	-	-	-
	yellow	3	3	4	5	5	5	6	9	-	6	16	-	10	14	-	-	-	-
	orange	4	5	6	7	13	-	14	-	-	9	16	-	10	14	-	-	-	-
	red	4	5	6	11	-	-	19	-	-	12	-	-	12	19	-	-	-	-
3	green	< 3	< 4	< 10	< 5	< 5	-	-	-	-	-	-	-	-	-	-	-	-	-
	yellow	3	4	10	5	5	-	-	-	-	-	-	-	-	-	-	-	-	-
	orange	4	6	10	18	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	red	5	8	16	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

Note. For the yellow, orange and red smileys, a – in the table means that the threshold value for the group and situation in question was not reached within 20 minutes. For the green smileys, a – means that safe escape was possible for the first 20 minutes.

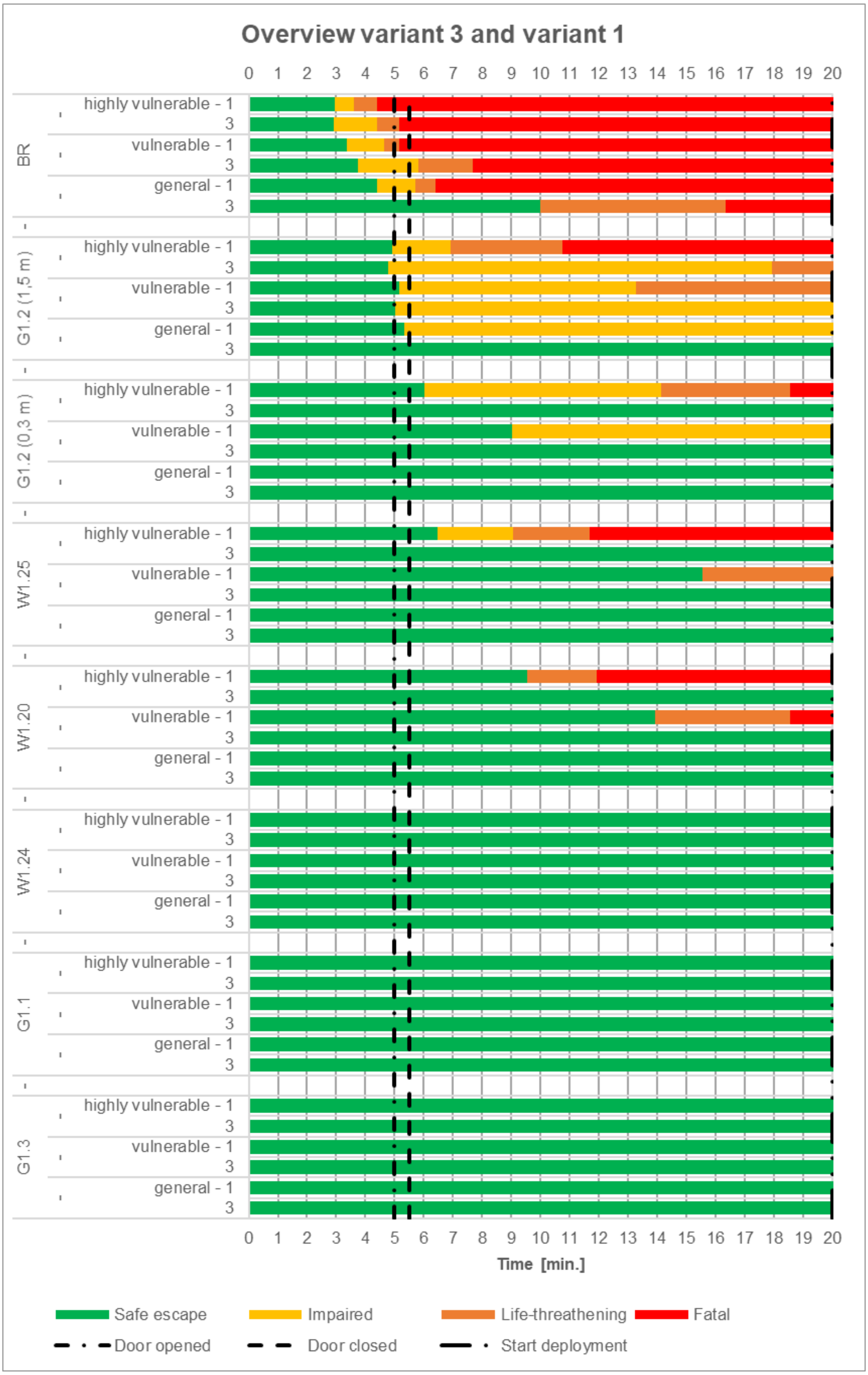


Figure 5.4 Times of the possibility of escape and survivability of variants 3 and 1

5.4.5 Analysis of variant 3 (mobile water mist and door closed)

The main findings from the results of the tests of variant 3 (mobile water mist and door closed) are discussed below.

> **Fire room**: the situation in the fire room took approx. 4 minutes to become life-threatening for the highly vulnerable group, 6 minutes for the vulnerable group, and 10 minutes for the general group. The situation became fatal for the highly vulnerable group within 1 minute after the situation had become life-threatening. This took 2 minutes for the vulnerable group and 6 minutes for the general group.

> **Corridor 1.2**: the situation at 1.5 metres high in corridor 1.2 was such that the possibility of escape was impaired for the vulnerable and highly vulnerable groups after 5 minutes. The vulnerable group could escape safely again after 8 to 9 minutes (this differed from test to test) in most situations. Visibility had returned to sufficient levels for this group in the corridor by then. Camera images showed that visibility had improved at a height of 1.5 metres in corridor 1.2. The fact that the situation had returned to a level where the vulnerable group could escape safely after 8 to 9 minutes is not reflected in the stacked bars. This is because once a threshold value has been exceeded this can no longer be reversed in the calculation method selected which underlies the figures with the stacked bars. However, these moments can be recognised in how the decisive condition for the impaired escape in corridor 1.2 developed (see Appendix 21): the visibility distance (FEC_{smoke}).
It took 13 minutes for a life-threatening situation to develop for the highly vulnerable group. The situation did not become life threatening for the vulnerable group for the first 20 minutes. The general group could use corridor 1.2 to escape safely for the first 20 minutes. At a height of 0.3 metres, the situation was such that all groups could escape safely during the first 20 minutes.

> **Other first floor residences**: the situation in all the other first floor residences was such that all groups could escape safely during the first 20 minutes of the test.

> **Corridors 1.1 and 1.3**: safe escape through corridors 1.1 and 1.3 was possible for the first 20 minutes. Camera images showed only light smoke in corridor 1.1 during the first 20 minutes and no smoke at all in corridor 1.3.

> **Other floors**: measurements did not measure any CO on the ground floor, the second floor, and the third floor. Camera images did not show any smoke.

Non-exceeded threshold values

In those cases where the thresholds were not exceeded within the first 20 minutes of the test, they were usually not *nearly* exceeded either. 66% of the threshold for a life-threatening situation for the highly vulnerable group was reached in residence 1.20 at t = 20 minutes. For the rest, the percentages reached for the threshold values in the other residences on the first floor tended to be less than 30%. This means that, for these cases, if people stayed in the residences for more than 20 minutes, no life-threatening situation would arise in the short term.

Decisive conditions

The asphyxiant gases were the first factor that caused the threshold values for life-threatening and fatal situations to be exceeded in the fire room. The irritant gases were the first factor that caused the threshold value for a life-threatening situation to be exceeded for the highly vulnerable group. Heat was not decisive for survivability, not even in the fire room. But since the temperature and radiation were measured in the lobby of the fire room at some distance from the fire object, heat might be decisive in the direct vicinity of the fire in the fire room. The visibility distance was the first factor which impaired escape in corridor 1.2; briefly after that irritant gases would also impair escape for the highly vulnerable group. The asphyxiant gases in corridor 1.2 caused the threshold value for a life-threatening situation to be exceeded for the highly vulnerable group.

5.4.6 Analysis of the comparison of variant 3 with variant 1

Table 5.11 shows the results of the comparison between variant 3 (mobile water mist and door closed) and variant 1 (door closed).

Table 5.11 Comparison between variant 3 and variant 1

Element	Comparison to variant 1 (door closed)
Survivability in the fire room	Unchanged for the highly vulnerable group Slight improvement for the vulnerable group Improvement for the general group
The possibility of escape in corridor 1.2	Improvement for the general group at a height of 1.5 m Improvement for all groups at 0.3 m Otherwise unchanged
Survivability in corridor 1.2	Improvement for the vulnerable and highly vulnerable groups Unchanged for the general group
Survivability in the other residences on the first floor for up to 20 minutes	Improvement for the vulnerable and highly vulnerable groups in residences 1.25 and 1.20 Unchanged for the general group in residences 1.25 and 1.20 Unchanged in residence 1.24
The percentage of non-exceeded threshold values in the other residences on the first floor at 20 minutes	Improvement in residence 1.25 and 1.20 Unchanged in residence 1.24
Survivability on the other floors	Unchanged
The effect of a mobile water mist and the door being closed for the different groups	Improvement in the fire room for the general group Improvement for the vulnerable and highly vulnerable groups in residences 1.20 and 1.25 No improvement for the highly vulnerable group and a minor improvement for the vulnerable group in the fire room

The combination of the mobile water mist and keeping the door closed resulted in an improvement that was mainly noticed in residences 1.25 and 1.20. The times in the fire room did not change for the highly vulnerable group and they improved slightly for the vulnerable group. There was an improvement in the fire room for the general group.

For the first 5 minutes, the CO concentration in the fire room was almost identical to that of the tests of variant 1 (door closed) without a mobile water mist. At that moment, the situation was already fatal for the highly vulnerable group. After 6 minutes, the CO concentration in the fire room significantly differed from that in the tests of variant 1 (door closed). The peak concentration in the fire room with the tests of variant 3 (mobile water mist and the door closed) was 1,300 to 1,500 ppm. For the tests of variant 1 (door closed) it was 7,000 to 21,000 ppm.

Contrary to the tests of variant 2 (mobile water mist and door open), no increase in temperature or in CO concentration was measured after the water from the mobile water mist tank had been used up.

5.5 Tests of variant 4 (mobile water mist, smoke resistant partition and door closed)

This section presents the times of the tests of variant 4 (mobile water mist, smoke resistant partition and door closed) and compares them with the times of the tests of variant 1 (door closed). This gives insight in the added value of combining the mobile water mist with a smoke resistant partition.

The fire room was provided with a mobile water mist system for the tests of variant 4 (mobile water mist, smoke resistant partition and door closed). Furthermore, the following modifications were made to the two fire rooms:

> Installation of a smoke resistant door (S200).
> The external and internal structure were made as airtight as possible by sealing gaps and seams.
> The ventilation opening in the hall of the residence leading to the ventilation duct was sealed.

The following modifications were made to residence 1.24:

> Installation of a smoke resistant door (S200).
> The external and internal structures were made as airtight as possible by sealing gaps and seams.

The above modifications were implemented in order to simulate an airtight situation as in a new structure.

During the tests of variant 4 (mobile water mist, smoke resistant partition and door closed), the door to the fire room was opened after 5 minutes and closed again after 5.5 minutes. This means that it was open for 30 seconds. After this, the door was kept closed until at least t = 20 minutes. Table 5.12 lists the relevant data of the tests of variant 4 (mobile water mist, smoke resistant partition and door closed) and variant 1 (door closed).

Table 5.12 Data of the tests of variant 4 and variant 1

Variant no.	Variant name	Number of tests	Test no.	Date no.	Fire room
1	Door closed	3	2 4 16	250619_1 260619_1 040719_1	1.21 1.21 1.21
4	Mobile water mist, smoke resistant partition, and door closed	2	10 11	010719_1 010719_2	1.21 1.19

5.5.1 Results of variant 4 (mobile water mist, smoke resistant partition, and door closed) and the comparison to variant 1 (door closed)

The results of the times for the possibility of escape and survivability of both variant 4 (mobile water mist, smoke resistant partition and door closed) and variant 1 (door closed) are presented below, both numerically in a table (see table 5.13) and visually (see figure 5.5) by means of the stacked bars, per room and per group. This enables a quick comparison between the times of these two variants.

Table 5.13 Times of the possibility of escape and survivability (in minutes) of variant 4 and variant 1

		fire room			Corridor 1.2 1.5 m			Corridor 1.2 0.3 m			Residence 1.25			Residence 1.20			Residence 1.24		
1		< 3	< 3	< 4	< 5	< 5	< 5	< 6	< 9	-	< 6	< 16	-	< 10	< 14	-	-	-	-
		3	3	4	5	5	5	6	9	-	6	16	-	10	14	-	-	-	-
		4	5	6	7	13	-	14	-	-	9	16	-	10	14	-	-	-	-
		4	5	6	11	-	-	19	-	-	12	-	-	12	19	-	-	-	-
4		< 3	< 4	< 9	< 5	< 6	-	< 15	-	-	-	-	-	-	-	-	-	-	-
		3	4	9	5	6	-	15	-	-	-	-	-	-	-	-	-	-	-
		4	5	9	18	-	-	-	-	-	-	-	-	-	-	-	-	-	-
		5	7	15	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

Note. For the yellow, orange and red smileys, a – in the table means that the threshold value for the group and situation in question was not reached within 20 minutes. For the green smileys, a – means that safe escape was possible for the first 20 minutes.

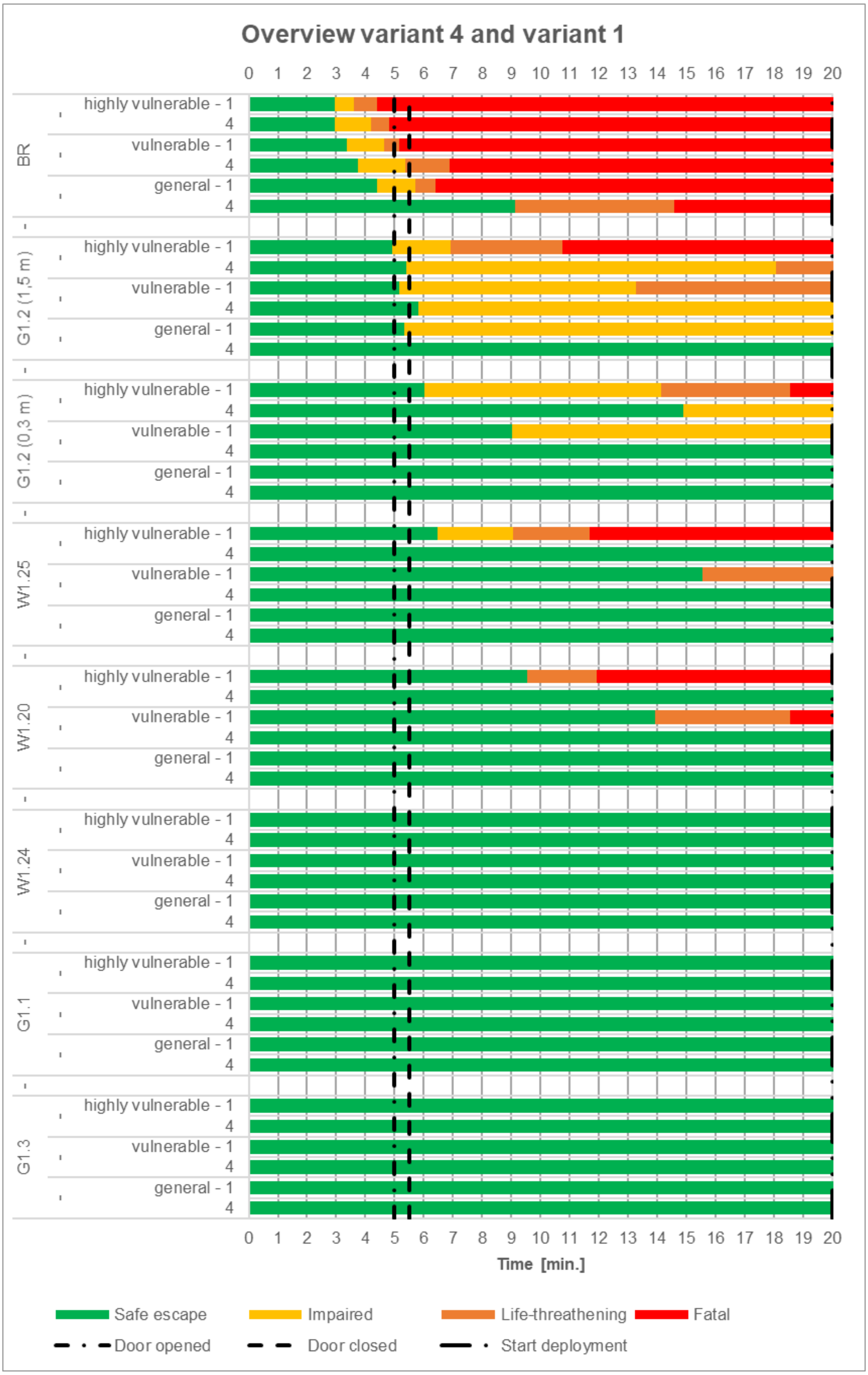


Figure 5.5 Times of the possibility of escape and survivability of variant 4 and variant 1

5.5.2 Analysis of variant 4 (mobile water mist, smoke resistant partition and door closed)

The main findings from the results of the tests of variant 4 (mobile water mist, smoke resistant partition and door closed) are discussed below.

> **Fire room**: the situation in the fire room took approx. 4 minutes to become life-threatening for the highly vulnerable group, 5 minutes for the vulnerable group, and 9 minutes for the general group. The situation became fatal for the highly vulnerable group within 1 minute after the situation had become a life-threatening situation. This took 2 minutes for the vulnerable group and 6 minutes for the general group.

> **Corridor 1.2**: the situation at 1.5 metres high in corridor 1.2 was such that the possibility of escape was impaired for the vulnerable and highly vulnerable groups after 5 to 6 minutes. The vulnerable group could escape safely again after 8 to 11 minutes (this differed from test to test). By then visibility in the corridor had returned to sufficient levels for this group. Camera images showed that visibility had improved at a height of 1.5 metres in corridor 1.2. The fact that the situation had returned to a level where the vulnerable group could escape safely after 8 to 11 minutes is not reflected in the stacked bars. This is because once a threshold value has been exceeded this can no longer be reversed in the calculation method selected which underlies the figures with the stacked bars. However, these moments can be recognised in how the decisive condition for the impaired escape in corridor 1.2 developed (see Appendix 21): the visibility distance (FEc_{smoke}).
It took 13 minutes for a life-threatening situation to develop for the highly vulnerable group. The situation did not become life threatening for the vulnerable group for the first 20 minutes. The general group could use corridor 1.2 to escape safely for the first 20 minutes. At a height of 0.3 metres, the situation was such that the general and vulnerable groups could escape safely during the first 20 minutes. The situation in corridor 1.2 at a height of 0.3 metres was such that the highly vulnerable group had the possibility to escape safely for the first 15 minutes.

> **Other first floor residences**: the situation in all the other first floor residences was such that all groups could escape safely during the first 20 minutes of the test.

> **Corridors 1.1 and 1.3**: safe escape through corridors 1.1 and 1.3 was possible for the first 20 minutes. Camera images showed only light smoke in corridors 1.1 during the first 20 minutes. Camera images did not show any smoke in corridor 1.3, but a CO concentration of less than 25 ppm was measured.

> **Other floors:** measurements did not measure any CO on the ground floor, the second floor, and the third floor. Camera images did not show any smoke.

Non-exceeded threshold values

In those cases where the thresholds were not exceeded within the first 20 minutes of the test, they were usually not *nearly* exceeded either. The highest percentage of a threshold value reached was 37% of a life-threatening situation for the highly vulnerable group in residence 1.25. It is likely that, if people stayed in the residences for more than 20 minutes, no life-threatening situation would arise for the other residences on the first floor in the short term.

Decisive conditions

The asphyxiant gases were the first factor that caused the threshold values for life-threatening and fatal situations to be exceeded in the fire room. The irritant gases also caused the threshold value for a life-threatening situation to be exceeded for the highly vulnerable group. Heat was not decisive for survivability, not even in the fire room. But since the temperature and radiation were measured in the lobby of the fire room at some distance from the fire object, heat might be decisive in the direct vicinity of the fire in the fire room. The visibility distance was the first factor which impaired escape in corridor 1.2; briefly after that irritant gases would also impair escape for the highly vulnerable group. The asphyxiant gases in corridor 1.2 caused the threshold value for a life-threatening situation to be exceeded for the highly vulnerable group.

5.5.3 Analysis of the comparison between variant 4 and variant 1

Table 5.14 shows the results of the comparison between variant 4 (mobile water mist, smoke resistant partition, and door closed) and variant 1 (door closed).

Table 5.14 Comparison between variant 4 and variant 1

Element	Comparison to variant 1 (door closed)
Survivability in the fire room	Unchanged for the vulnerable and highly vulnerable groups Improvement for the general group
The possibility of escape in corridor 1.2	Improvement for the general group at a height of 1.5 m Improvement for all groups at 0.3 m Otherwise unchanged
Survivability in corridor 1.2	Improvement for the vulnerable and highly vulnerable groups Unchanged for the general group
Survivability in the other residences on the first floor for up to 20 minutes	Improvement for the vulnerable and highly vulnerable groups in residences 1.25 and 1.20 Unchanged for the general group in residences 1.25 and 1.20 Unchanged in residence 1.24
The percentage of non-exceeded threshold values in the other residences on the first floor at 20 minutes	Improvement in residence 1.25 and 1.20 Unchanged in residence 1.24
Survivability on the other floors	Unchanged
The effect of the mobile water mist, smoke resistant partition, and door closed for different groups	Improvement in the fire room for the general group Improvement for the vulnerable and highly vulnerable groups in residences 1.20 and 1.25 No improvement for the highly vulnerable group and a minor improvement for the vulnerable group in the fire room

The combination of the mobile water mist and the smoke resistant partition resulted in an improvement that was mainly noticeable in residences 1.25 and 1.20. The times in the fire room did not change for the highly vulnerable group and they improved slightly for the vulnerable group. There was an improvement in the fire room for the general group.

For the first 6 minutes, the CO concentration in the fire room was rather identical to that of the tests of variant 1 (door closed) with no mobile water mist and no smoke resistant partition. At that moment, the situation was already fatal for the highly vulnerable group. After 6 minutes, the CO concentration in the fire room differed significantly from that in the tests of variant 1 (door closed). The peak concentration in the fire room with the tests of variant 4 (mobile water mist, smoke resistant partition, and the door closed) was 2,600 to 3,400 ppm. For the tests of variant 1 (door closed) it was 7,000 to 21,000 ppm.

Contrary to the tests of variant 2 (mobile water mist and door open), no increase in temperature or in the CO concentration was measured after the water from the mobile water mist tank had been used up.

5.6 Tests of variant 6 (organic fire load and door open) and variant 7 (organic fire load and door closed)

This section presents the times of the tests with an organic fire load (variants 6 and 7). It also compares the test of variant 6 (organic fire load and door open) to the tests of variant 0 (door open), and the test of variant 7 (organic fire load and door closed) to the tests of variant 1 (door closed). This gives insight in the added value of an organic fire load compared to a synthetic foam sofa as the fire object.

In the tests with an organic fire load (variants 6 and 7), the fire object was not a sofa, but an object consisting of organic material: a ‘crib’ of dried pinewood battens to represent a sofa made of cellulose materials such as wood, cotton and wool. The tests with an organic fire load were conducted both with an open door (variant 6; the door between the fire room and corridor 1.2 was opened after 5 minutes and it was kept in its maximum open position for the first 20 minutes) and with a closed door (variant 7; the door between the fire room and corridor 1.2 was opened after 5 minutes and closed again after 5.5 minutes until at least t = 20 minutes). Table 5.15 shows the relevant data of the tests of variant 6 (organic fire load and door open) and variant 1 (door open), and the tests of variant 7 (organic fire load and door closed) and variant 0 (door closed).

Table 5.15 Data of variant 6 and variant 0, variant 7 and variant 1

Variant no.	Variant name	Number of tests	Test no.	Date no.	Fire room
0	Door open	4	1 3 5 17	240619_1 250619_2 260619_2 040719_2	1.21 1.19 1.19 1.19
1	Door closed	3	2 4 16	250619_1 260619_1 040719_1	1.21 1.21 1.21
6	Organic fire load and door open	1	15	030719_2	1.19
7	Organic fire load and door closed	1	14	030719_1	1.21

5.6.1 Results of variant 6 (organic fire load and door open) and the comparison to variant 0 (door open)

The results of the times for the possibility of escape and survivability of both variant 6 (organic fire load and door open) and variant 0 (door open) are presented below, both numerically in a table (see table 5.16) and visually (see figure 5.6) by means of the stacked bars, per room and per group. This enables a quick comparison between the times of these two variants.

Table 5.16 Times of the possibility of escape and survivability (in minutes) of variant 6 and variant 0

		Fire room			Corridor 1.2 1.5 m			Corridor 1.2 0.3 m			Residence 1.25			Residence 1.20			Residence 1.24		
		Bedridden	Elderly	Adult	Bedridden	Elderly	Adult	Bedridden	Elderly	Adult	Bedridden	Elderly	Adult	Bedridden	Elderly	Adult	Bedridden	Elderly	Adult
0	Green smiley	< 3	< 3	< 4	< 5	< 5	< 5	< 6	< 8	< 9	< 6	< 6	< 8	< 9	< 12	< 18	< 12	< 16	-
	Yellow smiley	3	3	4	5	5	5	6	8	9	6	6	8	9	12	18	12	16	-
	Orange smiley	4	5	6	6	6	7	9	10	13	7	7	8	9	12	18	12	16	-
	Red smiley	4	5	7	6	7	7	9	11	16	7	8	8	11	15	-	15	-	-
6	Green smiley	< 12	< 15	< 20	< 6	< 8	< 14	< 10	< 14	-	< 15	< 18	-	-	-	-	-	-	-
	Yellow smiley	12	15	20	6	8	14	10	14	-	15	18	-	-	-	-	-	-	-
	Orange smiley	14	19	-	15	19	-	19	-	-	15	18	-	-	-	-	-	-	-
	Red smiley	17	-	-	17	-	-	-	-	-	17	-	-	-	-	-	-	-	-

Note. For the yellow, orange and red smileys, a – in the table means that the threshold value for the group and situation in question was not reached within 20 minutes. For the green smileys, a – means that safe escape was possible for the first 20 minutes.

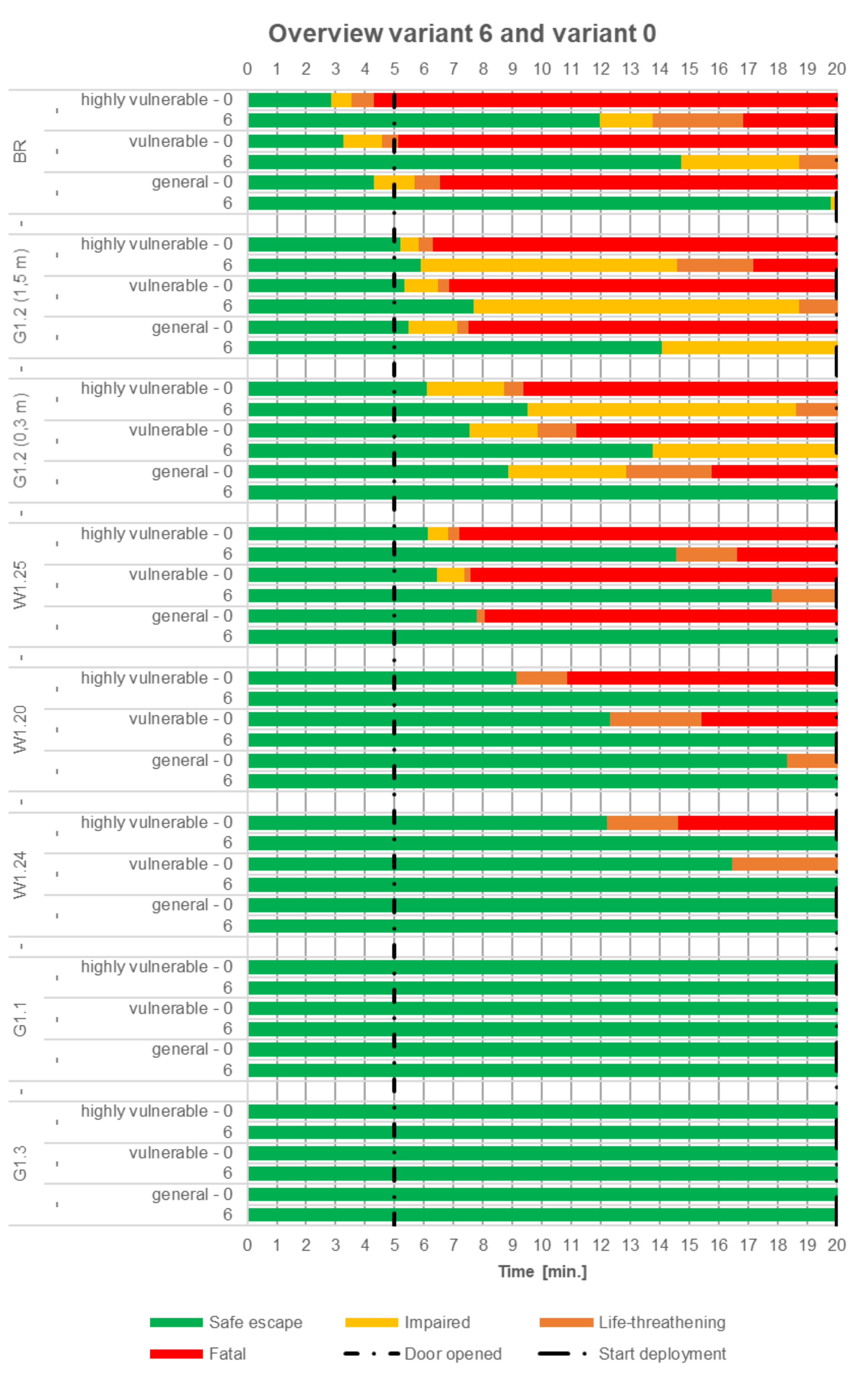


Figure 5.6 Times of the possibility of escape and survivability of variant 6 and variant 0

5.6.2 Analysis of variant 6 (organic fire load and door open)

The main findings from the results of the tests of variant 6 (organic fire load and door open) are discussed below.

> **Fire room**: the situation in the fire room became life threatening for the highly vulnerable group after approx. 14 minutes and it became fatal after about 17 minutes. It took 19 minutes for the situation to become fatal for the highly vulnerable group. There was no fatal situation for the vulnerable group during the first 20 minutes. The situation in the fire room never became life threatening for the general group.

> **Corridor 1.2**: depending on the group in question, escape was impaired at a height of 1.5 metres in corridor 1.2 after 6 to 14 minutes for all groups. The possibility of escape became impaired for the highly vulnerable group at a height of 0.3 metres after 10 minutes; this took 14 minutes for the vulnerable group. Safe escape was possible at a height of 0.3 metres for the general group in corridor 1.2 for the first 20 minutes.

> **Other first floor residences**: the situation in residences 1.20 and 1.24 was such that all groups could escape safely during the first 20 minutes. The situation in residence 1.25 was life threatening for the highly vulnerable group after 15 minutes and fatal after 17 minutes. There was a life-threatening situation for the vulnerable group in residence 1.25 after 19 minutes. There was no fatal situation for the vulnerable group during the first 20 minutes. Safe escape was possible for the general group from residence 1.25 for the first 20 minutes.
> The times for survivability in residences 1.20, 1.24 and 1.25 were the shortest in residence 1.25. This was due to the open door between residence 1.25 and corridor 1.2.

> **Corridors 1.1 and 1.3**: safe escape through corridors 1.1 and 1.3 was possible for the first 20 minutes. Camera images showed only light smoke in corridors 1.1 and 1.3 during the first 20 minutes.

> **Other floors**: Measurements did not measure any CO on the ground floor, the second floor, and the third floor. Camera images did not show any smoke.

Non-exceeded threshold values

In situations where the threshold values were not exceeded within the first 20 minutes, they might still have been *nearly* exceeded. 100% of the threshold value for a fatal situation for the vulnerable group was reached in residence 1.25. 57% of the threshold value for a life-threatening situation was reached for the general group in residence 1.25. A stay of more than 20 minutes might still lead to a life-threatening or fatal situation for these groups.
The highest percentage in residences 1.20 and 1.24 was 26%. This means that if people stayed in these residences for more than 20 minutes, no life-threatening situation would arise in the short term.

Decisive conditions

The asphyxiant gases were the first factor that caused the threshold values for life-threatening and fatal situations to be exceeded in the fire room. Heat caused the threshold value for a life-threatening situation for the highly vulnerable group to be exceeded in the fire room a couple of minutes later. Heat did not affect survivability for the general and vulnerable groups in the fire room. But since the temperature and radiation were measured in the lobby of the fire room at some distance from the fire object, heat might be decisive in the direct vicinity of the fire in the fire room.
Visibility distance was the first factor impairing escape in corridor 1.2. The heat might also become so high at a height of 1.5 metres in corridor 1.2 that this might have influenced the possibility to escape safely for the highly vulnerable group. The asphyxiant gases in corridor

1.2 caused the threshold values for a life-threatening or fatal situation to be exceeded for the vulnerable and highly vulnerable groups.
Where the threshold values for a life-threatening and fatal situation were exceeded in the other residences, this was also caused by the asphyxiant gases.

5.6.3 Analysis of the comparison of variant 6 with variant 0

Table 5.17 shows the results of the comparison between variant 6 (organic fire load and door open) and variant 0 (door open).

Table 5.17 Comparison between variant 6 and variant 0

Element	Comparison to variant 0 (door open)
Survivability in the fire room	Improvement
The possibility of escape in corridor 1.2	Unchanged at a height of 1.5 m for the highly vulnerable group A slight improvement at a height of 1.5 m for the vulnerable group Further improvement
Survivability in corridor 1.2	Improvement
Survivability in the other residences on the first floor for up to 20 minutes	The situation remained unchanged for the general group in residence 1.24 and it showed a slight improvement in residence 1.20 Further improvement
The percentage of non-exceeded threshold values in the other residences on the first floor at 20 minutes	Improvement
Survivability on the other floors	Improvement
The effect of an organic fire load and the door being open for the different groups	An improvement could be seen for all groups, also in the fire room

The organic fire load showed a major improvement in the conditions for all rooms and for all groups. The time during which the situation in the fire room was survivable increased significantly, even for the highly vulnerable group.

The organic fire load burned much more slowly than the sofa and had a lower speed of fire growth. As a result, less heat and fewer asphyxiant and irritant gases were released in the fire during the first 20 minutes. This greatly improved the possibility of escape and survivability.

5.6.4 Results of variant 7 (organic fire load and door closed) and the comparison to variant 1 (door closed)

The results of the times for the possibility of escape and survivability of both variant 7 (organic fire load and door closed) and variant 1 (door closed) are presented below, both numerically in a table (see table 5.18) and visually (see figure 5.7) by means of the stacked bars, per room and per group. This enables a quick comparison between the times of these two variants.

Table 5.18 Times of the possibility of escape and survivability (in minutes) of variant 7 and variant 1

		Fire room			Corridor 1.2 1.5 m			Corridor 1.2 0.3 m			Residence 1.25			Residence 1.20			Residence 1.24		
1	green	< 3	< 3	< 4	< 5	< 5	< 5	< 6	< 9	-	< 6	< 16	-	< 10	< 14	-	-	-	-
	yellow	3	3	4	5	5	5	6	9	-	6	16	-	10	14	-	-	-	-
	orange	4	5	6	7	13	-	14	-	-	9	16	-	10	14	-	-	-	-
	red	4	5	6	11	-	-	19	-	-	12	-	-	12	19	-	-	-	-
7	green	< 9	< 12	< 16	< 5	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	yellow	9	12	16	5	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	orange	10	12	16	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	red	11	14	20	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

Note. For the yellow, orange and red smileys, a – in the table means that the threshold value for the group and situation in question was not reached within 20 minutes. For the green smileys, a – means that safe escape was possible for the first 20 minutes.

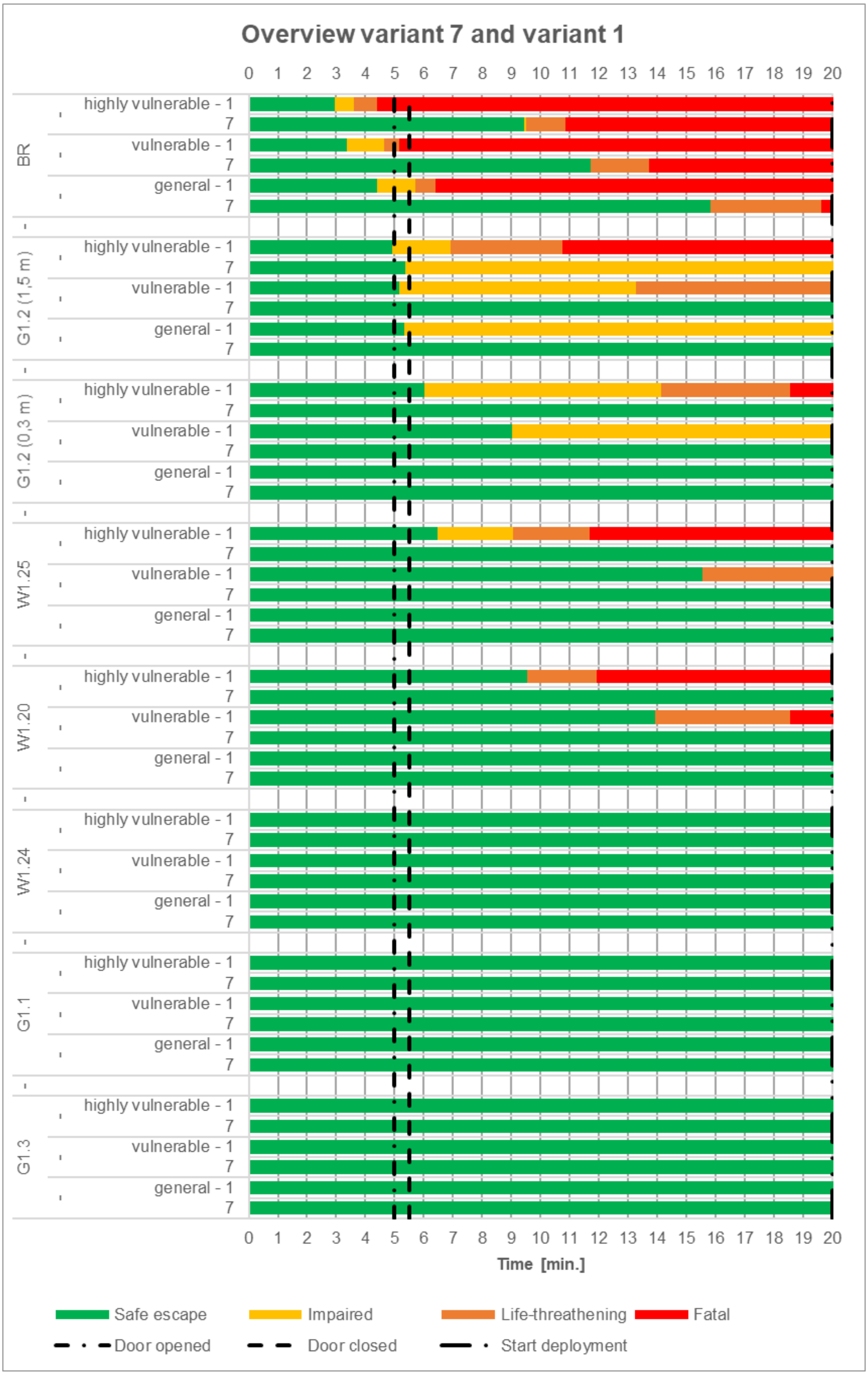


Figure 5.7 Times of the possibility of escape and survivability of variant 7 and variant 1

5.6.5 Analysis of variant 7 (organic fire load and door closed)

The main findings from the results of the tests of variant 7 (organic fire load and door closed) are discussed below.

> **Fire room**: depending on the group, the situation in the fire room became life threatening after approx. 10 to 14 minutes. The situation became fatal for the highly vulnerable group within 1 minute after the situation had become a life-threatening situation. This took 2 minutes for the vulnerable group and 4 minutes for the general group.
> **Corridor 1.2**: the situation at 1.5 metres high in corridor 1.2 was such that the possibility of escape was impaired for the highly vulnerable group after 5 minutes. The vulnerable and general groups could escape freely in corridor 1.2 at a height of 1.5 metres during the first 20 minutes. At a height of 0.3 metres, the situation in corridor 1.2 was such that all groups could escape safely during the first 20 minutes
> **Other first floor residences**: the situation in all the other first floor residences was such that all groups could escape safely during the first 20 minutes of the test.
> **Corridors 1.1 and 1.3**: safe escape through corridors 1.1 and 1.3 was possible for the first 20 minutes. Camera images showed only light smoke in corridor 1.1 during the first 20 minutes and no smoke in corridor 1.3.
> **Other floors**: measurements did not measure any CO on the ground floor, the second floor, and the third floor. Camera images did not show any smoke.

Non-exceeded threshold values

In those cases where the thresholds were not exceeded within the first 20 minutes of the test, they were usually not *nearly* exceeded either. The highest percentage of a threshold value reached was 45% for a life-threatening situation for the highly vulnerable group in residence 1.20. It is likely for the other residences on the first floor that if people stayed in the residences for more than 20 minutes, no life-threatening situation would arise in the short term.

Decisive conditions

The asphyxiant gases caused the threshold values for life-threatening and fatal situations to be exceeded in the fire room. Heat did not affect survivability in the fire room. But since the temperature and radiation were measured in the lobby of the fire room at some distance from the fire object, heat might be decisive in the direct vicinity of the fire in the fire room. The visibility distance impaired the possibility of escape in corridor 1.2 for the vulnerable and highly vulnerable groups.

5.6.6 Analysis of the comparison of variant 7 with variant 1

Table 5.19 shows the results of the comparison between variant 7 (organic fire load and door closed) and variant 1 (door closed).

Table 5.19 Comparison between variant 7 and variant 1

Element	Comparison to variant 1 (door closed)
Survivability in the fire room	Improvement
The possibility of escape in corridor 1.2	Identical for the highly vulnerable group Further improvement
Survivability in corridor 1.2	Improvement for the vulnerable and highly vulnerable groups Identical for the general group
Survivability in the other residences on the first floor for up to 20 minutes	Improvement for the vulnerable and highly vulnerable groups in residences 1.25 and 1.20 Unchanged for the general group in residences 1.25 and 1.20 Unchanged in residence 1.24
The percentage of non-exceeded threshold values in the other residences on the first floor at 20 minutes	An improvement in residence 1.25 and 1.20 Unchanged in residence 1.24
Survivability on the other floors	Unchanged
The effect of an organic fire load and the door being closed for the different groups	An improvement could be seen for all groups, also in the fire room

The organic fire load led to a major improvement for all rooms and for all groups. The time during which the situation in the fire room was survivable increased significantly, even for the highly vulnerable group.

The organic fire load burned much more slowly than the sofa and thus had a lower speed of fire growth. As a result, less heat and fewer asphyxiant and irritant gases were released in the fire during the first 20 minutes. This greatly improved the possibility of escape and survivability.

5.7 Summary of the effects of the measures for risk management

This section summarizes the effects of the different measures for risk management relative to the tests of variant 0 (door open) or variant 1 (door closed). This summary is presented in two tables: one table for the variants which have been compared to variant 0 (door open; see table 5.20) and one for the variants which have been compared to variant 1 (door closed; see table 5.21). The tables indicate whether any of the following situations occurred relative to variant 0 or variant 1:

> an unchanged situation (0)
> a slight improvement (+)
> an improvement (++)
> a slight deterioration (-).

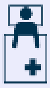
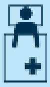
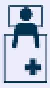
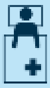
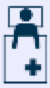
The tables are structured according to the same principle as the tables in the comparison of one variant to variant 0 or variant 1. The variant number in the top row of the table indicates which variant is concerned.

In summary, the following effects of the different measures relative to variant 0 (door open) or variant 1 (door closed) were found:

Table 5.20 Summary of the comparison of variants 1, 2, and 6 to variant 0

Element	1	2	6
Survivability in the fire room	0	0	++
	0	+	++
	0	++	++
The possibility of escape in corridor 1.2	1.5 m = 0 0.3 m = 0	1.5 m = 0 0.3 m = 0	1.5 m = 0 0.3 m = ++
	1.5 m = 0 0.3 m = 0	1.5 m = 0 0.3 m = +	1.5 m = + 0.3 m = ++
	1.5 m = + 0.3 m = +	1.5 m = + 0.3 m = ++	1.5 m = ++ 0.3 m = ++
Survivability in corridor 1.2	1.5 m = ++ 0.3 m = ++	1.5 m = + 0.3 m = ++	1.5 m = ++ 0.3 m = ++
	1.5 m = ++ 0.3 m = ++	1.5 m = ++ 0.3 m = ++	1.5 m = ++ 0.3 m = ++
	1.5 m = ++ 0.3 m = ++	1.5 m = ++ 0.3 m = ++	1.5 m = ++ 0.3 m = ++
Survivability in the other residences on the first floor until t = 20 minutes	W1.20 = 0 Rest = ++	++	++
	++	++	++
	W1.24 = 0 W1.20 = + W1.25 = ++	W1.24 = 0 W1.20 = + W1.25 = ++	W1.24 = 0 W1.20 = + W1.25 = ++
The percentage of non-exceeded threshold values in the other residences on the first floor at 20 minutes	++	++	++
	++	++	++
	++	W1.24 = + Rest = ++	++

Table 5.21 Summary of the comparison of variants 3, 4, 5, and 7 to variant 1

Element		3	4	5	7
Survivability in the fire room		0	0	0	++
		+	0	0	++
		++	++	0	++
The possibility of escape in corridor 1.2		1.5 m = 0 0.3 m = ++	1.5 m = 0 0.3 m = ++	1.5 m = 0 0.3 m = 0	1.5 m = 0 0.3 m = ++
		1.5 m = 0 0.3 m = ++	1.5 m = 0 0.3 m = ++	1.5 m = 0 0.3 m = 0	1.5 m = ++ 0.3 m = ++
		1.5 m = ++ 0.3 m = 0	1.5 m = ++ 0.3 m = 0	1.5 m = 0 0.3 m = 0	1.5 m = ++ 0.3 m = 0
Survivability in corridor 1.2		1.5 m = ++ 0.3 m = ++	1.5 m = ++ 0.3 m = +	1.5 m = 0 0.3 m = 0	1.5 m = ++ 0.3 m = ++
		1.5 m = ++ 0.3 m = 0	1.5 m = ++ 0.3 m = 0	1.5 m = 0 0.3 m = 0	1.5 m = ++ 0.3 m = 0
		1.5 m = 0 0.3 m = 0	1.5 m = 0 0.3 m = 0	1.5 m = 0 0.3 m = 0	1.5 m = 0 0.3 m = 0
Survivability in the other residences on the first floor until t = 20 minutes		W1.24 = 0 Rest = ++	W1.24 = 0 Rest = ++	0	W1.24 = 0 Rest = ++
		W1.24 = 0 Rest = ++	W1.24 = 0 Rest = ++	W1.25 = - Rest = 0	W1.24 = 0 Rest = ++
		0	0	0	0
The percentage of non-exceeded threshold values in the other residences on the first floor at 20 minutes		W1.24 = 0 Rest = ++	W1.24 = 0 Rest = ++	0	W1.24 = 0 Rest = ++
		W1.24 = 0 Rest = ++	W1.24 = 0 Rest = ++	0	W1.24 = 0 Rest = ++
		W1.24 = 0 Rest = ++	W1.24 = 0 Rest = ++	0	W1.24 = 0 Rest = ++

5.8 Overall analysis of the measures for risk management

This section provides an overall analysis of the measures for risk management. It is described which measures improve the times for the possibility of escape and survivability the most.

The times for the possibility of escape and survivability are first presented in a table (see table 5.22) followed by the stacked bars (see figure 5.8 to figure 5.11). The order of the variants in the table and the stacked bars is such that all the different variants with an open door are presented first, followed by all the variants with a closed door. The order of the variants in this section is as follows:

> tests of variant 0 (door open)
> tests of variant 2 (mobile water mist and door open)
> test of variant 6 (organic fire load and door open)
> tests of variant 1 (door closed)
> tests of variant 3 (mobile water mist and door closed)
> tests of variant 4 (mobile water mist, smoke resistant partition and door closed)
> tests of variant 5 (smoke resistant partition and door closed)
> test of variant 7 (organic fire load and door closed).

The presentation of the times is followed by a discussion of the extent to which the measures effectively improved the times for the possibility of escape and survivability.

Table 5.22 Times for the possibility of escape and survivability (in minutes) of all variants

		Fire room			Corridor 1.2 1.5 m			Corridor 1.2 0.3 m			Residence 1.25			Residence 1.20			Residence 1.24		
0		< 3	< 3	< 4	< 5	< 5	< 5	< 6	< 8	< 9	< 6	< 6	< 8	< 9	< 12	< 18	< 12	< 16	-
		3	3	4	5	5	5	6	8	9	6	6	8	9	12	18	12	16	-
		4	5	6	6	6	7	9	10	13	7	7	8	9	12	18	12	16	-
		4	5	7	6	7	7	9	11	16	7	8	8	11	15	-	15	-	-
2		< 3	< 4	< 11	< 5	< 6	< 7	< 7	< 10	< 13	< 7	< 12	< 16	-	-	-	< 16	-	-
		3	4	11	5	6	7	7	10	13	7	12	16	-	-	-	16	-	-
		4	6	11	7	9	13	11	14	19	9	12	16	-	-	-	16	-	-
		5	8	17	8	11	17	13	17	-	11	14	19	-	-	-	19	-	-
6		< 12	< 15	< 20	< 6	< 8	< 14	< 10	< 14	-	< 15	< 18	-	-	-	-	-	-	-
		12	15	20	6	8	14	10	14	-	15	18	-	-	-	-	-	-	-
		14	19	-	15	19	-	19	-	-	15	18	-	-	-	-	-	-	-
		17	-	-	17	-	-	-	-	-	17	-	-	-	-	-	-	-	-

1		< 3	< 3	< 4	< 5	< 5	< 5	< 6	< 9	-	< 6	< 16	-	< 10	< 14	-	-	-	-
		3	3	4	5	5	5	6	9	-	6	16	-	10	14	-	-	-	-
		4	5	6	7	13	-	14	-	-	9	16	-	10	14	-	-	-	-
		4	5	6	11	-	-	19	-	-	12	-	-	12	19	-	-	-	-
3		< 3	< 4	< 10	< 5	< 5	-	-	-	-	-	-	-	-	-	-	-	-	-
		3	4	10	5	5	-	-	-	-	-	-	-	-	-	-	-	-	-
		4	6	10	18	-	-	-	-	-	-	-	-	-	-	-	-	-	-
		5	8	16	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
4		< 3	< 4	< 9	< 5	< 6	-	< 15	-	-	-	-	-	-	-	-	-	-	-
		3	4	9	5	6	-	15	-	-	-	-	-	-	-	-	-	-	-
		4	5	9	18	-	-	-	-	-	-	-	-	-	-	-	-	-	-
		5	7	15	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
5		< 3	< 3	< 4	< 5	< 5	< 5	< 6	< 10	-	< 7	< 13	-	< 14	-	-	-	-	-
		3	3	4	5	5	5	6	10	-	7	13	-	14	-	-	-	-	-
		4	5	6	6	13	-	13	-	-	9	13	-	14	-	-	-	-	-
		4	5	6	10	19	-	17	-	-	11	-	-	18	-	-	-	-	-
7		< 9	< 12	< 16	< 5	-	-	-	-	-	-	-	-	-	-	-	-	-	-
		9	12	16	5	-	-	-	-	-	-	-	-	-	-	-	-	-	-
		10	12	16	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
		11	14	20	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

Note. For the yellow, orange and red smileys, a – in the table means that the threshold value for the group and situation in question was not reached within 20 minutes. For the green smileys, a – means that safe escape was possible for the first 20 minutes.

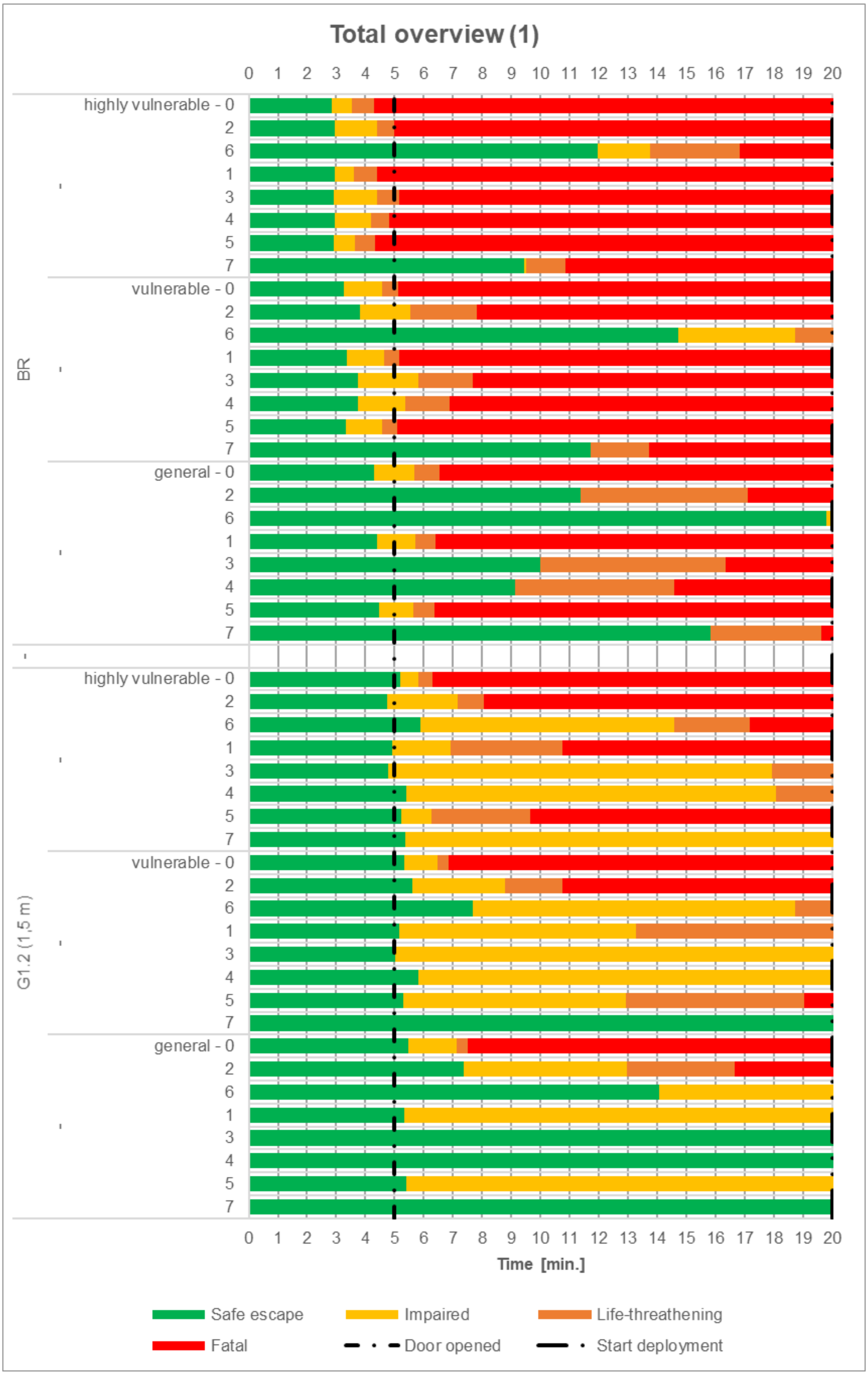


Figure 5.8 Times for the possibility of escape and survivability of all variants

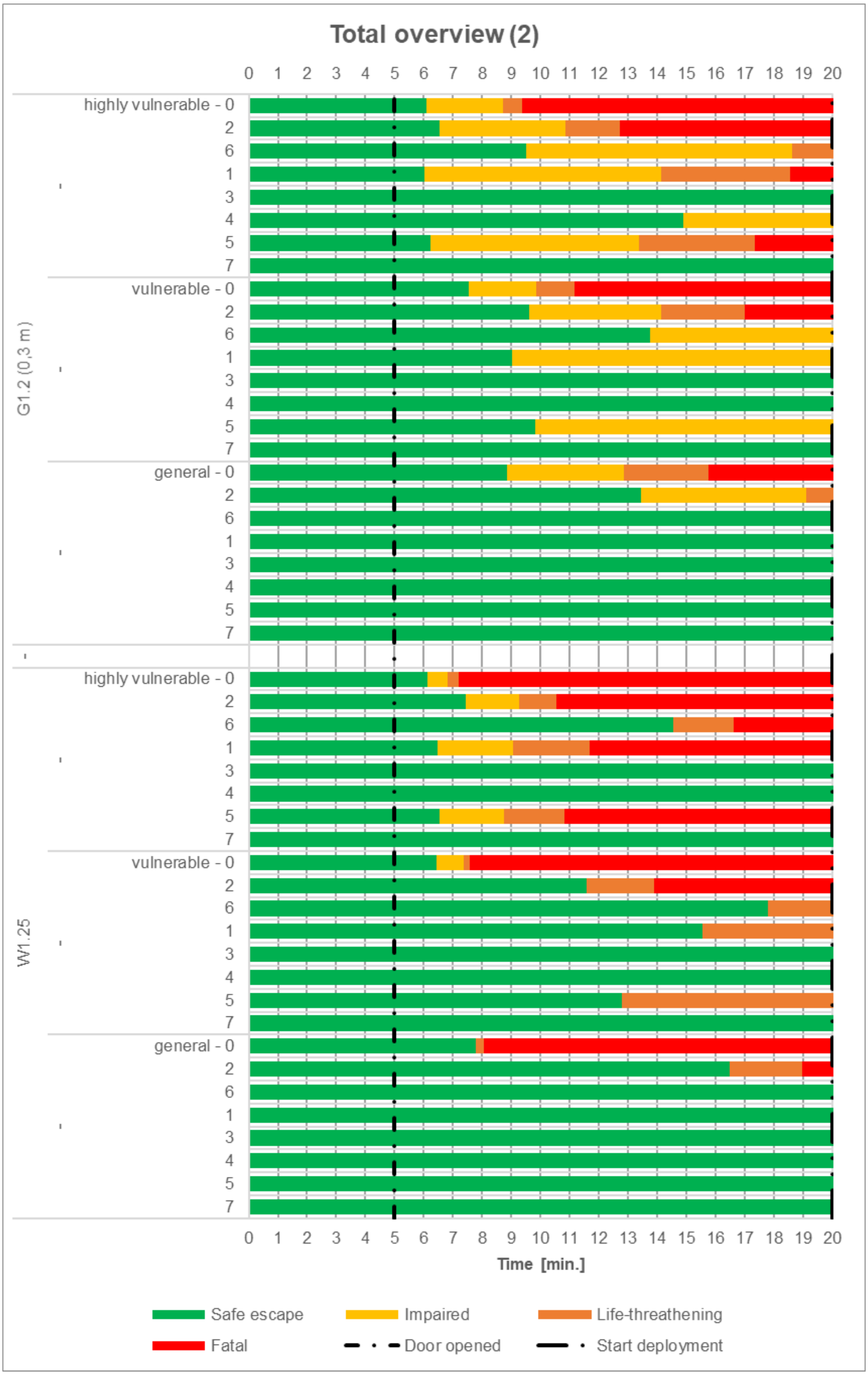


Figure 5.9 Times for the possibility of escape and survivability of all variants

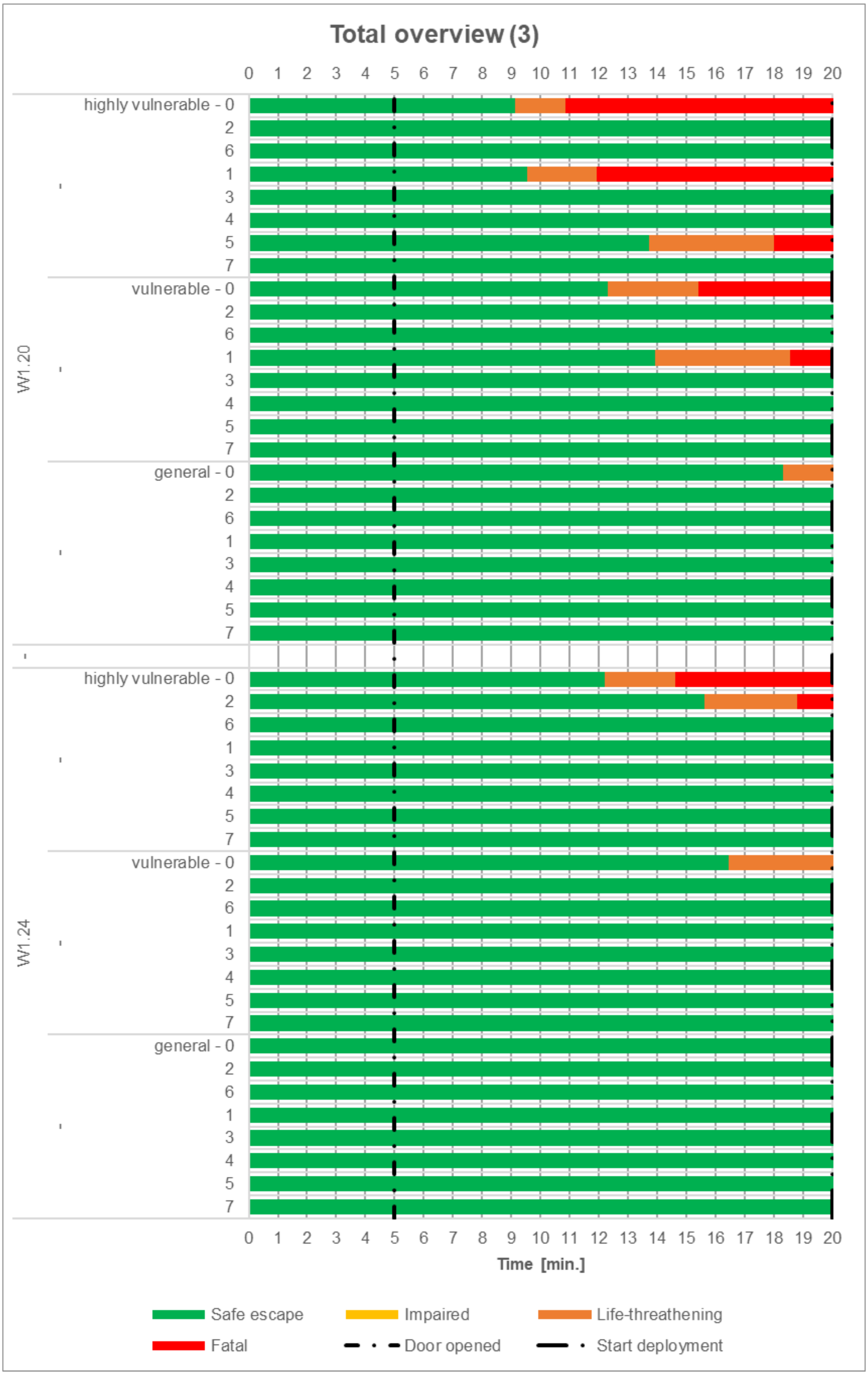


Figure 5.10 Times for the possibility of escape and survivability of all variants

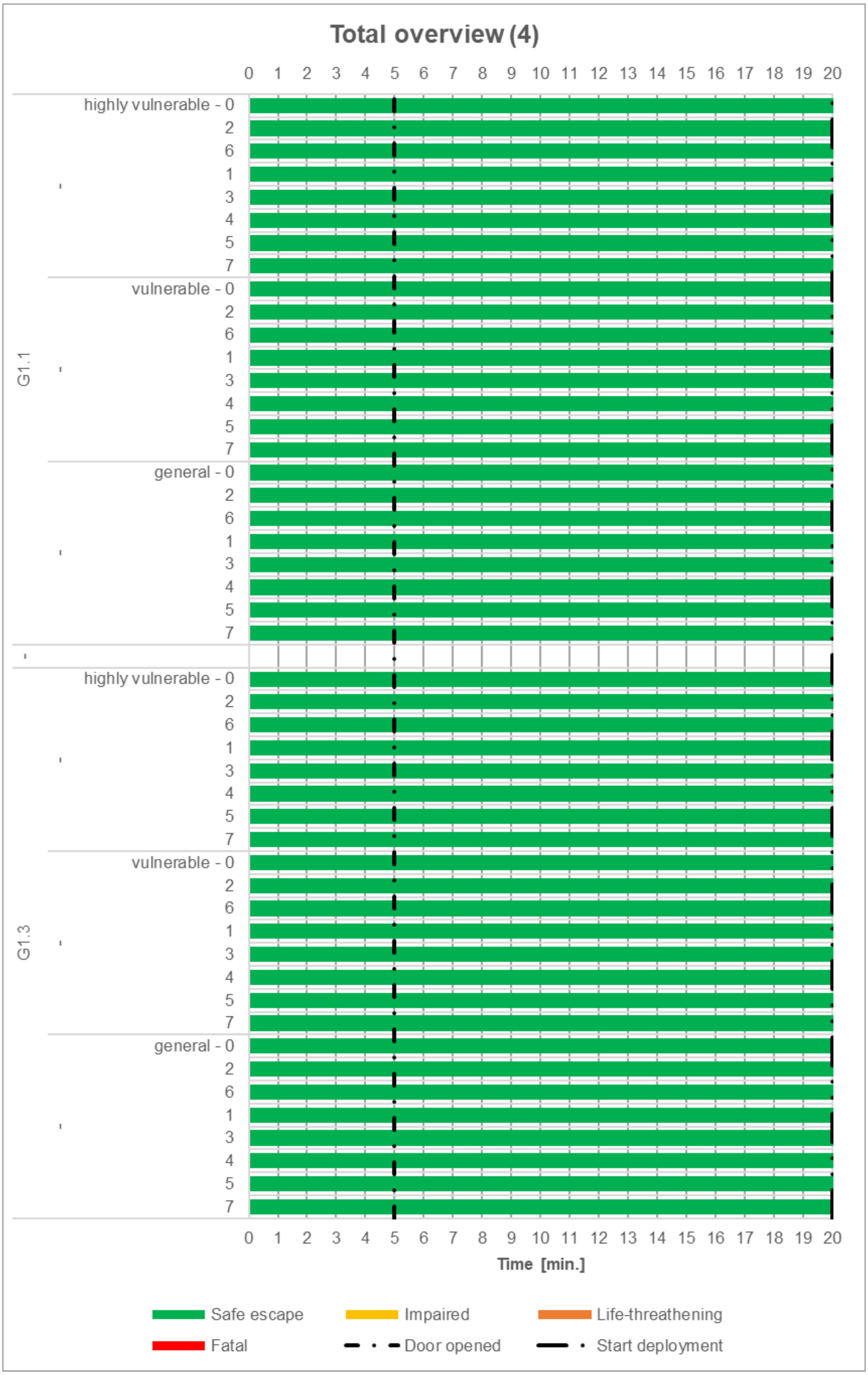


Figure 5.11 Times for the possibility of escape and survivability of all variants

Based on the times presented above, the following measures resulted in the longest availble times for the possibility of escape and survivability (ranked from the longest to the shortest available time):

> organic fire load and door closed
> mobile water mist and door closed / mobile water mist, smoke resistant partition and door closed
> organic fire load and door open
> mobile water mist and door open / door closed / smoke resistant partition and door closed.

This ranking was determined for all the groups and rooms together. The ranking might be different for specific groups. The added value of certain measures for improving the possibility of escape and survivability is explained below for every individual measure.

Organic fire load
The tests with the organic fire load showed that a fire in such a fire load developed less quickly than a fire in the sofa. As a result, the fire grew less quickly, had a lower heat release rate, and produced less smoke. This led to a major improvement in the times available for the possibility of escape and survivability. The tests with the organic fire load were the only tests that showed an improvement in all the rooms – compared to the tests of variant 0 (door open) or the tests of variant 1 (door closed) – and where the situation in the fire room itself also improved for the highly vulnerable group.
The door to the fire room being kept open or closed influenced the effects of the measure where the organic fire load was used. Where the door to the fire room was open, survivability in the fire room improved compared to the situation where the door was closed; however, the possibility of escape and survivability in corridor 1.2 and residence 1.25 worsened when the door to the fire room was open. In the other residences (front door closed), the situation was survivable for all groups for more than 20 minutes if the door to the fire room was open. The organic fire load was the only measure that showed this effect when the door to the fire room was open. The effect of the door to the fire room being kept open on the possibility of escape in corridor 1.2 was a lot less if the fire object was an organic fire load than if the fire object was a sofa. Where the door to the fire room was left open, the situation in corridor 1.2 at a height of 1.5 metres was such that the possibility of escape was impaired after about 6 to 14 minutes (depending on the group). After this time, the possibility of escape from the residences on this corridor was limited.

Mobile water mist
A mobile water mist system generally improves the possibility of escape and survivability. This improvement was better when the door to the fire room was kept closed, and furthermore, it was better for the general group than for the vulnerable and highly vulnerable groups. If the door to the fire room was kept open, a life-threatening or fatal situation could occur in the other residences. If the door to the fire room was closed, the situation was survivable for more than 20 minutes for all groups in the other residences. It is plausible that the situation in the residence next to the fire room (1.20) would only become life threatening for the highly vulnerable group after 20 minutes.

The mobile water mist lowered the CO concentration in the fire room. However, the effect of the decrease in CO concentration did not take place until a fatal situation had occurred in the

fire room for the highly vulnerable group. At that moment, the situation had become life threatening for the vulnerable group.
In the test where a mobile water mist was combined with an open door, the fire flared up again after the water in the mobile water mist tank had been used up (approx. 17 minutes after the fire started). This did not happen in the test with mobile water mist and the door closed.

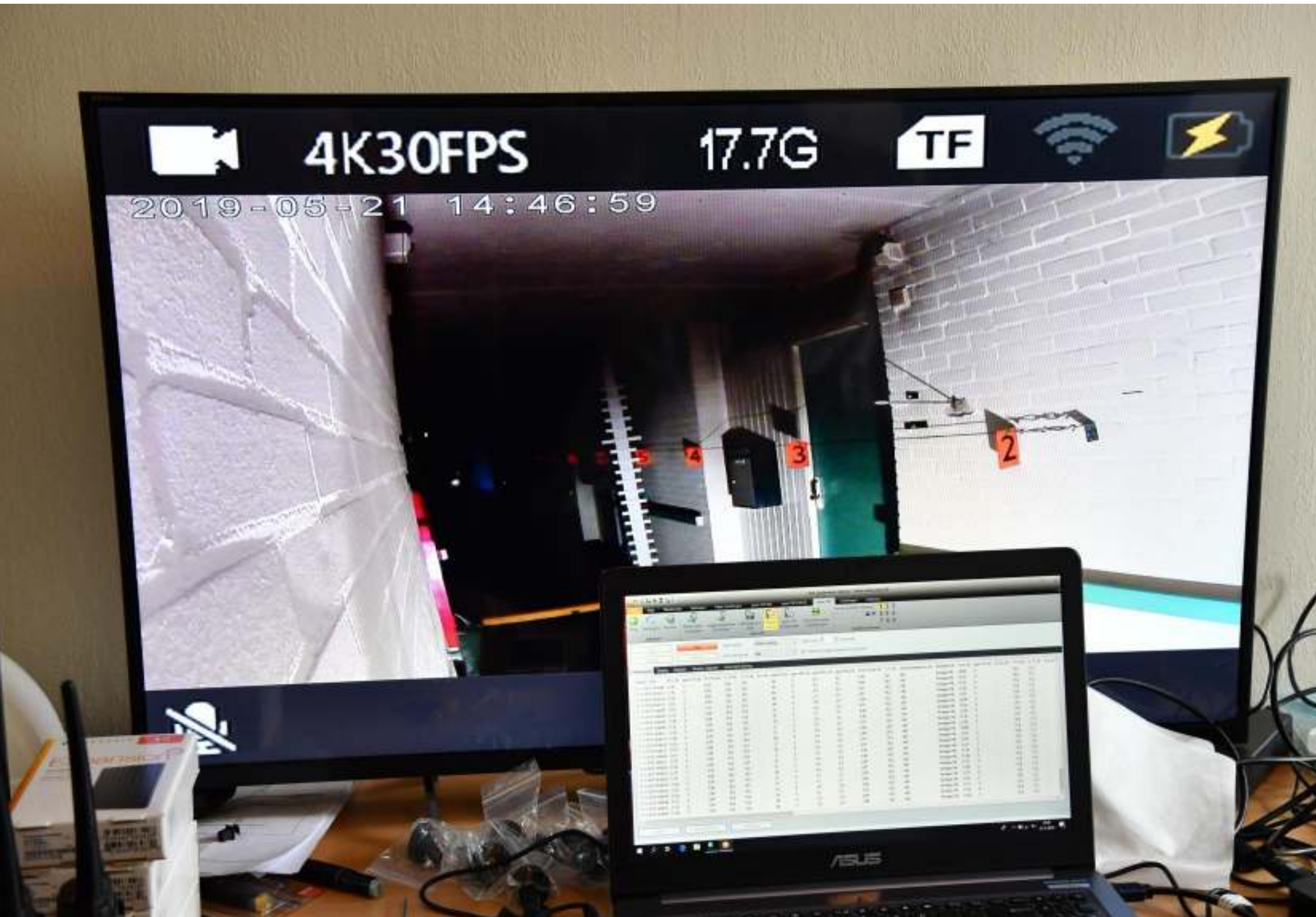
Mobile water mist and smoke resistant partition
Compared to the variant with a mobile water mist without a smoke resistant partition, the variant with a mobile water mist and a smoke resistant partition did not show any improvement of the possibility of escape and survivability. However, the pressures in the fire room were noted to be considerably lower than was the case in the tests with a smoke resistant partition without a mobile water mist (max. 140 Pa vs max. 1000 Pa).
Since no test combining a mobile water mist, a smoke resistant partition, and the door to the fire room open was conducted, it could not be assessed whether smoke resistant partitions in the other residences add value to the possibility of escape and survivability in those residences when the door to the fire room is open.

Door to the fire room closed
Closing the door after escaping the fire room improved the times for survivability in the other residences that did not directly adjoin the fire room. The situation in the opposite residence (1.24), where the door was kept closed, was such that people could survive there for more than 20 minutes. However, a life-threatening or fatal situation might occur in the residence next to the fire room (1.20). This was the case after 20 minutes for the general group and within 20 minutes for the vulnerable and highly vulnerable groups.

Smoke resistant partition
The tests with a smoke resistant partition and the door closed did not show any improvement in the times for the possibility of escape and survivability compared to the tests where the door was closed. Opening the door for 30 seconds in order to escape the fire room was decisive for the smoke propagation to the corridor.
A point worth noting with regard to the smoke resistant partition is that the pressures in the fire room were considerably higher (max. 1000 Pa) than the highest pressure to which elements of a smoke resistant partition are tested (50 Pa) according to the standard for smoke resistant partitions (NEN 6075:2020).
As stated, since no test with a smoke resistant partition was conducted while the door to the fire room was open, it could not be assessed whether smoke resistant partitions in the other residences add value to the possibility of escape and survivability in those residences when the door to the fire room is open.

The effect of the measures for the different groups
Not every measure has an equal effect for every group. For instance, the organic fire load as a measure led to an improvement for all groups in all rooms, whereas the mobile water mist as a measure combined with the door to the fire room being open only showed an improvement for the general group. This had little or no added value for the vulnerable and highly vulnerable groups. If the door to the fire room was closed after escaping the room, the mobile water mist outside the fire room did give an improvement for the vulnerable and highly vulnerable groups.

The measure of a closed door led to an improvement for all groups outside the fire room. This improvement was less for the vulnerable and highly vulnerable groups. The situation was only survivable for all groups for more than 20 minutes in the opposite residence where the door was kept closed (1.24).


4K30FPS
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6 The deployment method

6.1 Introduction

Upon arriving at a fire in a residential building with internal corridors the fire service is faced with a choice: should they prioritise extinguishing the fire or rescuing / evacuating the people present? In order to be able to make this choice, the question as to whether the people present in the building can safely stay in their residences for some time needs to be answered first. This can be quite hard to assess in practice due to a lack of information about the possibility of escape and survivability in the various rooms. In other words: how far has the smoke propagated through the building, how harmful is it for the people present, and which people should the fire service evacuate first? At the same time, the question is whether, and to what extent, the actual deployment influences the controlling and smoke propagation and the possibility of escape and survivability.

As shown in previous chapters, the degree of survivability depends on many factors that differ for every fire and every building. Based on this information, it can be concluded that the main consideration for the fire service is the extent to which a specific deployment method might improve or actually reduce the possibility of escape and survivability. This research tested two methods, i.e. an offensive one and a defensive one. In the case of an offensive method, priority is given to extinguishing the fire, whereas the priority of a defensive method is saving/evacuating.

This section looks into the influence of the deployment on the possibility of escape and survivability in the building during the deployment phase of the tests (t = 20 minutes to t = 55 minutes). The assessment of this influence is based on the gas concentration, visibility distance, temperature and radiation measurements. The times for the possibility of escape and survivability were determined on the basis of these measurement results. This was determined using the criteria listed in sections 1.3.5 and 2.5.2, and differentiating between four situations (see table 6.1). The times for the possibility of escape and survivability were established according to the same procedure as described in chapters 4 and 5. Furthermore, the measurements serve as a reference for examining the quantitative influence of the deployment on the conditions in the residences or rooms. This gives information about any improvement or deterioration in residences and rooms and supplements the possibility of escape and survivability to give an idea of the influence of the deployment.

This chapter starts with reading instructions. The external size-up is addressed next. This will answer the question as to whether the fire room can be identified and whether the degree of smoke propagation can be assessed from the outside. Furthermore, it is examined whether a deployment can offer added value compared to the situation where no action is taken in the event of variant 0 (door open). The section on the necessity of rescuing and evacuating examines the necessity of evacuating real or fictitious people from the residential building, the possibility of escape and survivability for the people present, and whether they can be evacuated via the corridor. The next point considered is which deployment method leads to the most optimum possibility of escape and survivability in specific situations, or in other words: should the priority be on rescuing people or on extinguishing the fire? The section on the effects of the fire service's actions takes a detailed look at the influence of the deployment on further smoke propagation in the residential building. Finally, the remaining results are discussed, such as post assessment, smoke visibility, and local differences.

6.2 How to interpret the results

The key below helps you to read the results. For example, the key features a floor plan with the names of the rooms that are used when discussing the results.

6.2.1 Key to the results

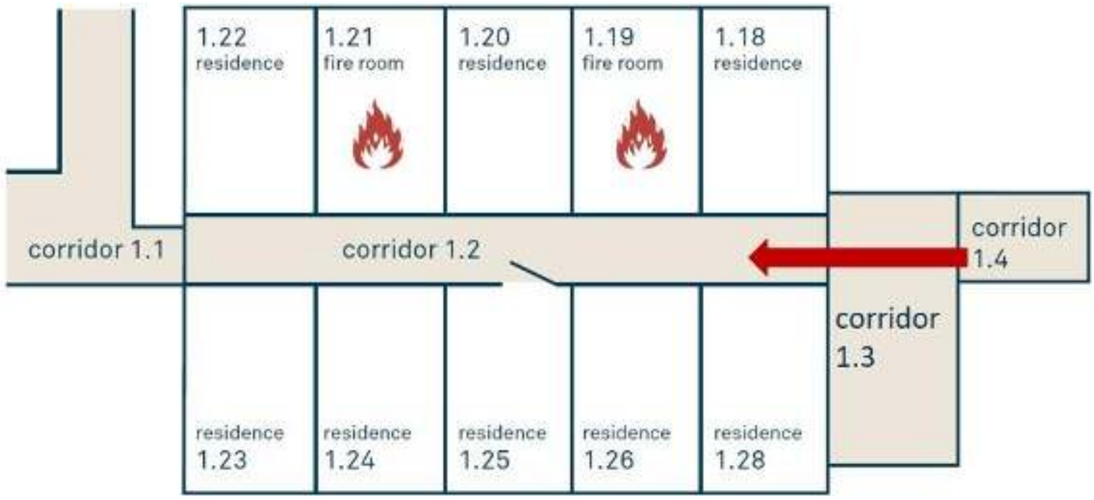

Figure 6.1 First-floor floor plan with the deployment route (red arrow)

Abbreviations

> Fire room [BR]
> Residence 1.25 [W1.25], this notation also applies to the other residences
> Corridor 1.1 [G1.1], this notation also applies to the other corridors

Variants

> Tests of variant 0 (door open)
> Tests of variant 1 (door closed)
> Tests of variant 2 (mobile water mist, door open)
> Tests of variant 3 (mobile water mist, door closed)
> Tests of variant 4 (mobile water mist and smoke resistant partition, door closed)
> Tests of variant 5 (smoke resistant partition, door closed)
> Test of variant 6 (organic fire load, door open)
> Test of variant 7 (organic fire load, door closed)
> Tests of variant 8 (balcony door open and door open, maximum ventilation)

Symbols and colours in the tables with the results of the times for the possibility of escape and survivability

Table 6.1 Situations and colours in the tables

Colour	Situation
	Safe escape
	Impaired escape
	Life-threatening situation
	Fatal situation / rescue no longer possible

6.2.2 Methods

The optimum method is determined by comparing two methods: an offensive and a defensive one. In case of an offensive method, priority is given to extinguishing the fire, whereas the priority of a defensive method is saving / evacuating. The sequence of actions while carrying out these methods is:

> Offensive method: priority on extinguishing.
1. Progressing to the fire room, entering the fire room, extinguishing the fire
2. Ventilating the corridor and the fire room
3. Ventilating and evacuating the residences adjoining the corridor
4. Ventilating the other residences / rooms on the first floor
5. Ventilating the residences / rooms on the ground floor, second and third floors.

> Defensive method: priority on rescuing.
1. Progressing to the fire room, and, if relevant, closing the door to the fire room
2. Evacuating the residences adjoining the corridor
3. Entering the fire room, extinguishing actions
4. Ventilating the corridor and the fire room
5. Ventilating the residences adjoining the corridor
6. Ventilating the other residences / rooms on the first floor
7. Ventilating the residences / rooms on the ground floor, second and third floors.

A global timeline of offensive and defensive (interior) attacks can be found in figure 6.2 and figure 6.3. An exact presentation of the actions during the deployment can be found in chapter 2 (see section 2.4.3).

Figure 6.2 Overview of the timeframe of the offensive interior attack

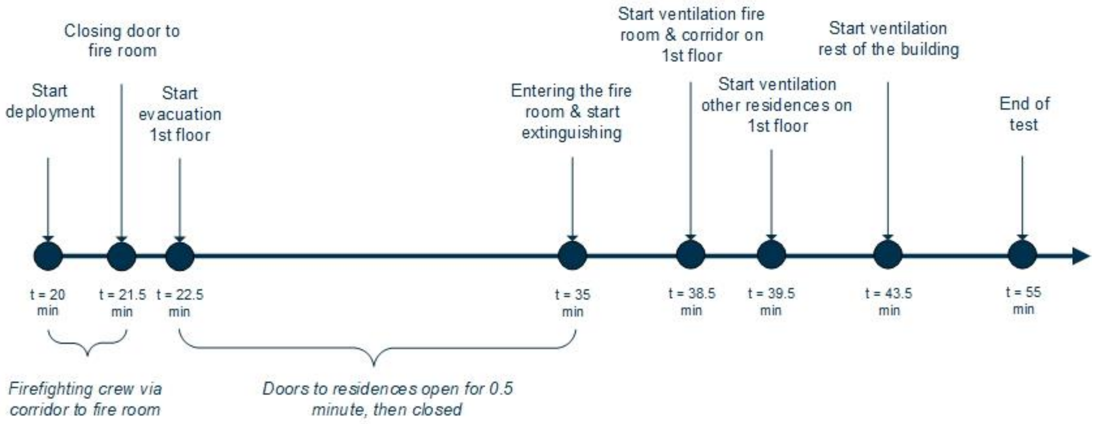

Figure 6.3 Overview of the timeframe of the defensive interior attack

6.2.3 Explanation of the presentation of the results

This section looks into the influence of the deployment on the possibility of escape and survivability in the building. This is considered for the deployment phase of the tests (t = 20 minutes to t = 55 minutes). This assessment is based on the gas concentration, visibility distance, temperature and radiation measurements. The full measurement results, per sensor and per test, can be found in Appendix 16. In order to form an opinion on the possibility of escape and survivability, the overview stating the calculated times for the possibility of escape and survivability for the different methods (FIC, FLD, FED_{in}, FED_{heat}, FEC_{smoke}) for each measurement location and test in Appendix 21 has also been taken into consideration.

The overview tables with the possibility of escape and survivability show colours indicating the specific situations (safe escape, impaired escape, a life-threatening situation, a fatal situation) that applied to a certain residence or room during a certain period while the deployment was taking place. The colours correspond to the situations according to the key. The deployment periods can be found in table 6.2.

Table 6.2 Times of the periods during a deployment (in minutes after the start of the test)

Period	Offensive	Defensive
Prior to the attack	20	20
During the attack / evacuation	20 to 25 extinguishing the fire	20 to 35 evacuation
After ventilation / evacuation	27 to 55 ventilation & evacuation	35 to 55 extinguishing & evacuation

Besides the possibility of escape and survivability for every room, the influence of the deployment on the CO concentrations in different rooms during the various deployment periods was considered as well. This was done because certain threshold values being reached or not reached does not show whether the CO concentration in a room has improved or deteriorated. E.g.: in a residence an evacuation resulted in an increase in CO by 300 ppm, but it did not cause a threshold value to be exceeded (deterioration). Or, conversely: the threshold value for a fatal situation was exceeded in the corridor, but the deployment lowered the CO concentration (improvement). In order to be able to consider the influence of the deployment on both the possibility of escape and survivability, as well as the CO concentrations, they have been brought together in the overview tables. Any deterioration or improvement of the CO concentration has only been included in the table if the deterioration or improvement was at least 10 ppm CO. The exact changes in the CO concentrations per deployment period during the deployment phase can be found in Appendix 16. The changes are represented by arrows, showing whether the situation improved (↑), deteriorated (↓) or remained unchanged (=) relative to the preceding period.

Where the previous chapters deal with all groups (general, vulnerable and highly vulnerable), this chapter only considers the general group. The reason for this decision is that, in many cases, the threshold values for safe or impaired escape had already been exceeded for the vulnerable and highly vulnerable groups at the start of the deployment. As a result, any influence of the deployment was no longer visible (once the threshold value has been exceeded, it continues to be recorded as such, even if an improvement has lowered the value to below the threshold again). Furthermore, an improvement (or deterioration) for the general group means that the conditions will also generally improve or deteriorate for the vulnerable and highly vulnerable groups.

6.3 External size-up

Locating the fire room from the outside is one of the basic principles of firefighting and is decisive for the deployment plan chosen by the fire service. Therefore this chapter will go into this first. The question is whether the fire service can determine from the outside where the fire is located in the building.

6.3.1 Results

The tests included an external size-up at the moment when the fire service arrived at the scene (15 minutes after the start of the test). Based on visibility and images of a thermal imaging camera it was examined whether any smoke or heat was visible from the outside of the building to help assess where the fire room was located.

Table 6.3 lists the signals visible near the fire room at the moment of the external size-up. ‘Yes’, ‘No’ and ‘Minimal’ in the table indicate whether any smoke and heat signals were visible. This has the following meanings:

- Yes: smoke or heat is clearly visible.
- Minimal: smoke or heat is difficult or very difficult to perceive; it is essential that distances and viewing angles be changed in order to be able to observe the smoke and heat.
- No: no smoke or heat was observed from the outside.

Table 6.3 External size-up for smoke and heat signals near the fire room

Variant no.	Variant name	Test no.	Deployment method	Smoke	Heat
0	Door open	1	None	-	-
		17	None	-	-
		3	Defensive	Yes	Yes
		5	Offensive	Yes	Yes
1	Door closed	2	Offensive	Yes	Minimal
		16	Offensive	Yes	Minimal
		4	Defensive	Minimal	Minimal
2	Mobile water mist and door open	7	Defensive	Minimal	Minimal
		9	Offensive	Yes	Yes
3	Mobile water mist and door closed	6	Offensive	Minimal	Minimal
		8	Defensive	Minimal	Minimal
4	Mobile water mist, smoke resistant partition, and door closed	10	Offensive	No	No
		11	Defensive	No	Minimal
5	Smoke resistant partition and door closed	12	Offensive	No	Minimal
		13	Defensive	No	Minimal
6	Organic fire load and door open	15	Offensive	Minimal	Yes
7	Organic fire load and door closed	14	Defensive	No	No
8	Balcony door open and door open (maximum ventilation)	18	Offensive	Yes	Yes
		19	Defensive	Yes	Yes

The general finding is that fewer signals of smoke and fire can be seen from the outside in tests with the door to the fire room closed than in tests where the door to the fire room was open. Furthermore, it was found that additional measures for risk management, which caused the temperature in the fire room to not become so high, negatively affected the ability to identify the fire room from the outside. An example of this can be seen in figure 6.5 and figure 6.4: more differences in heat were visible in the test without any additional measures for risk management.

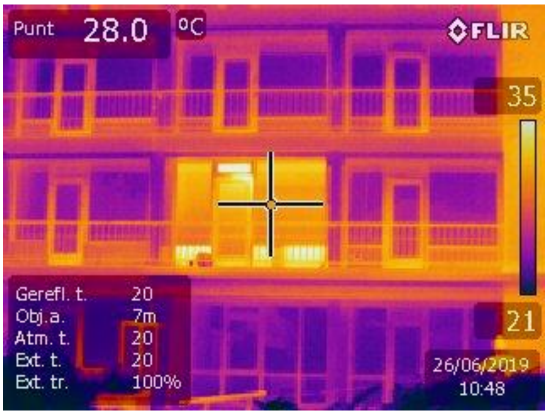

Figure 6.5 Thermal imaging camera (TIC) images of test 4 of variant 1 (door closed)

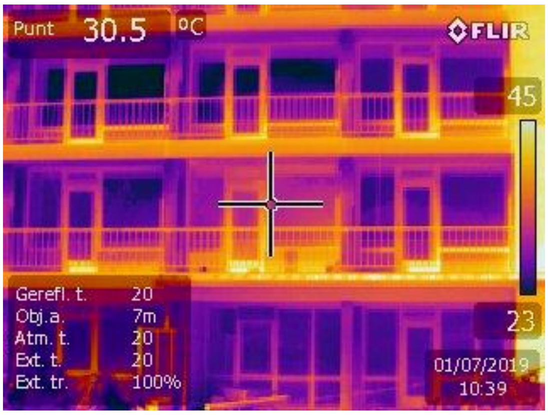

Figure 6.4 TIC images of test 10 of variant 4 (mobile water mist, smoke resistant partition, and door closed)

It should be noted that, regardless of the test in question, it was never visible from the outside what stage the fire growth was in, except for the test of variant 8 (balcony door open, maximum ventilation). Smoke was visible behind the windows in the various residences (not being the fire room), but this was not being ‘forced out’. The fact that visibility in the corridor was nil did not show from the outside either. In some cases, it was visible from the outside that smoke had already propagated into several other residences, leading to all the relevant limiting consequences for the possibility of escape and survivability. However, in most cases, at the moment the fire service arrived, it was not visible from the outside that smoke had already propagated to several residences.

6.3.2 Analysis

The location of the fire and the extent to which smoke had propagated could often only be determined from the outside of the building to a limited extent. However, there not being any indications on the outside of a residential building should never be taken to imply that the situation cannot be serious.

It has been found that the fire room can often be identified based on visibility and using a thermal imaging camera, but it is not as simple as one might imagine. The smaller the fire, the harder it is to see any visible difference in heat. Furthermore, a closed façade and airtight construction will also influence the heat release rate and thus the heat produced (less oxygen = a lower temperature). A building being airtight also influences the possibilities of seeing any smoke from the outside.

An external size-up requires concentration and the use of different distances and viewing angles. This increases the probability that any indicators, no matter how insignificant, will be recognised. Furthermore, measures for risk management and the door to the fire room being closed also lead to less heat being produced and /or less smoke being forced out.

6.4 Deployment, yes or no?

This section examines the possibility of escape and survivability for people in the residential building at the moment when the fire service arrived and the degree, if any, to which a deployment can contribute to improving the prevailing possibility of escape and survivability in the different residences and rooms, and on the floors. Simply put: does a deployment offer added value for the possibility of escape and survivability?

6.4.1 Results

Since the tests of variant 0 (door open) were conducted both with and without a deployment, they can be used to assess the difference between deploying or not deploying. Since no tests without deployment were conducted for variant 1 (door closed), it is not possible to compare the situation where the fire service deploys to where it does not deploy for this variant.

A table is presented below showing survivability in the different rooms for each period of the deployment (table 6.4). Based on this, it can be determined whether the situation in the residences was still such that people could survive there at the moment when the fire service arrived and when the fire service started to evacuate. It can be examined whether the possibility of escape was impaired on the first-floor corridors. The table also indicates the situation at the end of the test (t = 55 minutes) for the tests without a deployment so that it can be examined which changes occurred in specific situations if there was no attack. An extensive description of the results and the corresponding graphs can be found in Appendixes 21 and 25.

Table 6.4 Situation with / without a deployment (general group) by deployment periods

Var. no.	Test no.	Method	Period	BR	G1.2	W1.25	W1.20	W1.24	G1.1	G1.3
0	1	None	Prior to the attack							
			End of test							
	17	None	Prior to the attack							
			End of test							
0	3	Defensive attack	Prior to the attack							
			While evacuating							
			After evacuating							
	5	Offensive attack	Prior to the attack							
			During the attack							
			After ventilating							

Other floors

Table 6.5 shows the CO concentrations measured at the start of the deployment and the maximum CO concentrations measured during the deployment phase. These concentrations shed a light on the influence of the deployment on the propagation of CO to the ground floor, the second floor, and the third floor. Section 6.7 goes into this in more detail.

Table 6.5 CO concentrations (ppm) on the ground floor, the second floor, and third floor at the start of the deployment (t = 20 minutes) and the maximum CO concentrations during the deployment phase (t = 20 minutes to t = 55 minutes)

Room (sensor)	Test 1 [ppm]		Test 17 [ppm]		Test 3 [ppm]		Test 5 [ppm]	
	No attack		No attack		Defensive attack		Offensive attack	
	Start	Max.	Start	Max.	Start	Max.	Start	Max.
G0.1 (G17)	0	0	0	0	0	75	0	0
G0.2 (G18)	215	255	0	0	0	220	0	0
W2.19 / 2.21 (G9)	0	20	0	10	0	300	0	0
W2.24 (G10)	0	20	0	0	0	0	0	0
G2.2 (G11)	90	140	0	0	40	185	0	0
G2.2 (G12)	25	75	0	20	0	125	0	10
W3.19 / 3.21 (G13)	0	0	0	15	30	155	0	10
W3.24 (G14)	0	0	0	0	0	0	0	25
G3.2 (G15)	25	35	0	25	65	145	0	0
G3.2 (G16)	30	35	0	15	30	80	0	0

6.4.2 Analysis

If the door to the fire room is open, an offensive attack (extinguishing before rescuing) will improve conditions in the residences and the corridor sections compared to the conditions in the tests without a deployment. Opting for a defensive attack method (rescuing before extinguishing) deteriorated the situation in some rooms if the door to the fire room was open, compared to a situation of 'inaction' (no attack).

The tests without a deployment also showed the situation in the different rooms to deteriorate as more time went by. For instance, safe escape from residence 1.24 was still possible in test 17 (without a deployment) after 20 minutes, whereas the situation had become fatal by the end of the test.

However, in real-life situations, it does not show from the outside whether the door to the fire room is open or closed. This necessitates a deployment to assess the situation in the building. In the end, deploying is always better than not taking any action, even although a deployment may briefly deteriorate the possibility of escape and survivability in some locations.

6.5 The necessity of rescuing and evacuating

This section considers the situation in the residential building during the deployment, both at the start and while actions are being carried out. Based on this it can be assessed whether rescuing and/or evacuation by the fire service at the start of the deployment and during the deployment are necessary. Furthermore, an assessment can be made as to whether rescuing via corridor 1.2 is a realistic option.

6.5.1 Results: temperature, radiation and visibility distance

Temperature

The figures for the ground floor, the second floor, and the third floor during the deployment phase show that no relevant changes in temperature were measured during any test or in any room. Relevant here means: having an influence on the possibility of escape and survivability or on the deployment. The same applies to the ventilation ducts; no relevant changes in temperature were measured at or near the ventilation ducts on the ground floor, the second floor, and the third floor during the deployment phase. The graphs of the temperature measurements for each position can be found in Appendix 26.

The next step was examining all the temperatures on the first floor for the individual measuring positions at measurement heights of 2.40 and 1.50 metres (see Appendix 27). The fire room was not considered here since the possibility of escape and survivability *outside* this residence were considered. No relevant changes in temperature were measured in the residences with their doors closed. Relevant temperature increases were observed in corridor 1.2 and residence 1.25 at two moments during the deployment phase. This concerns both tests with a mobile water mist of variant 2 (mobile water mist and door open) with the temperature increasing to a maximum of 100 to 190 °C. Closing the door to the fire room or extinguishing the fire both led to a rapid decrease in temperature in corridor 1.2 and in residence 1.25. The other tests where the door was open also showed increased temperature readings in the corridor and in residence 1.25; however, these temperatures decreased quickly once the door to the fire room had been closed or the fire had been extinguished. No tests showed any relevant changes in temperature in corridors 1.1 and 1.3.

Radiation energy

The radiation energy was measured on the first floor in accordance with the measurement configuration described in chapter 2 (see section 2.4.5). The graphs of all radiation measurements for each position can be found in Appendix 28. No relevant radiation intensity threatening the possibility of escape and survivability or threatening the deployment (>2 kW/m^2) was measured in any test or in any room during the deployment phase (outside the fire room).

Visibility distance on the ground floor, the second floor and the third floor

Chapter 3 shows that smoke was observed on the ground floor, the second floor, and the third floor, both before and during the deployment phase. However, the results of chapter 3 show that the visibility distance on these floors was not impaired by smoke at any moment during the deployment phase. This means that reduced visibility distance did not impair the possibility of escape and survivability on these floors.

6.5.2 Results: situation per group when the fire service arrives

In order to be able to assess the groups for which, and the cases in which, rescuing is necessary, it should be established whether any threshold values have been exceeded at the moment when the deployment starts. For this purpose, values were clustered, based on the differences between tests with the door open and test with the door closed. The results correspond to the results from chapter 5. The tables can be found in Appendix 29.

The tables in Appendix 29 show that there are many cases where the situation is life threatening or fatal for the vulnerable and highly vulnerable groups in the residences on corridor 1.2. Safe escape via corridor 1.2 was not possible for the vulnerable and highly vulnerable groups in any test at the start of the deployment phase, except the test of variant 7 (organic fire load and door closed). The possibility of escape was impaired by the lack of visibility distance or the concentration of irritant or asphyxiant gases present. In many cases, the threshold value for a fatal situation had already been exceeded for the vulnerable and highly vulnerable groups in corridor 1.2 at the start of the deployment. The following tests were the only tests where the threshold value for a fatal situation had not been exceeded yet for vulnerable and highly vulnerable groups in corridor 1.2:

- tests 2 and 16 of variant 1 (door closed), only for the vulnerable group
- the tests of variant 3 (mobile water mist and door closed)
- the tests of variant 4 (mobile water mist, smoke resistant partition and door closed)
- the test of variant 7 (organic fire load and door closed)
- the test of variant 6 (organic fire load and door open), only for the vulnerable group.

It was found that there were more situations where the general group could escape or survive safely at the start of the deployment then was the case for the vulnerable and highly vulnerable groups. A general finding here was that if the door to the fire room was closed, the general group could still escape or be evacuated, albeit sometimes under impaired conditions, through corridor 1.2. If the door to the fire room was closed and the following measures for risk management, i.e. a mobile water mist, a mobile water mist and a smoke resistant partition, or an organic fire load, had been taken, safe escape was still possible. If the door to the fire room was open, the general group could still escape through the corridor, but only in the situation where there was an organic fire load. The situation was fatal in all other cases and the general group could not use corridor 1.2 as an escape or evacuation route either.

The CO concentrations in the residences on corridor 1.2 at the start of the deployment were comparable to the results for corridor 1.2: the amount of smoke present was often decisive (although there were exceptions), and the CO concentrations in the residences varied considerably. What is important here is that several tests also showed CO concentrations, some of which were high, in residences where the doors were closed (1.20 and 1.24). The values in residence 1.24 were between 15 and 4,000 ppm at the start of the deployment, and the values in residence 1.20 were between 30 and 7,000 ppm during all tests.

6.5.3 Results: necessity and possibility of rescuing and evacuating

The possibility of escape and survivability in the various residences and rooms were identified for the different deployment periods. It was checked whether the threshold value for the possibility of escape and survivability was exceeded in the room in question during a specific period. Any period(s) during the (simulated) incident in which rescuing or evacuating became necessary and/or possible could thus be established.

Besides the thresholds for a room being exceeded, the influence of the deployment on the CO concentrations in different rooms during the deployment phase was considered as well. This was done because a deterioration or improvement of the CO concentration in a room is not shown when threshold values have been exceeded. The situations for the possibility of escape and survivability and changes to the CO concentrations can be found in table 6.6.

Table 6.6 Situations for the possibility of escape and survivability for the individual deployment periods (general group) and CO concentrations (improvement (↑), deterioration (↓) or unchanged situation (=)) compared to the preceding period

Var. no.	Test no.	Method	Period	BR	G1.2	W1.25	W1.20	W1.24	G1.1	G1.3
0	1	No attack	Prior to the attack							
			During the attack / evacuation							
			After ventilation / evacuation							
	17	No attack	Prior to the attack							
			During the attack / evacuation							
			After ventilation / evacuation							
0	3	Defensive attack	Prior to the attack							
			While evacuating	↓	=	=	↓	↓	↓	↓
			After evacuating	=	=	=	↓	↓	↓	=
	5	Offensive attack	Prior to the attack							
			During the attack	↑	↓	↓	↓	↓	↓	↓
			After ventilating	↑	↑	↑	↑	↑	↓	↓
1	2	Offensive attack	Prior to the attack							
			During the attack	↑	↓	↓	↓	↓	↓	↓
			After ventilating	↑	↑	↓	=	↓	↓	↓
	4	Defensive attack	Prior to the attack							
			While evacuating	=	↓	↓	↓	↓	=	=
			After evacuating	↑	↓	↓	↓	↓	↓	↓
	16	Offensive attack	Prior to the attack							
			During the attack	=	↓	↓	↓	↓	=	=
			After ventilating	↑	↑	↓	↑	↑	↓	↓
2	7	Defensive attack	Prior to the attack							
			While evacuating	↓	↑	↓	↓	↓	↓	↓
			After evacuating	↑	↓	=	↑	↑	↓	↓
	9	Offensive attack	Prior to the attack							
			During the attack	=	↓	↓	=	=	↓	↓
			After ventilating	↑	↑	=	↓	↓	↓	↓
3	6	Offensive attack	Prior to the attack							
			During the attack	↑	↓	↓	↓	↓	=	=
			After ventilating	↑	↑	↑	↑	↑	↓	↓
	8	Defensive attack	Prior to the attack							
			While evacuating	=	↓	↓	↓	↓	=	=
			After evacuating	↑	↓	=	=	↑	↓	=

4	10	Offensive attack	Prior to the attack							
			During the attack	=	↓	↓	↓	↓	=	=
			After ventilating	↑	↑	↑	↑	↑	↓	=
	11	Defensive attack	Prior to the attack							
			While evacuating	=	=	=	=	=	=	=
			After evacuating	↑	↓	=	↓	=	↓	=
5	12	Offensive attack	Prior to the attack							
			During the attack	↑	↓	↓	↓	=	=	=
			After ventilating	↑	↑	=	=	↓	↓	↓
	13	Defensive attack	Prior to the attack							
			While evacuating	=	=	↓	=	=	↓	=
			After evacuating	↑	↓	=	↓	↓	↓	=
6	15	Offensive attack	Prior to the attack							
			During the attack	↓	↓	↓	↓	↓	=	=
			After ventilating	↑	↑	=	=	↓	↓	↓
7	14	Defensive attack	Prior to the attack							
			While evacuating	=	↓	=	↓	=	=	=
			After evacuating	↑	↑	↓	↑	↓	↓	↓
8	18	Offensive attack	Prior to the attack							
			During the attack	↑	=	=	=	↓	↓	↓
			After ventilating	↑	↑	=	↑	↑	↓	=
	19	Defensive attack	Prior to the attack							
			While evacuating	=	=	↓	↓	↓	↓	↓
			After evacuating	↑	↑	↑	↑	↑	↓	↑

Other floors

The general and vulnerable groups could escape safely from the ground floor, the second floor, and the third floor during the deployment phase. The values were exceeded in two tests for the highly vulnerable group, i.e. twice for a test of variant 0 (door open): test 1 without a deployment and test 3 with a defensive attack method. These exceeded values can be found in table 6.7 and in Appendix 21. This table also lists the times when the threshold values were exceeded, expressed as minutes after the start of the test (t = 0 minutes). The measurements for the other tests did not show any situations where threshold values were exceeded.

Table 6.7 Situations on the ground floor, the second floor, and third floor for the highly vulnerable group (threshold values and minutes after the start of the test when the threshold value was exceeded)

Test	G0.1	G0.2	W2.19 / 2.21	W2.24	G2.2 (G11)	G2.2 (G12)	W3.19 / 3.21	W3.24	G3.2 (G15)	G3.2 (G16)
1		49			40					
3			52		46	53	46		37	

Even if no threshold value was exceeded, smoke propagation can still be a reason for the fire service to evacuate all or part of the building, or for people to escape from the building on their own. The CO concentration in the building measured during the tests is often a good reference for how significantly smoke has propagated. The maximum CO concentrations measured in the different rooms for the individual tests can be found in Appendix 16. The maximum CO concentrations measured give information about the extent to which smoke has propagated in the residential building and the possible necessity to evacuate during the deployment phase.

6.5.4 Analysis of the necessity and possibility of rescuing and evacuating at the start of the deployment

When the fire service arrived, there had already been horizontal smoke propagation on the first floor in all cases. Furthermore, two tests showed vertical smoke propagation having taken place to other floors at the start of the deployment. The extent to which smoke generally propagates is often determined by the position of the door (open or closed) to the fire room.

Escaping through the corridor directly adjoining the fire room (corridor 1.2) was often not possible on the first floor. There were only a few cases where there was still a possibility of safe escape through corridor 1.2 at the start of the deployment. This means that if there were any people in the residences adjoining corridor 1.2, their only option would be to wait for the fire service to rescue them.

CO was found in the majority of the tests in the residences on corridor 1.2 – including those residences where the door was closed. Its concentration did not keep equal pace with the degree to which smoke propagation was visible. This means that the presence of visible smoke does not always give a reliable indication of the extent to which people are at risk and this makes CO concentrations a better indicator of smoke propagation. At the start of the deployment, there were many situations where the CO concentration measured in corridor 1.2 was higher than that measured in the residences on corridor 1.2 where the door was closed. Many tests showed the concentration of asphyxiant and irritant gases in the corridor to be so high that evacuating unprotected people would lead to health problems, which might be serious.

Visibility was not found to be impaired and a low CO concentration was measured in only two tests on one or several floors on the ground floor, the second floor, and the third floor at the start of the deployment. Given the situation at the start of the deployment phase, priority was given to an attack on the first floor, and then especially for the residences that were on the same corridor as the fire room, i.e. corridor 1.2.

6.5.5 Analysis of the necessity and possibility of rescuing during the deployment

The main findings regarding the necessity and possibility of rescuing during the deployment are described below.

Residences near the fire room

Based on the results, it can be established that the residences on corridor 1.2 (which the fire room was also on) needed to be evacuated. This was caused on the one hand because smoke had already propagated to these residences in many situations prior to the start of the deployment. On the other hand, the method employed by the fire service as part of its actions might lead to extra smoke propagation to these residences. Staying in these residences might harm people's health and might be fatal, particularly for vulnerable and highly vulnerable groups.

Evacuation along the corridor
A logical follow-up question is whether people could still be evacuated safely from these residences through the corridor. This would not be possible for people without protection during the tests with an open door to the fire room, but, in theory, this might be possible in some tests with the door closed for members of the general group; however, this does not apply to the vulnerable and highly vulnerable groups.

It should be noted that the distinction between safe and unsafe is easy to determine on the basis of measurement data from field experiments. However, the exact CO concentration in the corridor will not be immediately known during an actual incident. Unless measurements are conducted, it cannot be established whether the corridor is sufficiently safe, and, besides this, it is not always clear whether a person is a member of the general group or the vulnerable group. Therefore, it is not clear to what extent the distinction between safe and not safe, which can be determined quite well in theory, will actually work in practice.

Evacuation from the other residences in the building
The corridor sections (1.1 and 1.3) directly adjoining corridor 1.2 and the residences on that same corridor were threatened to a certain extent, depending on the amount of smoke at the start of the deployment and the additional smoke propagation caused by the deployment. Chapter 3 showed that smoke propagation can be unpredictable at times. The actual smoke propagation is hard to estimate, specifically for the fire service, since it has to act under time pressure, has only a limited knowledge of the building and its use, and of the actual situation during the incident. And the deployment adds to the unpredictability of the smoke propagation because of the flow in the building being influenced by people walking about and doors being opened. Only an assessment based on visibility and good measurements for any gases, including invisible ones, can provide objective certainty, but this takes time. A practical approach would seem to be to start from the assumption that, as a minimum, the corridor sections immediately adjoining corridor 1.2, including the adjoining residences, should be evacuated as a preventative measure, since it is quite probable that smoke (and asphyxiant gases) will propagate, or will have propagated, to these corridor sections and residences.

Another question is whether to evacuate residences located above and below the first floor. There were only a few cases where there was smoke on the ground floor, the second floor, and the third floor at the start of the deployment. With regard to the overall deployment phase, it can be noted that many tests would require attention to be paid to the residences on these floors because of the CO concentrations measured there. All deployment methods caused CO to propagate to these floors during the deployment phase; this applied to both tests with the door to the fire room being open and tests where this door was closed. Different degrees of intensity were measured (from negligible to serious health risks). It also became clear that it is quite unpredictable as to on which floor and in which room there is any visible smoke or CO. The 'cube philosophy[32]' should be abandoned here; smoke and fire gases often skip a storey or are found to be present in unexpected locations elsewhere in the building.

In all cases, the fire service will have to measure and assess on all floors and in all residences of the building or the part of the building in order to find out whether, and, if so, to

[32] The cube philosophy assumes that a fire can spread via all sides of a cube (room).

which extent smoke has propagated, and whether the building or the part of the building in question should be evacuated.

Support from other emergency assistance providers while evacuating
Vertical and unpredictable smoke propagation to other floors occurred both before and during the deployment. The police or other emergency responders often lend a hand to help people find their way out when evacuating a residential building. These field experiments have shown that there can be certain CO concentrations on the other floors prior to and during the deployment and that their locations cannot be predicted. The concentrations were such that this might cause problems for emergency assistance providers who were not wearing any PPE.

6.6 Rescue or extinguish first?

To determine which deployment method offers the best possibility of escape and survivability, a comparison was made between the offensive and defensive attack methods. This was done for those situations that are most common in real-life situations (variant 0: door open and variant 1: door closed) without taking any additional measures for risk management. This section first presents the results of the comparison between these two variants. This is followed by an analysis to establish the effect of the two attack methods (offensive / defensive) on survivability in the residences and on the possibility of escape / survivability in the corridors.

6.6.1 Results of variant 0 (door open)

Since the tests of variant 0 (door open) were carried out both with an offensive and a defensive attack method, they can be used to assess the differences between these two methods if the door to the fire room is open. A table is presented below showing the situations in the different rooms at different moments during the deployment (see table 6.8). Based on this, it can be established whether the situation in the residences was still such that people could survive there at the moment when the fire service arrived and when the fire service started to evacuate people from the different rooms. It can also be established whether the possibility of escape through the corridors was impaired. An extensive description of the results and the corresponding graphs can be found in Appendixes 21 and 25.

Table 6.8 Relative influence of the deployment on the first floor (general group, in threshold values for the possibility of escape and survivability) and CO concentrations (improvement (↑), deterioration (↓) or unchanged situation (=)) compared to the previous period

Var. no.	Test no.	Method	Period	BR	G1.2	W1.25	W1.20	W1.24	G1.1	G1.3
0	3	Defensive attack	Prior to the attack							
			While evacuating	↓	=	=	↓	↓	↓	↓
			After evacuating	=	=	=	↓	↓	↓	=
	5	Offensive attack	Prior to the attack							
			During the attack	↑	↓	↓	↓	↓	↓	↓
			After ventilating	↑	↑	↑	↑	↑	↓	↓

The effect of the two deployment methods on the possibility of escape and survivability for variant 0 (door open) has been summarised in table 6.9.

Table 6.9 Summary of the offensive attack method vs the defensive attack method for variant 0 (door open)

Offensive attack method	Defensive attack method
At the start of the deployment there were relatively high concentrations of asphyxiant gases in corridor 1.2 and in the residences on this corridor. Extinguishing efforts increased the gas concentrations in corridor 1.2, residence 1.24 and residence 1.25. Mechanical ventilation lowered the concentrations of asphyxiant and irritant gases after some time. Visibility in the fire room, corridor 1.2 and residence 1.25 remained unchanged. Mechanical ventilation increased the CO concentration in residences 1.20 and 1.24. Opening the window in these residences while mechanical ventilation was taking place, led to lower CO concentrations. Mechanical ventilation deteriorated CO concentrations in corridor 1.1 and, in some cases, in corridor 1.3. The conditions at the end of the test had improved because of the deployment when compared to the conditions before the start of the deployment.	At the start of the deployment there were relatively high concentrations of asphyxiant gases in corridor 1.2 and in the residences on this corridor. Progressing through the corridor and closing the door to the fire room resulted in fluctuations and in an increase in asphyxiant gases in other residences than the fire room, particularly in residence 1.20. Evacuating people from the residences caused fluctuations and a slight increase in asphyxiant gases in corridor 1.2 and the residences along this corridor. Little influence was noticeable in corridor 1.1. There was a higher increase in corridor 1.3, particularly when the double doors between corridor 1.2 and this corridor were opened for evacuation purposes. Opening the door to the fire room and extinguishing the fire had relatively little influence on the conditions in corridor 1.2, in the residences along corridor 1.2 and in the other parts of the corridors (1.1 and 1.3). Mechanical ventilation had a minor effect on the CO concentrations in the fire room, in corridor 1.2 and in the other residences on corridor 1.2. However, there was an improvement in CO and nitrogen oxide concentrations. Opening windows in the other residences on corridor 1.2 led to a slow improvement in CO concentrations. Mechanical ventilation had relatively little effect on the conditions in corridors 1.1 and 1.3; they remained unchanged to the condition before mechanical ventilation started. The deployment slightly worsened conditions. The conditions in some rooms and corridor sections had improved by the end of the test, whereas conditions in other areas had actually worsened.

Other floors
Table 6.5 (see section 6.4.1) shows the CO concentration measured at the start of the deployment (t = 20 minutes) and the maximum concentrations measured during the deployment phase (t = 20 minutes to t = 55 minutes). These concentrations shed light on the influence of the deployment on the propagation of CO to the ground floor, the second floor, and the third floor. Section 6.7 goes into this in more detail.

6.6.2 Results of variant 1 (door closed)

Since the tests of variant 1 (door closed) were carried with both the offensive and defensive attack methods, they can be used to assess the difference between the two methods when the door to the fire room is closed. A table is presented below showing the situations in the different rooms during the different deployment periods (see table 6.10). This can be used to assess whether the situation in the residences was still such that people could survive there at the moment when the fire service arrived and when the fire service started to evacuate people from the different rooms. It can also be examined whether the possibility of escape through the corridors was impaired. An extensive description of the results and the corresponding graphs can be found in Appendixes 21 and 25.

Table 6.10 Relative influence of the deployment on the first floor (general group, in threshold values for the possibility of escape and survivability) and CO concentration (improvement (↑), deterioration (↓) or unchanged situation (=)) compared to the previous period

Var. no.	Test no.	Method	Period	BR	G 1.2	W1.25	W1.20	W1.24	G1.1	G1.3
1	2	Offensive attack	Prior to the attack							
			During the attack	↑	↓	↓	↓	↓	↓	↓
			After ventilating	↑	↑	↓	=	↓	↓	↓
	4	Defensive attack	Prior to the attack							
			While evacuating	=	↓	↓	↓	↓	=	=
			After evacuating	↑	↓	↓	↓	↓	↓	↓
	16	Offensive attack	Prior to the attack							
			During the attack	=	↓	↓	↓	↓	=	=
			After ventilating	↑	↑	↓	↑	↑	↓	↓

The effect of the two methods on the possibility of escape and survivability for variant 1 (door closed) has been summarised in table 6.11.

Table 6.11 Summary of the offensive attack method vs the defensive attack method for variant 1 (door closed)

Offensive attack method	Defensive attack method
At the start of the deployment there were relatively low concentrations of asphyxiant gases in corridor 1.2 and in the residences along corridor 1.2. Opening the door to the fire room led to a significant decrease in the visibility distance and the oxygen concentration in corridor 1.2. The CO, carbon dioxide and nitrogen oxide concentrations increased. Extinguishing the fire reinforced this effect. Mechanical ventilation resulted in an increase in asphyxiant and irritant gases, particularly in the residences on corridor 1.2. There were significant local differences in the conditions in corridor 1.2. The concentrations of asphyxiant gases and visibility in the fire room and corridor 1.2 decreased after some time. Conditions in residence 1.25 remained relatively worse for a long time. Mechanical ventilation resulted in a deterioration of gas concentrations in the other residences on corridor 1.2. Opening windows in residence 1.20 and residence 1.24 led to an improvement of the CO concentrations. Mechanical ventilation led to a deterioration of the visibility and an increase in gas concentrations in corridor 1.1 and, in some cases, it also led to a deterioration in corridor 1.3. The deployment worsened conditions. Conditions had improved and returned to an acceptable level by the end of the test.	At the start of the deployment there were relatively low concentrations of asphyxiant gases in corridor 1.2 and in the residences along corridor 1.2. Progressing through the corridor to the fire room created fluctuations and an increase in asphyxiant gases in residences along corridor 1.2. Evacuating people from the residences caused slight fluctuations and an increase in asphyxiant gases in corridor 1.2 and the residences on this corridor. There was hardly any effect on the conditions in corridors 1.1 and 1.3. Opening the door to the fire room led to a significant decrease in the visibility distance and the oxygen concentration in corridor 1.2, and also increased the CO, carbon dioxide and nitrogen oxide concentrations. Extinguishing the fire reinforced this effect. The residences on corridor 1.2 had already been evacuated by then. Mechanical ventilation caused a decrease in the concentration of asphyxiant gases and an improvement of visibility in the fire room and corridor 1.2 after some time. It took longer for the situation in residence 1.25 to improve. Mechanical ventilation increased the CO concentrations in residences 1.20, 1.24 and 1.25. Opening windows in residences 1.20, 1.24 and 1.25 led to a gradual decrease in CO concentrations. Mechanical ventilation led to a deterioration of visibility and an increase in gas concentrations in corridors 1.1 and 1.3. The deployment had relatively little influence on the conditions. Conditions had improved and returned to an acceptable level by the end of the test.

Other floors

Table 6.12 shows the CO concentrations measured at the start of the deployment (t = 20 minutes) and the maximum concentrations measured during the deployment phase (t = 20 minutes to t = 55 minutes). These concentrations shed light on the influence of the deployment on the propagation of CO to the ground floor, the second floor and the third floor. Section 6.7 goes into this in more detail.

Table 6.12 CO concentration (ppm) on the ground floor, the second floor, and third floor at the start of the deployment (t = 20 minutes) and the maximum CO concentration during the deployment phase (t = 20 minutes to t = 55 minutes)

Room (sensor)	Test 2		Test 16		Test 4	
	Offensive		Offensive		Defensive	
	Start	Max.	Start	Max.	Start	Max.
Corridor 0.1 (G17)	0	0	0	0	0	0
Corridor 0.2 (G18)	0	25	0	0	0	0
Residences 2.19 / 2.21 (G9)	0	0	0	0	0	0
Residence 2.24 (G10)	0	0	0	0	0	0
Corridor 2.2 (G11)	0	0	0	0	0	0
Corridor 2.2 (G12)	0	25	0	0	0	0
Residences 3.19 / 3.21 (G13)	0	0	0	0	0	0
Residence 3.24 (G14)	0	0	0	0	0	0
Corridor 3.2 (G15)	0	0	0	0	0	0
Corridor 3.2 (G16)	-	-	0	0	0	0

6.6.3 Analysis: offensive attack versus defensive attack

The optimum deployment method for the possibility of escape and survivability differs from variant to variant (door to the fire room open or closed). Therefore, in order to prepare the deployment plan, the fire service should know whether the door to the fire room is open or closed. However, this cannot be seen from outside the building and should therefore be determined by means of an assessment. The effects of the two deployment methods (offensive attack or defensive attack) on the possibility of escape and survivability in the building are described below for each variant.

Variant 0 (door open)

Where the door to the fire room was open when the fire service arrived, an offensive method (extinguishing the fire before rescuing) was found to have the most positive influence on the possibility of escape and survivability. The conditions on the first floor were improved by bringing the fire under control and then ventilating the building to expel the fire gases. It should be noted here that mechanical or natural ventilation may have a negative influence on smoke propagation to other residences, corridors and floors (see section 6.7).

Extinguishing as part of the offensive attack caused a deterioration in residences along corridor 1.2 and corridor sections adjoining corridor 1.2. For instance, the CO concentration in residence 1.24 increased more sharply than when a defensive method was used. At the moment when the fire service would start evacuating people from residence 1.24, the situation in residence 1.24 would have become fatal and rescuing would no longer be possible. However, the conditions in corridor 1.2 (visibility and the concentration of asphyxiant and irritant gases) were so bad that evacuating people would not be realistic unless the corridor was first further cleared of smoke.

In case of a defensive attack method (rescuing before extinguishing), residence 1.24 would be the only residence on corridor 1.2 from which rescuing would still be possible at the start of the deployment. The defensive attack method would bring the fire service to residence 1.24 quickly and the situation in that residence would not yet be fatal at the moment when its occupants were evacuated. However, evacuating via corridor 1.2 was not a realistic option for variant 0 (door open). The conditions in this corridor were too bad for this option. The evacuation movements and the mechanical ventilation led to increased smoke propagation (see section 6.7).

Variant 1 (door closed)
Where the door to the fire room was closed, an offensive method (extinguishing before rescuing) had a negative influence on the possibility of escape and survivability outside the fire room. Opening the door to the fire room in order to extinguish the fire would deteriorate conditions in corridor 1.2 and, subsequently, in the other residences on this corridor and corridors 1.1 and 1.3. After ventilating for a long time (see figure 6.2 and figure 6.3) after extinguishing the fire, the deteriorated conditions, caused by the fire service, would neutralise after some time. After some time, ventilating after having extinguished the fire will cause the CO concentration to return to values of before the moment when the door to the fire room was opened in order to extinguish the fire.

Where the door to the fire room was closed when the fire service arrived, a defensive method (rescuing before extinguishing the fire) was found to have the most positive influence on the possibility of escape and survivability. Because there was less smoke in corridor 1.2, evacuation movements through this corridor had a slighter effect on smoke propagation to other residences than was the case in tests with an open door. However, it should be noted that several tests with a closed door showed that the high concentrations of gas in the corridor might still be a valid reason to not evacuate any people through that corridor if they were unprotected.

The evacuation actions during a defensive attack would often cause a slowly increasing CO concentration in residences and corridor sections. Although opening doors to the residences for evacuation purposes caused the visibility distance in the residences to deteriorate (see chapter 3), the CO concentration increased only slightly.

The effect of extinguishing and rescuing
An offensive attack method (specifically extinguishing and ventilating) nearly always caused an improvement of conditions in the fire room and in the corridor. A defensive attack method actually often caused the conditions in the fire room to deteriorate.

Giving priority to extinguishing (offensive attack method) often caused a brief deterioration of conditions in the corridor and in the residences along corridor 1.2, and also in the residences where the door was closed (1.20 and 1.24). Prioritising evacuation (defensive method) often caused a slow deterioration of the possibility of escape and survivability in corridor 1.2 and in the residences along corridor 1.2, but only if the door to the fire room was closed. If the focus of the deployment was on rescuing a person from one of the residences, the choice of method depended on the position of the door to the fire room and the time factor, i.e.: the speed at which extinguishing or evacuating could take place versus the speed at which extra smoke propagation caused by the deployment deteriorated the situation in the corridor and in residences.

6.7 The effects of the fire service's actions

This section takes a detailed look into the effects of the fire service's actions on the possibility of escape and survivability in the building. The moments when the fire service conducted actions, such as extinguishing, ventilating or evacuating, were examined as part of the different tests. The measuring data (visibility, asphyxiant gases, irritant gases, etcetera) and camera images were examined for any visible changes for these moments. This section first presents the results and then analyses them.

6.7.1 Results

All the tests show some peculiarities. The first one is that all the actions performed by the fire service are visible in the measurement data (gases such as CO, but also visibility, irritant gases, etcetera), with the intensity of this influence being partly determined by the amount of smoke present in those locations where the deployment is conducted and the position of the door to the fire room. Table 6.13 describes the effects of the fire service actions during the deployment that have been identified.

Table 6.13 Fire service actions and their effects

Action	Effect
Fire service personnel opening (double) doors or laying a hose that keeps the (double) door(s) open	Slight increase in CO concentration in the 'cleaner' corridor sections.
Walking in a smoke-filled corridor (1.2)	A slight increase in the natural CO concentration in residences whose door was closed, fluctuations in the visibility distance and pressure in the corridor, smoke propagation to residences on corridor 1.2.
Opening the door to the fire room	A sharp deterioration of conditions in the corridor because of a strong impulse of smoke from the fire room filling the corridor. This has consequences for both the visibility distance and the gas concentrations.
Closing the door to the fire room	The conditions in the corridor stabilised or improved. This is reflected in decreases in temperature, radiation, carbon dioxide and nitrogen oxides, and an increase in the oxygen percentage, as well as increasing gas concentrations in the fire room and residence 1.20.

Extinguishing action in the fire room	A brief deterioration of conditions in corridors 1.1, 1.2, 1.3 and 1.4 and in residences as a result of an increase in toxic gases, a decrease in visibility and oxygen and, in some cases, brief pressure increases in the fire room and residence 1.20.
Evacuating people from residences	Opening doors to residences (in order to evacuate them) caused smoke to propagate from the corridor to the residences in question, resulting in a deterioration in visibility distance and an increase in gas concentrations.
Natural ventilation	Depending on the wind pressure on the outer wall, opening a window led to either an improvement in the residence or a deterioration in the corridor with regard to gas concentrations. Opening a window mostly led to an improvement.
Mechanical ventilation	The moment when the fan was started could be recognised immediately in almost all gas readings. In general, starting the mechanical ventilation in accordance with the research design led to a decrease in gas concentrations and an improvement of visibility in the fire room and in corridor 1.2, but also to an increase in gas concentrations (and sometimes deteriorated visibility) in all other rooms. This applied to all the residences (regardless of door open or closed) and all the corridor sections (1.1, 1.3 and 1.4).

Smoke propagating to other floors
Smoke propagation to the ground floor, the second floor and the third floor as a consequence of the fire service actions was also examined. Appendix 30 lists the results of measurements on the other floors for the individual tests. Appendix 31 contains an overview table of the moments when gases were measured and the related deployment moments. These are the results of measurements at fixed points and of mobile measurements during and after the tests. The FED overviews (threshold values for possibility of escape and survivability) from Appendix 21 and the results from chapter 4 are used as well.

Based on the data, the following can be derived from the CO measurements on the other floors:

> The propagation of CO to the other floors is unpredictable. Similar tests (the same method or the same position of the door to the fire room) did not always measure CO in the same locations, let alone that any concentrations measured were similar.

> CO propagated in all combinations of method and doors being open / closed and in all degrees of intensity (from harmless to serious and to involving serious health risks).

> Vertical CO propagation was often very local and, as described in chapter 3, this went through ventilation ducts and openings and via wall sockets, to name just a few paths. Local here means in a specific location in a room, without a similar concentration being measured in the neighbouring rooms. An example of this is when CO was measured in the left-hand section of corridor 3.2, but no CO was measured 10 metres further down the corridor. CO was also found to easily accumulate in small rooms, such as bathrooms.

> The tests where the door to the fire room was closed showed the least propagation of CO to other floors during the deployment phase, but, nevertheless, some CO still propagated.

> The tests with the door to the fire room open often showed a CO concentration in different rooms on the other floors for a longer time than the tests with the door closed.
> No difference could be identified between an offensive and a defensive method with regard to the propagation of CO to other floors. Both methods sometimes led to CO propagating to other floors; however, it also happened that neither method caused CO to propagate to the other floors.
> Where CO did propagate to the other floors, the values measured at the fixed measurement points during all the tests that were conducted were between 10 and 300 ppm of CO. Mobile measurements showed locally higher values up to a maximum of 500 ppm of CO (see Appendix 30).
> There were five tests where there was no vertical propagation of CO, even in the deployment phase; the other fourteen tests did show vertical propagation. All of these five tests were tests where the door to the fire room was closed. There is no unambiguous explanation as to why there was no vertical smoke propagation in these five cases and why smoke did propagate vertically in the other fourteen tests, even though the test design had not been changed.
> As stated in chapter 3, CO was measured in some cases where no smoke was visible. This occurred specifically during the deployment phase. Of course, it is known that CO is a colourless and odourless gas, but until now the assumption has always been that smoke propagation is visible.

The results of this assessment are summarised in table 6.14.

Table 6.14 Influence of actions as part of the deployment on the propagation of CO to the ground floor, the second floor, and the third floor

No.	Variant name	Test no.	Method	Increase due to extinguishing actions	Increase due to evacuation actions	Increase due to natural ventilation	Increase due to mechanical ventilation	Decrease due to mechanical ventilation
0	Door open	1	None					
		3	Defensive		X		X	X
		5	Offensive				X	
		17	None					X
1	Door closed	2	Offensive				X	
		4	Defensive				X	
		16	Offensive					X

2	Mobile water mist and door open	7	Defensive	X			X	
		9	Offensive	X		X	X	
3	Mobile water mist and door closed	6	Offensive				X	
		8	Defensive					
4	Mobile water mist, smoke resistant partition, and door closed	10	Offensive					
		11	Defensive				X	
5	Smoke resistant partition and door closed	12	Offensive	X			X	
		13	Defensive			X		
6	Organic fire load and door open	15	Defensive					
7	Organic fire load and door closed	14	Offensive			X	X	
8	Balcony door open and door open (maximum ventilation)	18	Offensive				X	X
		19	Defensive					

Smoke propagating to the other corridor sections on the first floor

Mobile measurements were conducted to examine the moments when, and the extent to which, CO was propagated to the escape routes leading from the first floor. They are the main staircase adjoining corridor 1.1 on the left, and corridor 1.4 and the other corridor sections towards the secondary staircase on the right, which adjoin corridor 1.3. Corridor 1.4 is also the side that the fire service used as its deployment route (see figure 6.1 in section 6.2.1). Table 6.15 shows an overview of the maximum CO concentrations measured during the deployment phase.

Table 6.15 Maximum CO concentrations (ppm) during the deployment phase on escape routes[33]

No.	Variant name	Test no.	Method	Escape route on corridor 1.1 side	Escape route on corridor 1.3 side
0	Door open	1	None	135	170
		3	Defensive	290	1080
		5	Offensive	170	1620
		17	None		30
1	Door closed	2	Offensive	165	80
		4	Defensive		130
		16	Offensive		1180
2	Mobile water mist and door open	7	Defensive	20	455
		9	Offensive	250	920
3	Mobile water mist and door closed	6	Offensive		25
		8	Defensive		
4	Mobile water mist, smoke resistant partition, and door closed	10	Offensive		
		11	Defensive		
5	Smoke resistant partition and door closed	12	Offensive	130	1010
		13	Defensive		
6	Organic fire load and door open	15	Defensive		115
7	Organic fire load and door closed	14	Offensive		40
8	Balcony door open and door open (maximum ventilation)	18	Offensive		365
		19	Defensive		

[33] If a cell does not show any measurement reading, no CO was measured in this escape route.

Table 6.15 shows that CO was measured in many tests on the side where the deployment crew entered the corridor (corridor 1.3 side). CO was measured in 7 of the 19 tests in the escape route on the lift side (corridor 1.1 side). The values vary widely. The moments when smoke propagated in the direction of the escape routes were the same moments when vertical propagation occurred, i.e. during the mechanical ventilation as part of the fire extinguishing actions.

Mechanical ventilation
The mechanical ventilation influenced the propagation of asphyxiant gases in the residences along corridor 1.2 and the corridor sections adjoining corridor 1.2. Depending on the amount of smoke present, switching on the fan led to an increase in CO in residences and corridor sections on the first floor. Here, a closed door was found to be insufficiently effective to stop or reduce the propagation of gases to these rooms.[34] The increase in CO differed from test to test, but varied from an increase by 100 to 12,000 ppm for residences 1.20 and 1.24 leading to values of between 50 and 2,000 ppm for corridors 1.1 and 1.3. The differences in the increases in concentration are mainly due to the amount of smoke present and thus the amount of smoke that can be propagated by ventilating mechanically.

In most cases, starting natural and mechanical ventilation improved the conditions in the fire room and corridor 1.2. The situation in corridor sections 1.1 and 1.3, adjoining corridor 1.2, often continued to deteriorate or remained unchanged. Both in the event of an offensive and a defensive attack, mechanical ventilation had a major influence on improving or deteriorating conditions in residences and corridor sections. The start of mechanical ventilation caused the smoke gases to propagate further in many cases. Mechanical ventilation always led to an improvement in the fire room and corridor 1.2, but it actually deteriorated conditions in corridors 1.1 and 1.3.

Another result is that mechanical ventilation led to local pressure differences in corridor 1.2 (see Appendix 16). These pressure differences varied between 2 and 10 Pa between the two measuring points on the left and the right in the corridor. The pressure difference was the greatest when using fire room 1.19. This was caused because a larger dead space was created in corridor 1.2 while using fire room 1.19. This is explained in further detail in the analysis in section 6.7.3.

A second fan was installed at the end of the test. This blew from corridor 1.1 towards corridor 1.2 in order to remove any residual concentrations of gases from the building. Noteworthy here was that several tests did not show any smoke on camera images in corridor 1.2. At the moment when the fan was turned on, several strong increases in CO were measured in corridor 1.1 with values between 200 and 1,300 ppm. Since corridor 1.1 directly adjoined the staircase, this may have impaired the possibility of escape through this escape route. Since the staircase was not a fixed measurement point in the tests, this cannot be established with definite certainty.

Other effects
Besides the direct influence of the deployment, there was a blind spot effect in residence 1.25. There were many tests where the CO and nitrogen oxide concentrations in residence 1.25 were higher than in corridor 1.2 or in other residences / corridor sections. In addition,

[34] The smoke propagation routes can be found in chapter 3.

these gas concentrations remained in residence 1.25 longer than in corridor 1.2. This effect was the strongest in tests where the door to the fire room was open.

6.7.2 Analysis of the fire service actions

The main findings from the above sections are discussed below.

Action = reaction

Any action performed by the fire service led to a smoke propagation reaction. Any element of the deployment can thus affect the degree of smoke propagation in the entire building. This can be either positive (the situation improves in terms of visibility distance, gas concentrations, etc) or negative (the visibility distance deteriorates, smoke propagates to other residences / corridor sections, gas concentrations increase).

Elements of the deployment that had consequences for smoke propagation were:

> Walking in a smoke-filled corridor (1.2): extra smoke propagated to the residences on corridor 1.2.

> Opening the door to the fire room: strong smoke propagation to corridor 1.2 and other corridor sections.

> Closing the door to the fire room: reduced smoke propagation to corridor 1.2, but extra smoke propagation to the neighbouring residence.

> The extinguishing action: brief smoke propagation to corridor 1.2 and extra smoke propagation to other floors.

> Evacuation: extra smoke propagation to the residences to be evacuated because of the doors being opened.

> Natural ventilation: possibly extra smoke propagation in connection with wind pressure on the outer wall and extra smoke propagation to other floors.

> Mechanical ventilation: extra smoke propagation to residences along corridor 1.2, to corridor sections adjoining corridor 1.2 and to other floors.

Smoke already produced

The fire service's influence on smoke propagation (and thus on conditions in the residences and corridor sections) is greatly influenced by the amount of smoke which was produced initially, i.e. prior to the start of the deployment. In addition, initial smoke production was also found to be a determining factor for the extent to which the deployment influences the possibility of escape and survivability. A closed door to the fire room has a strong influence on the degree of smoke production and smoke propagation. A limited influx of oxygen to the fire decreases heat production and thus the amount of cooling required to extinguish the fire. A measure for risk management ensures that less smoke propagates to the corridor, and thus that the amount of toxic gases which may be 'forced' to other rooms or floors by the mechanical ventilation decreases.

Therefore, managing the amount of smoke produced by closing doors in combination with other measures for risk management can be taken to also have a positive effect on the degree of smoke propagation caused by the fire service. Simply put: the less smoke there is in a room, the less smoke the fire service can dislocate and propagate during the deployment. However, the deployment will have to attempt to maintain these measures for risk management as much as possible, including closing the door to the fire room or keeping it closed as much as possible.

6.7.3 Analysis of the influence of ventilation

As the results show that ventilation, including mechanical ventilation, has a great influence on smoke propagation in the building, the consequences of ventilating are discussed separately below.

Mechanical ventilation

In this research, mechanical ventilation was responsible for further smoke propagation in almost all cases. As soon as the fan was switched on, visible smoke and CO increased in the corridors, other residences and on the other floors. Mechanical ventilation is the fire service action that is the most likely to cause smoke propagation, both in a horizontal and a vertical direction. It should be noted here that the greater the distance from the fan, the less smoke propagation will be caused by the fan.

Flow profile and dead spaces

Ventilation, and specifically mechanical ventilation, is, in practice, not an easy job for fire service personnel as many different factors can be involved. An effective flow profile is important here. This is achieved by creating the proper ratio of inflow and outflow openings, maintaining the shortest possible distance between these openings and providing sufficient thrust and minimising the number of ‘dead spaces’.

The results show that mechanically ventilating this residential building with internal corridors is complex. The distance between the inflow and outflow openings is relatively long, the outflow opening is relatively small, the fan is not really in the ideal location, and there are dead spaces along the path. The dead spaces are shown in figure 6.7; as the results show, the pressure while ventilating is higher in the dead space (orange) than in the flow profile. This is caused by the fact that the dead space must be filled first, before the fire room can be filled. This can be compared to communicating vessels as shown in figure 6.6: vessel 1 cannot be filled until vessels 2, 3 and 4 have been filled.

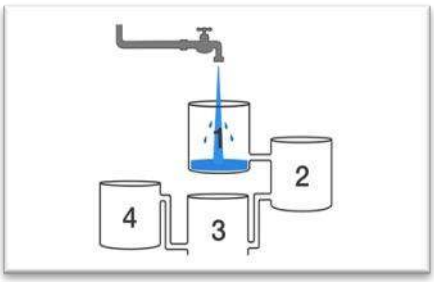

Figure 6.6 Communicating vessels

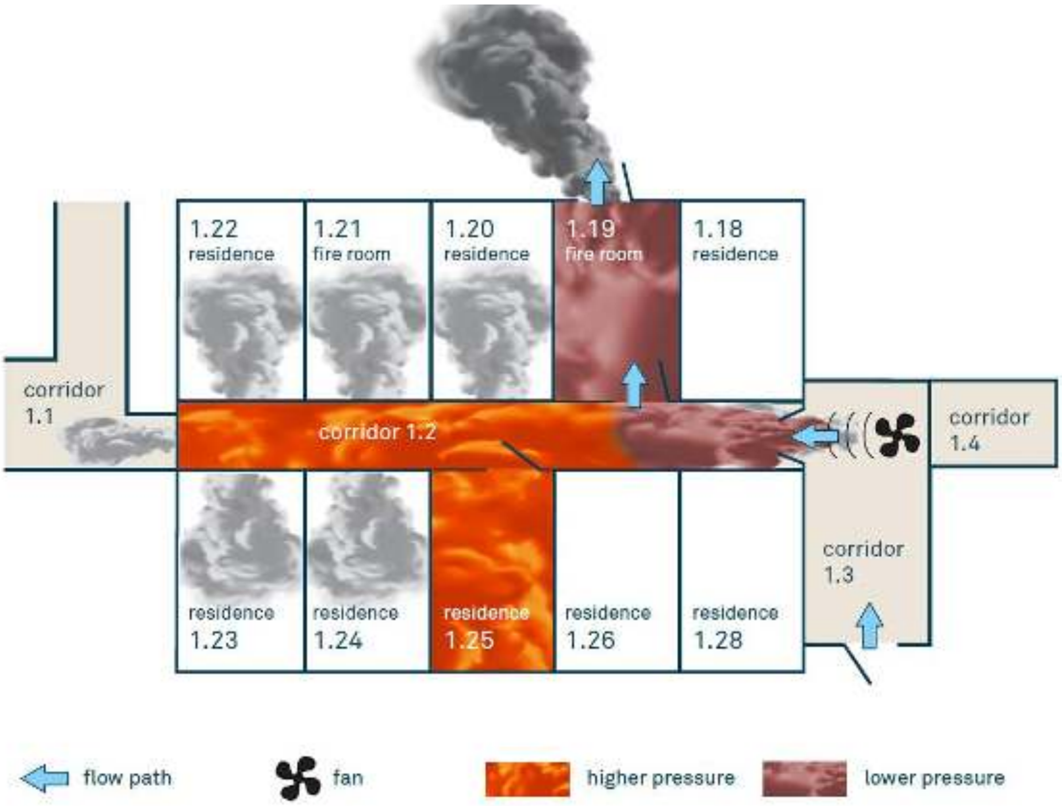

Figure 6.7 Pressure build-up during mechanical ventilation

The increased pressure in the dead space causes smoke to propagate to the residences and corridor sections adjoining the dead space. Furthermore, the excess pressure built up by the fan will cause smoke to propagate to the section of the corridor with the fan and the adjoining corridor section. This is illustrated in figure 6.8. Here, a sub-optimum flow profile will cause extra pollution of the deployment path and of one of the escape routes.

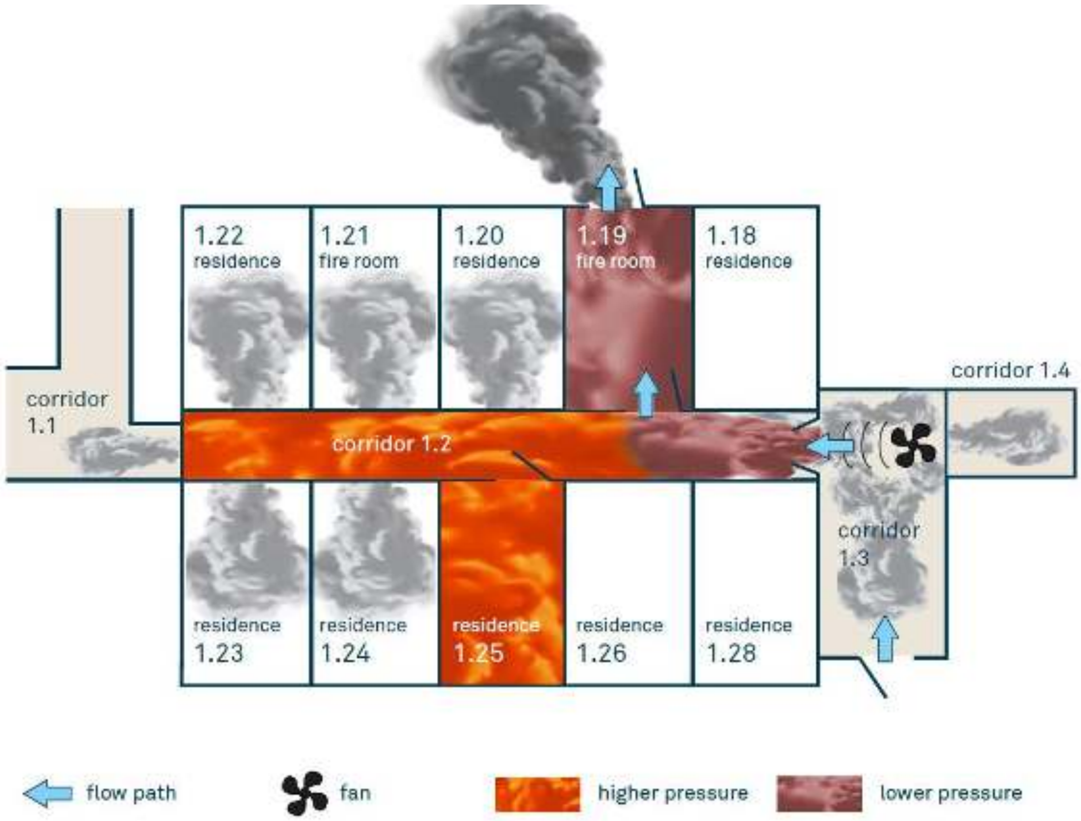

Figure 6.8 Pressure excess during mechanical ventilation

The hypothesis with respect to flow profiles and dead spaces in the event of mechanical ventilation is: the longer the distance between the inflow and outflow openings and the greater the dead spaces, the more mixing will take place, the greater the smoke volume will be, and the more difficult it will be to forecast the effect of mechanical ventilation.

Human error

Several mistakes were accidentally made by the deployment crew while ventilating during tests. Examples are opening windows too fast or too slowly, starting the fan while the flow profile was not yet ready or letting a door blow shut. The analysis of the results was either corrected for these errors, or the effects of these errors were taken into account.

These human errors led to a sharp increase in gas concentrations and a decrease in the visibility distance in corridors 1.3 and 1.4. This also happens in practice: errors are also possible when mechanically ventilating as part of a deployment. Ventilating during or after deployment is found to be a high-precision job for which there is often too little time, or for which too little time is taken, during the repressive reality. The amount of time taken to prepare and implement mechanical ventilation does not match this technique's impact on smoke propagation.

Second fan

Installing and switching on a second fan was responsible for a sharp increase in gas concentrations in corridors adjoining corridor 1.2 in some tests, even though no smoke was visible in the corridor that was to be ventilated. This means that ventilating rooms that are free of smoke can also influence smoke propagation.

6.7.4 Analysis of the influence of the deployment on evacuation routes

Although the effect of evacuation was only tested to a limited extent, the results allow a judgement to be made about the optimum evacuation routes in terms of the (further) smoke propagation and the impact on the possibility of escape and survivability. It is clear that the conditions in corridor 1.2 did not allow the safe evacuation of (unprotected) people. A difference was also noticed between the extent to which smoke propagated to corridor sections behind fully or partly opened partitions (due to the deployment) on the side where the deployment crew entered the corridor, and to corridor sections behind closed partitions on the side of corridor 1.1. In many tests, the evacuation route via the deployment route of the fire service (side of corridor 1.3) was threatened by high CO concentrations, but the staircase on the side of corridor 1.1 sometimes also contained concentrations of hundreds of ppm of CO.

Since every partition that is opened causes additional smoke propagation to an, until then, relatively smoke-free part of the building, it is important that partitions are kept closed as much as possible in order to prevent any further propagation (minimising the pollution of 'clean' areas). Horizontally evacuating people from residences near the fire room will therefore have to take place via the deployment route of the fire service in order to thus prevent smoke propagation to the staircase on the corridor 1.1 side. Evacuating along a smoke-filled corridor is not preferred. Horizontal evacuation is only possible if the escape routes are safe with regard to gas concentrations. Using escape masks would be an alternative.

It should be noted that establishing evacuation routes, and thus separating the fire service's deployment route and the route taken by people who attempt to escape, is an important task which sets high requirements on the mental abilities of the commanding officers present.

Further research would be needed to establish whether vertical evacuation via the balconies is a safer option. Research into people being rescued from residential fires (Fire Service Academy, 2020b) showed that smoke can also be very dense on balconies. Actually, vertical evacuation via the balcony is not always feasible as it is only possible if rescue vehicles can be parked close to and on the side of a balcony, and that possibility is often not available. Furthermore, the height of the building also plays a role: hand ladders are actually only effective to the height of the second floor and rescue vehicles do not reach higher than 30 metres.

6.8 Other results

Besides the sections discussed, there are other results that are relevant when answering the research questions or translating them into (fire service) practice. They are listed in this section.

6.8.1 Post assessment

When the test had ended and after ventilating, the safety crew conducted measurements to determine whether the building could be entered safely again. These measurements showed that CO was still present in highly diverse locations at several times in spite of the prolonged natural and mechanical ventilation. Examples are bathrooms on all floors, rooms with open windows on the ground floor, corridors in more remote parts of the building and the control room. Although these measurements were not part of the test, they can be considered as results that firstly show the unpredictability of smoke propagation: it has been found to be impossible to predict where the smoke will propagate to. Secondly, this shows that expelling (invisible) fire gases calls for a very thorough assessment of the building.

6.8.2 Visible smoke ≠ carbon monoxide

To establish the possibility of escape and survivability and to prioritise evacuation, residences and corridors have to be assessed. As part of this assessment, it is established visually where the visible smoke has propagated to. However, the results show that there can be a CO concentration in a room even though there is no visible smoke. This is in line with the theory: after all, CO is an invisible gas. This means that a visual assessment is not sufficient to establish smoke propagation; this will have to be supported by measurements.

6.8.3 Local differences

It has been found that smoke propagation can be very local. It can be concluded here that the further away from the fire room, the more erratic and localised the smoke propagation will be. Smoke can propagate for both short and long periods of time. Examples are:

- A substantial difference in gas concentrations on the left and the right of the corridor directly adjoining the fire room.
- A short-lived CO concentration on the ground floor of less than one minute.
- A corridor on the third floor where nothing was measured on the left and where a CO concentration (>200 ppm) was measured for a long time on the right.
- A bathroom with a relevant CO concentration (>100 ppm), while no CO was measured in the living room.

Since it is difficult to predict where these effects will occur and since CO is invisible, a broad assessment in all the rooms of the building, including measuring for CO, will have to be opted for. Only thus can it be established how far the smoke has propagated and based on this it can be decided which areas to evacuate. The conclusion is that the fire service will not only have to conduct an assessment and measurements everywhere in the building section, but also that measurements should also be conducted at multiple locations in a room or corridor in order to identify any local differences.

6.9 Summary

Smoke propagation outside the fire room is the norm and is no exception. The conditions in the escape routes on the first floor (fire floor) were threatened even before the deployment started. This often make escaping without help (unprotected) no longer possible. Circumstances in several residences were already life-threatening or fatal at the start of the deployment, or they became life-threatening or fatal during the deployment. A deployment is necessary for the safety of the people in the part of the residential building threatened by smoke propagation.

The overarching goal of the deployment should be to maximise people's possibility of escape and survivability. This goal can be achieved by evacuating people, fighting fire and reducing further smoke propagation as much as possible.

The position of the door to the fire room is decisive for the choice of deployment method. Where the door to the fire room is open when the fire service arrives, prioritising extinguishing was found to have the best effect on the possibility of escape and survivability. However, if the door to the fire room is closed at the moment when the fire service arrives, prioritising rescuing is the best option.

It is important the fire service realises that all their actions cause smoke propagation to a certain extent, both horizontally and vertically. Walking in smoke-filled corridors, opening and closing doors and fire extinguishing activities are all actions that cause a certain amount of smoke to propagate to adjacent rooms. Mechanical ventilation is dominant in this respect; it is responsible for the further smoke propagation, and particularly of CO, in almost all cases.

Additional measures for risk management combined with the door to the fire room being closed reduces the smoke propagation through the building during the escape phase and reduces the influence of the fire service actions on smoke propagation during the deployment phase. However, such measures also lead to heat and smoke not being visible at all or hardly being visible during an exterior size-up.

A major challenge for the fire brigade is to determine which part of the residential building should be evacuated and which routes should be used for this evacuation. Smoke propagation is quite unpredictable, the more so the further a room is located away from the source. Furthermore, the absence of visible smoke does not mean that there is no possibility of asphyxiant gases being present. An extensive assessment of, and extensively measuring in, the building is the only way to establish which residences, corridors and escape routes are safe. Evacuating floors or parts of the building seems to be the obvious choice here, although this can also cause further smoke propagation.


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7 Generalisability

7.1 Introduction

Previous chapters have presented the results of the field research into smoke propagation as conducted at the specific test location. This research seeks to broadly map the effect of smoke propagation in relation to measures for risk management and methods of firefighting on the possibility of escape and survivability in the event of fire in a residential building with internal corridors. This is why it is important to pay attention to the generalisability – also referred to as the external validity – of the research. Therefore, this chapter discusses the degree to which the results can be generalised.

Section 2.6.3 already indicated that the external validity of the research consisted of:
> Ecological validity: the extent to which the research results correspond to the real-life situation.
> Generalisability of the sample: is the sample representative for the population?
> Validity of meaning: the degree to which a concept measures what should be understood by that concept / what the meaning of the concept is (exclusivity of meaning). This part of the external validity has been discussed in section 2.6.3 and chapters 3, 4 and 5. Based on this, it can be assessed that the validity of meaning of this research is high.

Based on the ecological validity, the generalisability of the sample and the validity of meaning, the generalisability is eventually determined.

7.2 Generalisability of the sample

At first glance, important limitations with regard to the generalisability of the sample can be identified: the field research was conducted in only one building with one fixed scenario and fire object, whereas in real life there are many different versions of residential buildings with internal corridors, the fuel is diverse, and the number of potential fire scenarios is almost infinite. At the same time, it can be stated that the test location in Oudewater has a specific shape and layout, this is quite a common building type in the Netherlands and, also based on the results, there is no reason to assume that, for example, a slightly broader corridor would lead to a fundamentally different result.

For the sake of comparability and reliability of the research, only one scenario was tested, but there is no reason to assume that this scenario is not realistic or that it fundamentally misrepresents the real-life situation. Furthermore, because every fire involves a different scenario due to the prevailing conditions, the question may be asked whether, for example, doubling or tripling the number of scenarios as part of the research relative to the total number of potential scenarios would lead to a fundamental increase in generalisability. The answer to that question will most likely be ‘no’.

Finally, the conclusion is justified that the generalisability of the choice of fuel is substantial: choosing a sofa and organic fuel created a full picture of the spread of the effect of smoke propagation when burning a material that produces a lot of smoke relative to the effect when burning a material that produces little smoke. Furthermore, section 1.5.1 already stated that sofas or mattresses are involved in 25% of all fatal residential fires.

7.3 Ecological validity

The *Trends om van te leren* report (Fire Service Academy & Organisation of Dutch Fire Services, 2017, p. 8) stated that “the main finding is that smoke propagation is much more extensive than current knowledge and experience would lead us to expect. The training courses and exercises also mainly focus on the fire and fire growth; much less attention is paid to smoke and smoke propagation. The case studies have proved this to be wrong. The smoke can propagate via ducts, lift and other shafts, and ventilation systems, as well as via (inadequate) structural fire prevention facilities and by a deployment.”

The conclusion stated in *Branden in seniorencomplexen: regelgeving en praktijk* (Fire Service Academy, 2016a, p. 17) with regard to the basic assumption (from the building regulations) that 'the smoke stays within the apartment for at least 30 minutes’ was: “This basic assumption is disproved much more often (than the previous basic assumption concerning fire growth). Even if the fire stays within the confines of the fire compartment (and/or the apartment), this does not mean that the smoke will behave likewise. The smoke can propagate through a major part of the senior citizens’ housing and even enter other apartments, without the fire growing further.”

The field research in Oudewater was designed on the basis of this prior research into real-life incidents, laying a basis for the ecological validity. To determine the extent to which this approach was successful, this section compares recent real-life examples of smoke propagation to the research results. This enables an examination of whether, and to what extent, findings in the research setting differ from the real-life situation. Since *Trends om van te leren* and *Branden in seniorencomplexen* already concluded that smoke propagation is a common phenomenon, this does not need to be demonstrated again. However, comparing how smoke propagates is relevant here. To do so, five recent fires were selected. All of them involved a fire in a residential building with internal corridors where smoke propagated. Not all these fires started in a residence. However, this only has limited relevance since smoke did propagate into the building and it was examined how the smoke propagated and to what extent this matches the findings of the field research.

Since no, or hardly any, measurements are conducted during an actual fire, this can only be a qualitative comparison, both of the individual incidents and against the results of this field research. TBO[35] reports and evaluation reports of the fire services involved were used for this comparison. It should be noted here that only TBO and evaluation reports were used of those incidents where smoke actually propagated. It cannot be ruled out that incidents also occurred where smoke propagation was relatively limited and where no TBO or incident reports were prepared. The findings of this qualitative comparison are presented below in table 7.1.

[35] Team Brandonderzoek (Fire Research Team).

Table 7.1 Real-life incidents where smoke propagated

	Harm Smeengekade (Zwolle, 2020)[36]	Grote Beer (Rotterdam, 2020)[37]	Söderblomflat (Rotterdam, 2017)[38]	Wittebrug (Poeldijk, 2018)[39]	Heycop (Breukelen, 2018)[40]
Type of building	Senior citizens' block of flats	Residential building	Residential building	Residential building	Residential building
Number of storeys	8	5	20	5	6
Occupants	Vulnerable to highly vulnerable	General and vulnerable	General and vulnerable	Vulnerable	Vulnerable to highly vulnerable
Location of the fire	First-floor balcony, the fire entered the building	5th (top) floor apartment	7th floor residence	Bicycle storage	Started on the first-floor balcony, the fire entered the building
Final extent of the fire	2 residences involved in the fire	1 residence	1 residence	1 scooter and some boxes of paper for recycling	1 residence
Front door to the fire room	Closed	Open	Open	Open	Open
Smoke in the escape route near the fire room	Yes	Yes	Yes	Yes	Yes
Smoke in residences on the fire floor	?	Yes	Yes	Yes	Limited
Smoke in escape routes on other floors	Yes	No	Yes	Yes	Yes
Smoke in residences on other floors	?	No	Yes	Yes	No
Smoke partitions	Failed to work or left open	Partly left open	No smoke in the escape staircase	Broken through while escaping	Regularly open while evacuating

[36] Based on 'infosheet brandonderzoek' IJsselland safety region.
[37] Based on 'Grootschalige ontruiming na kleine brand', Rotterdam-Rijnmond safety region.
[38] Based on Brand Söderblomresidence Rotterdam research report, Rotterdam-Rijnmond safety region.
[39] Based on Wittebrug fire research report, Haaglanden safety region.
[40] Based on 'Brand woongebouw 't Heycop Breukelen', Utrecht safety region.

Smoke propagation via ventilation	Yes	?	Yes	Yes	Limited
Smoke propagation via gaps/seams	Yes	Yes	Yes	Yes	Limited
Deployment	Transitional attack	Offensive interior attack	Offensive interior attack	Offensive interior attack	Offensive interior attack
Size of the deployment	12 fire appliances	8 fire appliances	12 fire appliances	4 fire appliances	13 fire appliances
Rescue/ evacuation	Via internal escape routes	Via the balcony	Via internal escape routes + escape balconies	Via internal escape routes	Via internal escape routes
Deployment contributed to smoke propagation	Yes	Yes	Yes	Yes	Yes
Specific detail		Complex building (split-level structures)	Hoarding caused extra and long-lasting smoke		
This scenario is most similar to:	Maximum ventilation, offensive interior	Door open, offensive interior	Door open, offensive interior	Door open, offensive interior	Maximum ventilation, offensive interior

Comparing table 7.1 with the results of the chapters 3, 4 and 5 shows that the smoke propagation in the five real-life incidents selected largely matches the manner of smoke propagation as identified during the field research in Oudewater.

> In practice, all incidents involve both horizontal and vertical smoke propagation.

> The door (open / closed) has been found to also be a dominant factor for smoke propagation in actual fires, particularly on the floor with the fire room. It is not uncommon for the (front) door to the fire room to be left open in practice when people escape from the room.

> However, in those situations where the front door to the fire room was / remained closed, smoke still propagated through seams, gaps and ventilation systems.

> People in other residences were trapped due to the smoke propagation and smoke entered some of those residences.

> Upon its arrival, the fire service was confronted by advanced smoke propagation and was forced to deploy a large number of units to evacuate the building.

> The deployment caused further smoke propagation in certain locations in these five incidents, because smoke partitions had to be opened for evacuation purposes or to create a deployment route to the fire.

There were also differences between the experiments and the five real-life experiments.

- Several incidents involved a fire which entered the building from the outside. This scenario was not tested. However, the question is to what extent this influenced the smoke propagation in the building.
- Large open pipe or lift shafts played a role in some incidents. There were no such shafts in the part of the building that was used for the research.
- Often, the fire load is much more than one sofa. When combined with circumstances that supply extra oxygen to the fire and where the building is exposed to wind, more smoke will propagate for a longer time, even more than in the scenario of variant 8 (balcony door and door open, maximum ventilation) that was tested.
- There were several incidents where it took a long time until the deployment could start, because people in the building used the deployment route to escape or had to be assisted. This means that, in some cases, the deployment phase started later than the 20 minutes assumed for the field research.

The extent to which these differences affected the smoke propagation patterns and scope cannot be established retrospectively. In any case, practice has shown that the scenarios chosen for the field research are definitely not too positive or optimistic.

Establishing the effects of smoke propagation retrospectively in terms of the possibility of escape and survivability can only be done indirectly: since no measurements were conducted, it is not possible to make any calculations of, for example, the dose rate (of CO and other substances). However, records were kept of many incidents showing that people with inhalation trauma had to be taken to hospital and /or had to escape through the smoke. This merits the assumption that, as a minimum, these five fires also involved an impaired escape situation.

7.4 Conclusion

It was concluded that the generalisability of the sample is not high, but that the ecological validity and the validity of meaning of the research are high. Therefore, there is no reason to assume that the findings cannot be generalised sufficiently to other residential buildings with internal corridors. However, it should be noted that real-life incidents have shown that local circumstances can cause unique smoke propagation patterns.

Although the results of this research provide general information about which measures have the most or least influence on the smoke propagation, they cannot simply be generalised to other building types. The only exception to this is likely to be deck access flats with enclosed walkways. Elements from the research can be used in order to answer questions about fire safety in other types of buildings, such as Dutch *portiekflat*[41] buildings (low rise blocks of flats with communal access). This may include aspects as the effect of open or closed doors, the routes along which smoke propagates, and the effects of measures for risk management.

[41] Residences that can be reached directly from the staircase.

8 Conclusion

Based on the previous chapters, this chapter answers the sub-questions that were key to this research. Each sub-question is answered in a separate subsection. The main question is answered in the last section of this chapter.

8.1 Answers to the sub-questions

8.1.1 How can the possibility of escape and survivability be defined?

The prevention of fire casualties is determined by the possibility for those people present to escape safely or to survive the fire until they are rescued. This is because, in a fire situation, it is important that the available safe escape time (ASET) is longer than the required safe escape time (RSET) (Instituut Fysieke Veiligheid, 2017). The conditions to which people are exposed in the rooms in question, and their vulnerability for those conditions, are decisive for the available safe escape and survival time.

The conditions that influence the occupants' possibility of escape and survivability in case of a fire are:
> irritant and asphyxiant gases;
> heat;
> visibility.

These fire conditions can lead to an impaired escape, a life-threatening situation, or even a fatal situation (see figure 8.1).

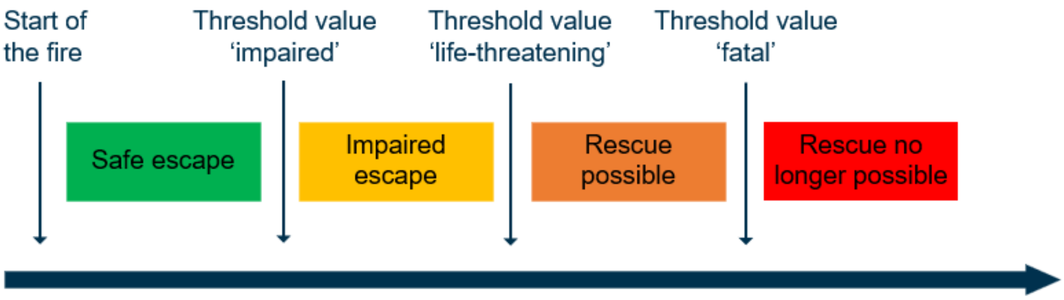

Figure 8.1 Diagram of the possibility of escape and survivability for occupants in the event of fire

The threshold values where one situation transitions into another can be established using different standards. The methods in these standards often concern the ratio between a concentration or a dose and the limit for that concentration or dose threatening the possibility of escape and survivability. The threshold values for different situations can distinguish between different groups (sub-populations), each of which has its own sensitivity factor (sf) for irritant and asphyxiant gases, for heat and for (impaired) visibility. The groups distinguished in this report are 'general', 'vulnerable and 'highly vulnerable'. The possibility of escape and survivability can be defined based on the situations from figure 8.1, the corresponding threshold values and the groups listed above. Table 8.1 shows the result. A further explanation can be found in sections 1.3.4, 1.3.5 and 2.5.2.

Table 8.1 Overview of threshold values according to SFPE

Fire condition	Method	Impaired			Life-threatening			Fatal		
		Highly vulnerable	Vulnerable	General	Highly vulnerable	Vulnerable	General	Highly vulnerable	Vulnerable	General
Irritant gases	FIC/FLD	0.1	0.3	1.0	0.5	1.5	5	0.1	0.3	1.0
Asphyxiant gases	FED_{IN}	-	-	-	0.1	0.3	1.0	0.2	0.6	2.0
Heat	FED_{heat}	0.1	0.3	1.0	0.8	2.4	8.0	1.2	3.6	12.0
Visibility	FEC_{smoke}	0.1	0.3	1.0	-	-	-	-	-	-

8.1.2 Based on simulations, what fire development and smoke propagation situations can be expected in the residential building?

Fire development based on the simulations
Based on the simulations, it is concluded that the simulation with the door open can be expected to lead to an almost fuel-controlled fire development. The simulation with the door closed is expected to give an oxygen-controlled fire development.

Smoke propagation based on the simulation with the door open
In the simulation with the door open, smoke propagated to all the rooms (projected in the simulation) on the first floor, except residence 1.24. Smoke propagation was also observed in the corridors on the other floors and the ground floor, the residences above or below the fire room and the residence which shares its ventilation duct with the corridor. In the simulation, the ventilation ducts played an important role in the smoke propagation through the building.

Smoke propagation based on the simulation with the door closed
The ventilation ducts played an important role in the smoke propagation through the building in this simulation as well. Opening the door from the fire room to corridor 1.2 for 30 seconds was decisive for the smoke propagation to corridor 1.2. On the other floors, the smoke did not propagate beyond the corridors and the residences above or below the fire room during the simulation with the door closed.

8.1.3 In the event of fire in the residential building, how does the smoke actually propagate in practice and what are the decisive factors for this propagation?

In all the tests, smoke propagated outside the fire room through several horizontal and vertical routes and sub-routes (see figure 8.2 and figure 8.3).

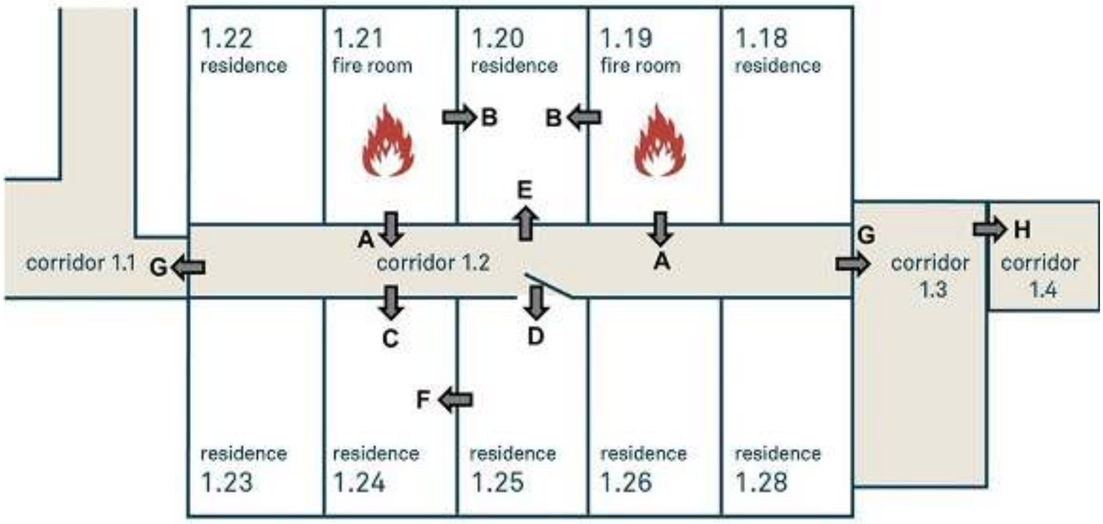

Figure 8.2 Horizontal smoke propagation routes on the first floor

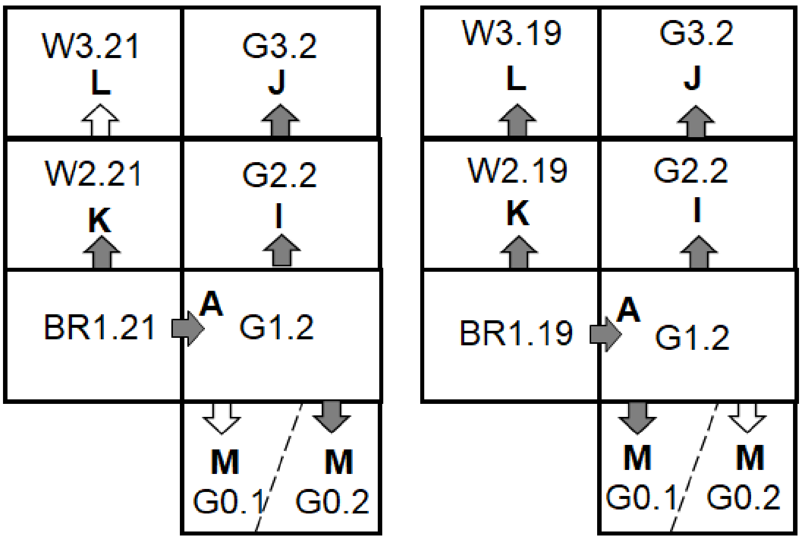

Figure 8.3 Vertical smoke propagation routes along several floors

This involved both horizontal and vertical smoke propagation to different rooms in the residential building. This means that if only part of a sofa was on fire in one room, high-risk situations still occurred in several locations in the residential building.

This research revealed more horizontal than vertical smoke propagation. Although smoke propagation was observed in many tests on other floors, the visually observed quantities and the gas concentrations measured on these floors were lower than on the fire floor. In addition, vertical smoke propagation was less consistent than horizontal smoke propagation and smoke propagation was more erratic during the deployment phase than during the escape phase. It seems that, in addition to the fire service deployment, more variables and factors influence smoke propagation.

In general, smoke mainly propagates via open doors, ventilation ducts and wall sockets. Horizontal smoke propagation is mainly via doors: the highest extent of smoke propagation is visible where doors are open or when doors are opened. Vertical smoke propagation is mainly via ventilation ducts and wall sockets.

Every opening between rooms causes smoke propagation, with large openings leading to faster smoke propagation and in larger quantities. Whether smoke propagates, and to which extent it propagates, is influenced by the factors below.

- The composition of the fire object: organic or synthetic fuel. Organic fuel leads to a lot less smoke being produced than synthetic fuel.
- Opening doors or keeping doors closed affects the propagation of large quantities of smoke. A closed door limits the smoke propagation.
- Other openings and penetrations in the partitioning structure have a more limited effect on smoke propagation. The smaller the opening or the penetration, the less smoke propagation is caused by it.
- The presence of a mobile water mist and/or smoke resistant partition reduces the smoke propagation.
- The specific location of the fire room influences vertical smoke propagation.
- The deployment influences the smoke propagation as doors are opened and fans are used.

Smoke consists of solids, liquids and gases. Often, they propagate together and there will be visible smoke (soot particles and liquid particles) and invisible fire gases in the same location. However, there are situations where gases and particles propagate differently and it was found that there was no or hardly any visible smoke in several rooms, while CO was measured in those rooms. The opposite was also observed in some locations: visible smoke, without CO being measured.

The conclusion is that smoke propagates rapidly through the residential building and that smoke propagation is a phenomenon that is impossible to predict, particularly at greater distances from the fire room. And the fact that not all smoke is visible adds to the difficulty of estimating the severity and extent of the propagation of the smoke.

8.1.4 What effect does the observed smoke propagation have on the possibility of escape and survivability in the residential building for people with different degrees of vulnerability?

A sofa on fire will lead to a fatal situation in the fire room within 4 to 7 minutes. Almost immediately after opening the door to the fire room (t = 5 minutes), a situation will be reached in the corridor next to the fire room which seriously impairs the possibilities for people in other residences to escape, since the corridor will fill with smoke within a matter of seconds, reducing visibility to very poor levels. The concentrations of asphyxiant and irritant gases measured in the corridor are so high that a life-threatening situation arises, in particular for vulnerable and highly vulnerable groups.

Once the door to the fire room has been opened, people in the other residences along the same corridor are then 'stuck' in their residences. The smoke can propagate to these other residences and to other corridors on the same floor from this corridor. Fatal situations, particularly for vulnerable and highly vulnerable groups, can occur in these residences (where there is no fire) due to smoke entering the residences. Smoke will mainly propagate to other corridors if the doors between these corridors are opened, even if only briefly, for example by people escaping the building or trying to look into the corridor to see what is going on. This may also impair the possibility of escape for people in other residences elsewhere in the building.

Smoke also propagates to the other floors. Although, according to the analysis method used, this smoke propagation does not impair the possibility of escape, increased CO concentrations were measured on these floors.

8.1.5 In the event of fire, to what extent are existing and future smoke resistant partitions, a mobile water mist system, and furniture made of organic material effective in improving the possibility of escape and survivability in the residential building for people with different degrees of vulnerability?

Opting for furnishing made of organic material instead of synthetic material (a foam-filled sofa) has been found to be the most effective measure to reduce smoke production, and thus smoke propagation. This makes this measure the most effective in improving the possibility of escape and survivability for all groups in all rooms. Nevertheless, if furnishing made of organic material catches fire, and the door to the fire room is open, the possibilities for all groups to escape through the corridor will also be impaired after some time (6 to 14 minutes).

A mobile water mist system is also an effective measure of improving the possibility of escape and survivability. If the door to the fire room is left open after people have escaped from the room, the improvement created by a mobile water mist system compared to a situation without a mobile water mist system will be greater for the general group than for the vulnerable or highly vulnerable groups. Closing the door after escaping the fire room improves the situation for all groups.

Closing the door to the fire room after escaping as an (individual) measure does not improve, or hardly improves, the possibility of escape. The possibility of escape is reduced for all groups in the corridor once the door has been opened. However, this measure does improve survivability in the other residences that do not adjoin the fire room and where the doors are closed. There is a survivable situation for all groups in the residences that do not adjoin the fire room for the first 20 minutes. This is not the case in residences adjoining the fire room or residences whose doors are open.

Applying a specific smoke resistant partition does not improve, or hardly improves, the possibility of escape or survivability compared to the situation where the door is kept closed. While escaping, opening the door to the fire room for 30 seconds is a decisive factor for the worsening of conditions in the corridor and the adjacent residences. A smoke resistant partition as a measure to prevent smoke propagation is more effective if the doors remain closed during the entire fire situation. A further point of consideration is that the pressure in the fire room can increase substantially, both before the door is opened (up to more than 300 Pascal) and after it is closed (up to more than 1000 Pascal). This can lead to smoke propagating via other routes.

None of the (additional) measures for risk management tested was found to be autonomously able to sufficiently improve the possibility of escape and survivability for all groups in all situations. Individual measures were often found to mainly achieve an improvement for the general group, whereas little or no improvement was found for vulnerable and highly vulnerable groups.

Additional to examining individual measures, the degree to which combinations of measures improve the possibility of escape and survivability was also examined. They are listed below, with the most effective combination listed at the top.

1) Furnishing made of organic material combined with a closed door.
2) A mobile water mist combined with a closed door or a mobile water mist in combination with a smoke resistant partition and a closed door.
3) A closed door combined with a smoke resistant partition.

The conclusion is that a combination of a source and effect measure is sufficiently effective to improve the possibility of escape and survivability for all groups (options 1 and 2 from the list above). An individual effect measure or a combination of effect measures does not suffice to improve the possibility of escape and survivability for vulnerable and highly vulnerable groups.

8.1.6 In the event of fire in the residential building, which deployment method gives the best possibility of escape and survivability?

Even before the deployment starts, the possibility of escape has often already been reduced on the first floor, due to which many occupants are no longer able to escape without help. Life-threatening conditions will also have arisen in several residences. A deployment (rescuing and extinguishing) was necessary for the safety of all people in the residential building.

Since smoke had already propagated outside the fire room in all tests before the deployment started, these circumstances should be assumed to be the basic situation in order for the fire service to decide how to attack. However, the scope and severity of smoke propagation are difficult to determine due to the complexity of the building and the unpredictable smoke propagation situation. This is made all the more difficult by the fact that the absence of visible smoke does not mean that there is no unsafe situation for the people present. An extensive assessment of, and measuring in, the residential building is the only way to establish which residences, corridors and escape routes are safe.

Besides fighting the fire, the goal of the fire service deployment should also be to reduce any further smoke propagation as much as possible. The situation of the door to the fire room, i.e. open or closed, at the moment when the fire service arrives is decisive for determining which deployment method should be used to achieve these objectives. Where the door to the fire room was open when the fire service arrives, extinguishing the fire before rescuing was found to have the best effect on the possibility of escape and survivability. However, where the door to the fire room was closed, rescuing before extinguishing the fire was found to be the most beneficial to the possibility of escape and survivability.

However, every fire service action will cause more smoke propagation, both horizontally and vertically. Walking through smoke-filled corridors, opening and closing doors, and fire extinguishing activities are all actions that lead to a certain amount of smoke to propagate to adjacent rooms. Mechanical ventilation has a dominant influence. In nearly all cases it is responsible for the (further) smoke propagation, and particularly CO, to multiple rooms and floors.

Measures for risk management combined with the door to the fire room being closed reduces the smoke propagation through the building during the escape phase and reduces any smoke propagation due to the fire service actions during the deployment phase.

8.1.7 To what extent can the results be generalised to cover residential buildings with internal corridors?

In this research, it was concluded that the generalisability of the sample is not high, but that the ecological validity and the validity of meaning of the research are high. Therefore, there is no reason to assume that the findings cannot be generalised sufficiently to other residential buildings with internal corridors. However, it should be noted that real-life incidents have shown that local circumstances can cause different smoke propagation patterns.

Although the results of this research provide general information about which measures have the most or least influence on the smoke propagation, they cannot simply be generalised to other building types. The only exception to this is likely to be deck access flats with enclosed walkways. Several elements from the research can be used in order to answer questions about fire safety in other types of buildings, such as Dutch *portiekflat* buildings (low rise blocks of flats with communal access). This may include aspects as the effect of open or closed doors, the routes along which smoke propagates, and the effect of measures for risk management.

8.2 Answering the main question

What is the effect of smoke propagation on the possibility of escape and survivability in the event of fire in the residential building with internal corridors, and how can smoke propagation be reduced?

Practice has shown that smoke propagating outside the fire room is the norm and is definitely not an exception. During this research, smoke propagated to the rest of the building, through cracks, seams and penetrations, as quickly as two minutes after ignition. This smoke propagation was accelerated by the door to the fire room being opened briefly. Horizontal and vertical smoke propagation occurred almost simultaneously. This means that even a small fire can cause dangerous situations to arise in several locations in the residential building. Whether smoke propagates, and to which extent it propagates, depends on the following factors:

> the fire object: organic or synthetic fuel
> opening doors or keeping doors closed
> other openings and penetrations in the partition construction
> the presence of (additional) measures for risk management (a mobile water mist and /or smoke resistant partition)
> the location of the fire room
> the deployment.

The exact propagation of the smoke greatly depends on the local circumstances.

The smoke propagation influences the possibility of escape and survivability in the following locations in the residential building:

> *The corridor adjoining the residence where the fire is located*
  Almost immediately after opening the door to the fire room (t = 5 minutes), the possibility for people in other residences to escape is seriously impaired because the corridor fills with smoke within a matter of seconds. Visibility in the corridor is so poor and the concentrations of asphyxiant and irritant gases are so high that a fatal situation arises.
> *Other residences adjoining the corridor*
  Once the door to the fire room has been opened, people in the other residences along the same corridor are 'stuck'. Fatal situations can also occur in these other residences (where there is no fire) due to smoke entering the residence. This applies in particular to situations involving vulnerable and highly vulnerable groups.
> *The rest of the building*
  In this research, the effect of smoke propagation on the possibility of escape and survivability in other building parts and floors was found to be limited. However, this does not mean that no smoke propagated to other building parts and floors: increased CO concentrations were measured in several locations and they can be a health hazard if people are exposed to them for a long period. In the event that an incident has occurred, such circumstances are a reason to evacuate the building or large sections of the building.

Smoke propagation can be reduced by taking measures for risk management. With regard to the measures tested, it can be concluded that only a combination of source and effect measures is effective to sufficiently improve the possibility of escape and survivability for all groups. The combination of limiting the use of synthetic materials (especially foams) in the furnishing and closing the doors has the most influence on improving the possibility of escape and survivability. A mobile water mist combined with closing the doors is also effective. Only taking an effect measure, such as closing the door or a smoke resistant partition, is not sufficient to improve the possibility of escape and survivability for vulnerable and highly vulnerable groups. Measures for risk management combined with the door to the fire room being closed reduce the smoke propagation through the building during the escape phase and reduce any smoke propagation caused by the fire service during the deployment phase.

Smoke will have already propagated outside the fire room before the arrival of the fire service and this should therefore be the basic assumption for the deployment. However, the scope and severity of smoke propagation are difficult to determine due to the complexity of the building, the unpredictable smoke propagation situation and the fact that the absence of visible smoke does not mean that there is no unsafe situation for the people present. An extensive assessment of, including measuring in, the residential building is the only way to establish which residences, corridors and escape routes are safe.

Besides fighting the fire, the goal of the fire service deployment should be to reduce further smoke propagation as much as possible. The situation of the door to the fire room, i.e. being open or closed, is decisive for determining which deployment method should be used to achieve these objectives. Where the door to the fire room is open, extinguishing the fire before rescuing was found to have the best effect on the possibility of escape and survivability. However, where the door to the fire room is closed, rescuing before extinguishing the fire was found to be the most beneficial to the possibility of escape and survivability.

However, every fire service action will cause more smoke propagation, both horizontally and vertically. Walking through smoke-filled corridors, opening and closing doors, and fire extinguishing activities are all actions that lead to a certain amount of smoke propagating to adjacent rooms. Mechanical ventilation has a dominant influence and it almost always causes smoke, and particularly CO, to propagate further to other rooms and floors.

9 Discussion

As is often the case with research, this research also has its expected and less expected results. The section below presents a closer interpretation of the results (9.1). Possible explanations of the results are given and the relation to the theoretical framework is discussed. Section 9.2 deals with the limitations of the research. The last section (9.3) gives suggestions for follow-up research.

Chapter 10 discusses how the results of this research are relevant to the subjects of fire safety and fire service science.

9.1 Interpretation of the results

9.1.1 Smoke propagation

The results show that even only part of a sofa catching fire can lead to rapid horizontal and vertical smoke propagation in a residential building with internal corridors.

This result with regard to smoke propagation is in line with the expectation based on real-life incidents (see the introduction and other parts of the report) and previous research (see chapter 1). These incidents and this prior research show that even a minor fire can cause smoke to propagate quickly through a building. Furthermore, the results show that the smoke propagating routes are often through open doors or seams and gaps around closed doors, wall sockets and ventilation ducts. This is largely in line with expectations as well, except the horizontal and vertical smoke propagation via wall sockets which had not been immediately expected. A possible explanation for this is the configuration of the electrical installation in the test location since it looks like there are direct connections between the wall sockets of different residences. However, the exact configuration of the electrical installation was not known.

The extent of vertical smoke propagation to other floors was not fully in line with expectations. Based on practical case studies and the simulations, more extensive vertical smoke propagation was expected than shown by the research results. Although this research showed that there was vertical smoke propagation to other floors, this was relatively limited and quite erratic. The research does not help to explain the cause of this limited smoke propagation and unpredictability.

Possible explanations are the influence of specific building characteristics (such as the height of the building and the number of floors, the ventilation system and the layout of the building) and of weather conditions. Buildings with more floors and other ventilation systems than the test location might involve a stronger stack effect and other pressure differences resulting in more vertical smoke propagation (Jacoby et al., 2016). Weather influences, such as temperature differences between the interior and the exterior and different wind pressures on the building, can also lead to more vertical smoke propagation. Of course, these weather influences also depend on the actual situation in the event of an actual fire in a residential building.

9.1.2 Possibility of escape and survivability

The amount of smoke produced by a minor fire (in a sofa) is such that the possibility of escape and survivability quickly deteriorate once the door to the fire room has been opened. The situation in the corridor became fatal within 3 minutes after this door was opened. Previous research had shown that fires in upholstered furniture produce large amounts of smoke. The effect on the possibility of escape and survivability in the residence where the fire is located was in line with expectations and with previous research (Fire Service Academy, 2015c; Fire Service Academy, 2017).

Expectations were also that the smoke production and the associated smoke propagation would impair escape routes. It had not been expected beforehand that this smoke would also have such a significant effect on survivability *outside* the fire room. For example, CO concentrations with peaks of between 17,000 and 30,000 ppm were measured in the corridor 2 to 4 minutes after the door to the fire room was opened. The concentrations measured remained constant at about 10,000 ppm from 4 minutes after the door was opened until the end of the escape phase. Such CO concentrations can be fatal within tens of seconds to a couple of minutes. A combination of asphyxiant gases can be fatal within a couple or tens of seconds. Measurements by the Dutch RIVM showed that large quantities of hydrogen cyanide (HCN) were also found in the smoke. HCN is about 25 times as toxic as CO. Although this report does not consider the effect of HCN on the possibility of escape and survivability, measurements by the RIVM justify the claim that the influence of the smoke on the possibility of escape and survivability will actually be even greater.

Furthermore, the results show that the possibility of escape and survivability can be improved by measures for risk management. However, not every individual measure is equally effective for all groups. It should be noted here that, the earlier the intervention in the fire and the production of smoke takes place, the more effective the measure will be, and that combinations of source and effect measures are the most effective. A common opinion so far has been that measures in a residence are mainly effective for the possibility of escape and survivability of people in the room in question. This research has clearly shown that these measures are actually necessary in order to improve the possibility of escape and survivability in the *surrounding* residences.

This research did not demonstrate that smoke resistant partitions improve the possibility of escape and survivability. The results showed that opening the door to the fire room caused the smoke resistant partition around the fire room to be broken through. If the door to the fire room remains closed, a smoke resistant partition might actually improve the possibility of escape and survivability in rooms in the vicinity. The smoke resistant partition around other residences was only tested in the situation where the door to the fire room had been opened for 30 seconds. The added value of a smoke resistant partition around other residences on survivability in those other residences may increase if the door to the fire room is kept open longer. However, keeping the door to the fire room open longer is not logical, given the fact that the smoke propagation in the building should be minimised. It should also be noted here that the doors to the other residences with the smoke resistant partition should be kept closed in such a situation.

9.1.3 Deployment

Prior to the research, it was not expected that the fire service deployment would have such a significant impact on smoke propagation as was found. Extensive smoke propagation had occurred by the time the fire service arrived, as a result of which all fire service actions in the building automatically had an effect on this. This started when the smoke partitions were opened in order to be able to reach the fire, followed by extinguishing the fire and, where necessary, rescuing or evacuating people, and, finally, ventilating the building. A logical explanation for this is that every action requires doors to be opened after which movement takes place through smoke, resulting in further smoke propagation.

Before entering a building, the fire service often decides which method to follow: rescue or extinguish. Apart from the fact that this research has shown which method gives the optimum possibility of escape and survivability in specific situations, this research also offers valuable conclusions regarding the moment when this choice should be made. This choice should not be made in advance, but at the moment when the first crew has reached the door to the fire room and can see whether the door is open or closed. This finding calls for a different approach to decision-making.

An unexpected finding was the fact that ventilation actually causes further smoke propagation, also to rooms that had been (relatively) free of smoke until ventilating started. In practice, ventilating a building is not easy, although many people tend to think otherwise. One finding that was definitely unexpected was the distinction between visible and invisible smoke. The conclusion ‘no visible smoke does not mean that there is no danger’ is valuable new information for action in the event of fire in general. This is yet another reminder that one should not always act merely by what one can see, although our eyesight is the primary sense to lead our actions.

9.2 Limitations of the research

There are limitations to this research which are a consequence of the choices made prior to or while conducting the research. These limitations are discussed here in three steps. General limitations of the research are identified first, after which the limitations concerning the primary choices made when establishing the research design are addressed. Finally, the limitations of the secondary choices will be discussed.

9.2.1 General limitations

A general limitation is that 'only' 19 tests were conducted in a specific building and with a specific fire scenario, whereas both experiments and actual fire practice have shown that the fire scenario, smoke propagation and the effects on the possibility of escape and survivability greatly depend on a large number of factors. However, it was impossible to examine all of these factors in all variations. Despite the fact that ‘only’ 19 tests were conducted, this is a very extensive number of tests and of corresponding variants for field research (on this scale). In addition, all variants were tested twice as a measure to try and achieve sufficiently reliable results.

9.2.2 Primary choices when designing the research

As part of the research, choices were made regarding measures for risk management and the deployment methods used. They are primary choices since they determined the design of the research.

Other measures for risk management, such as smoke control systems (smoke removal systems), pressure equalisation systems and other types of fire control installations, as well as other combinations of measures, can also be effective measures of improving the possibility of escape and survivability. Although not all systems and not all combinations of measures have been considered in this research, the results found may contribute to a better understanding of the extent to which other measures for risk management or combinations of such measures might be effective.

This also applies to other deployment methods for the fire service: there are more options for deployment methods than only ‘extinguish first and then rescue’ and ‘rescue first and then extinguish’, and it is conceivable that such other methods can also be useful for fighting fires in residential buildings. Examples are an offensive exterior attack for a fire that has reached the outside of the building (maximum ventilation) and rescuing / evacuating people from the outside using hand ladders or rescue vehicles. Other options as part of the methods tested, or the use of tools or special equipment (e.g. the smoke stopper), can lead to other results as well. However, the results found do offer information about the feasibility and added value of these other deployment methods.

9.2.3 Secondary choices when designing the research

The secondary choices refer to how the test design is given shape in order to enable proper research into the primary choices. The secondary choices regarding the test design and the time schedule used are discussed here.

Test design

The test design used in this research has specific fire and building characteristics which influenced the results, such as the dimensions of rooms, the fire scenario, the ventilation method (natural ventilation), the building structure and the period when the building was built.

The 21 square metre fire room is small for an average residence. However, this is an average size for a living room in a residence. The volume of the fire room is relevant for the fire scenario and for the associated smoke production and smoke propagation. Indirectly, this means that the size of the fire room also influences the possibility of escape and survivability. Furthermore, during this research, the conditions in the fire room were measured at approx. 2.5 metres from the fire object. Another location of the measurement equipment, e.g. closer to the fire object, would definitely have influenced the measurement results in the fire room.
The volume of the fire room is as expected but has a limited influence on the possibility of escape and survivability outside the fire room; the main decisive factors were the opening of the door to the fire room, the time when this was opened, and how long it was open.

Another shape or volume of the corridor adjoining the residences might have had an influence on the possibility of escape and survivability. The test corridor of 19 metres long and 1.8 metres wide is representative for corridors in residential buildings. Although the size of the fire room and the corridor may have influenced the possibility of escape and survivability, this research has shown that it is particularly smoke production by the source and opening the door to the fire room that influence the possibility of escape and survivability in and outside the fire room.

Opting for two different fire rooms also influenced the results. For example, (local) differences were found in how smoke propagated from the two fire rooms to other rooms. This can be partly attributed to a difference in the gaps and seams in the partitions around the fire rooms, and partly to the difference in position relative to other rooms. These differences were taken into account as much as possible by conducting multiple tests; the analysis method was also selected with an eye to this.

Another fire scenario might lead to different results as well. Apart from practical objections against infinite variations, the fire scenario should be as identical as possible in order to enable the smoke propagation to be compared. To be able to carry out a comparable fire scenario, an identical fire object (the sofa) and an identical ignition method (the ignition location and source) were chosen for 17 of the 19 tests. All these choices were decisive for the fire scenario used. The fire scenario chosen is definitely a realistic one. See the theoretical reference for this (section 1.2).

Dried piled up pinewood was used as the fire object for two tests; this is comparable to the material of a traditional sofa of organic material. In order to reproduce the heat release rate scenario of a traditional sofa, the wood was piled up according to a specific method. Other materials and /or another piling method might have led to different results. The choice of materials or the composition of materials in a traditional sofa particularly influences smoke production (soot and gases). Although dried pinewood as a material does not fully match a traditional sofa of, for example, cotton, wool and wood, the results are a good indication of the possibility of escape and survivability in the event of a fire in a traditional sofa.

The location of the mobile water mist relative to the fire object influences the effectiveness of this installation, since positioning it directly opposite the sofa would probably lead to better extinguishing. The position chosen represents an ‘average’, so as to avoid any disproportionately positive or negative influences on the test results. Another location of the water mist would therefore probably only lead to a different degree of effectiveness at a detail level.

Modifications to the fire rooms prior to and during the research may also have had a (limited) influence on the results. This refers to lining the fire room (the wall and part of the ceiling) with fire board and installing and removing smoke resistant partitions between the tests. These modifications may have influenced the ventilation profiles of the fire rooms and thus the fire scenario and the associated smoke propagation. This may also have affected the building's external heat profile which in turn may have affected the external size-up.

As show in the theoretical framework, international literature has identified several different methods for determining the possibility of escape and survivability. Scientists are not unanimous as to which methods and threshold values to use. For instance, they disagree as to the actual threshold values, the duration of exposure to (fire) conditions, and the interaction between different conditions and their effect on the possibility of escape and survivability. Other or new information about or views on, for example, threshold values may lead to different results. However, the researchers are of the opinion that the methods and threshold values used offer a good insight into the possibility of escape and survivability for different groups of people. As indicated before, the methods and threshold values were used for the quantities measured (temperature, heat radiation, visibility distance, oxygen, carbon monoxide, carbon dioxide and nitrogen oxides). However, there are many more combustion gases that can affect the possibility of escape and survivability, such as hydrogen cyanide, hydrogen chloride, formaldehyde, acrolein, etcetera). An example of another possible influence on the possibility of escape and survivability is inhaling a combination of soot and gases. It should also be noted that the threshold values for the different groups are not hard and fast threshold values for individuals: they are merely an indication of the available safe escape time (ASET) for a group. Whether a person can escape or will survive the fire depends on several location-specific and person-specific properties.

Another important aspect to take into account when reading the results is that conditions were measured at a limited number of positions and heights. Although this research features many measuring points, gas measurements in the fire room and the other residences were measured at one position and one height. There may be local differences in concentrations inside a room. Depending on the measurement position, this can have either a positive or a negative effect on the results for the possibility of escape and survivability.

Timeline for the escape and deployment phases
Some limitations also apply to the specific details of the scenario and the associated timeline for the escape and deployment phases. This is a direct consequence of the fact that, from the moment the fire starts, ever more factors influence the outcome of the fire and the smoke propagation.

The first limitation is formed by the details of the timeline for escaping and alerting. The following parts of this timeline influence the results:
- the time when the fire is discovered and reported
- the decision-making time and the escape time inside the fire room
- opening the door to the fire room, the time when it is opened and how long it is left open.

This research assumes discovery and alerting/reporting by an operational smoke detector within 3 minutes after the fire started. A period of 2 minutes was assumed for the decision-making time and escape time inside the residence. These basic assumptions can be viewed from different perspectives. For example, since not all residences currently contain operational smoke detectors, it can take longer for the fire to be discovered and for people to escape. On the other hand, there is a possibility of a fire being discovered earlier than after 3 minutes, especially if the occupant is near the fire object. Whether the door to the fire room is opened depends on the possibility of escape for example. The time when the door is opened depends on the discovery and alerting times referred to above, and how long it is open can depend on several factors, for example the number of people who have to escape through the door, their behaviour, and the design of the closing mechanism of the door (self-closing or not and the design and control mechanism of the self-closing feature).
All these factors influence smoke propagation and thus the results of the research. In retrospect, it can be said that every choice that was made with regard to the timeline could have been realistic, too positive and too negative at the same time, because all scenarios are possible in theory. However, given the fact that smoke detectors will be compulsory in

the near future and that doors have been required to be self-closing[42] since mid-2020, and that the number of vulnerable people living on their own in residential buildings with internal corridors will only increase, the timeline chosen is, first and foremost, a realistic one.

A similar consideration applies to the timeline for the deployment. The deployment, and particularly its speed, also depends on many factors. First of all, an important factor is the amount of time it takes for the discovery and alerting (rapid discovery and alerting lead to a smaller fire and less smoke propagation at the moment of arrival than late alerting). Next, the response time and how quickly the local situation can be assessed when on site are also decisive, as is the question of whether the fire service needs to help people evacuate. Many real-life incidents have shown that the first fire service unit to arrive is fully occupied in supporting the evacuation. All these factors influence the timeline (and the deployment method) and required choices to be made with regard to the design and implementation of the research.

In practice, the deployment method of the fire service depends on many factors: the degree to which a crew is familiar with the building, the specific equipment, the specific professional skills, etc. Subjects for further discussion can be found in the technical implementation of the methods formulated. However, this does not affect the goal of this research: it is about the result of the deployment method and not about how it is conducted. One exception to this must be mentioned: smoke stoppers were not used. However, this choice can be justified by the fact that there has been previous research into this subject and this tool is used by only a few brigades.

This research shows that ventilating a building is not an easy job, and, moreover, that it is an action that can actually contribute to further smoke propagation. Choices were also made with respect to ventilation, including its technical implementation (such as the location where the fan was positioned) and the ventilation path. And there were differences in how some tests were conducted. This supports the conclusion that ventilation often results in further (unintentional) smoke propagation.

9.2.4 Conclusion regarding the limitations of this research

Although all the limitations listed above influence the results of this research, the choices made are representative for the real-life situation, they have not been chosen too conservatively or too favourably, and they can therefore be justified. This justifies the conclusion that the results are extremely valuable in order to help make general statements about the effect of smoke propagation on the possibility of escape and survivability, about the differences in effectiveness of measures for risk management, and about the influence of the deployment on smoke propagation.

9.3 Follow-up research

This research has identified many potential subjects for follow-up research. This section only lists the main ones:

> This research focussed on the available safe escape time (ASET). Since the question as to whether safe escape or survivability is still possible depends on the comparison

[42] Smoke detectors will become mandatory for both existing structures and new structures with effect from 1 July 2022 and doors being self-closing has been a mandatory requirement for new structures since 1 July 2020.

between the available safe escape time (ASET) and the required safe escape time (RSET), conducting further research into the RSET is advised.

> Further research into the effect of measures for risk management which were not part of this research into reducing smoke propagation would also be welcome. This research might also include other elements, for example the effect of an airtight construction on smoke propagation.
> Conducting further research into specific factors that influence smoke propagation is also recommended. Examples of such factors are the effect of different ventilation systems in combination with a large number of floors.
> Furthermore, further research should be carried out into ventilating buildings after a fire. The research showed that this is not easy. Follow-up research can examine whether there are any other methods that lead to better results.
> Further research into the feasibility of the stay-in-place principle and the measures needed for this would also be welcome.
> The results of this research could be used to optimise and validate simulation models for fire growth and smoke propagation. Optimised models can possibly be used to conduct some of the follow-up research referred to above without having to conduct full-scale tests.

10 Interpretation

10.1 Introduction

This research into smoke propagation in residential buildings with internal corridors has been very extensive, both with regard to its implementation and the analysis. The research yielded a wealth of results which will make an important contribution to the knowledge of fire safety and fighting fires in residential buildings.

In general, we can conclude that smoke propagation in residential buildings is a serious problem. Incidents in recent decades have increasingly shown that smoke propagation has increased to such an extent that circumstances can definitely be considered to have changed compared to the past. These observations are confirmed in this practice-focussed research. Today's fires are not the same as the fires of the past. Modern fires release much more smoke and they become ventilation-controlled faster. Escaping is a major problem in ever more situations and there is a need to evacuate buildings much more often than before. The fire service is often faced with an impossible, horrible dilemma: whether to use their limited resources, i.e. the limited number of fire service personnel and equipment, to fight the fire first or to first evacuate the building?

This chapter gives meaning to the conclusions of this research. What can we say about the significance of this research for the daily practice that fire prevention consultants and incident fighters find themselves in in their efforts to prevent, control and fight fires in residential buildings where smoke propagation is a worrying problem? What is the implication of the results of this research for building regulations? Or, to put it more concretely: what do the lessons learned from this study tell us about the existing rules to prevent smoke propagation in the current Dutch Building Decree 2012 and the future Dutch Building Decree (BBL) that will take effect in 2022? And do our findings justify that we only look at building regulations, or do they also have a bearing on other regulations?

10.2 Implications for fire prevention and regulations

10.2.1 New requirements in the future Dutch Building Decree

The relationship between science and policy is always troubled. There is an increasing call for policy, which is often translated into laws and regulations, to be scientifically substantiated. But if the scientific substantiation does not match the policy conducted so far, or the desired policy, it becomes difficult for policymakers to simply incorporate the new scientific evidence into existing policy, regulations and procedures. This is something that we realise. Where this research finds that the starting points and basic assumptions underlying the current requirements do not match the current reality of smoke propagation, this does not disqualify the prevailing regulations. However, this is an emphatic call to evaluate these regulations and think about whether they are futureproof.
Two preventative facilities that will be made mandatory for new structures in the future Dutch Building Decree, other than in the current Building Decree 2012, are smoke resistant

partitions featuring smoke resistant access doors to residences (Sa / S200) and the requirement that these doors should be self-closing. The regulations on smoke movement were copied into the future Dutch Building Decree in line with the 'Advies normcommissie NEN 6075 rookdoorgangscriteria' (recommendation of the NEN 6075 standards committee on smoke movement criteria) on Sa / S200. That advice is based on research by Efectis. Since the Dutch Building Decree was introduced in 1992, the aspect of smoke resistance / smoke movement of a partitioning structure has been regulated via the structure's fire resistance. In practice, this means that smoke resistant structures are allowed to let substantial amounts of smoke pass through.

The Efectis research contained the recommendation that the S200 performance of doors should be combined as much as possible with a requirement to make them self-closing. The requirement for doors in residential buildings with a corridor to be self-closing took effect on 1 July 2020 pursuant to the Dutch Building Decree 2012. The explanatory notes to its publication in the Dutch Bulletin of Acts and Decrees state that doors being self-closing ensures that an access door will not remain open when people escape from a burning residence. This limits smoke propagation into adjoining interior escape routes. The experiments as part of this research have shown that these facilities definitely have an added value for an average group of occupants, but that their value is more limited for vulnerable and highly vulnerable occupants.

With effect from 1 July 2022, existing residences will also be required to have one or more smoke detectors inside. Smoke detectors significantly shorten discovery and alert times in many cases. The experiments assumed the presence of a smoke detector in the residence, i.e. a favourable circumstance with regard to the discovery of the fire and the moment when the occupant escapes from the residence where there is a fire.

10.2.2 Airtight construction

In order to prevent unwanted heat loss, ever more requirements are set on the airtightness of buildings. In practice, airtightness is almost always achieved in the thermal envelope (outer wall, roof, ground floor level floor) of the building. Passive building or other forms of very low-energy construction require a major degree of airtightness. By way of comparison: residences with a cubic capacity of 500 m^3 are allowed to have a maximum air volume flow for class 3 of 30 dm^3/s. Pursuant to the Dutch Building Decree 2012, 200 dm^3/s is allowed.

This airtight construction has an influence on pressure differences that occur in a residence in the event of a fire. In turn, these pressure differences influence smoke propagation and the possibility of escape. The experiments have shown that the extent of smoke propagation in the building seems to depend on the airtightness ratio of the internal and external partition structures. The more airtight the outer wall is, the greater the difference between the internal and external airtightness, and the more smoke will propagate in the building.
High pressure in the residence can lead to escape problems in airtight buildings since the door swings inwards and the pressure will make it impossible to open for some time (Hostikka & Janardhan, 2017). However, this situation did not occur in the field experiments.

10.2.3 'Too busy mopping up the floor to turn off the tap'

This Dutch saying is most certainly true if we only focus on reducing smoke propagation, as envisaged by the measures referred to above, and we fail to address smoke production. The fire object in the experiments was the sofa that is sold the most in the Netherlands. This was chosen for a reason: statistics show that fires in sofas and mattresses claim the most casualties. It is not for nothing that the fire services, both in the Netherlands and internationally, are concerned about the flammability and smoke production of these products. But policy makers and legislators still consider preventing smoke production and limiting smoke propagation to be two separate subjects which are managed by different ministries. This research has undeniably shown that measures which reduce smoke propagation will only have an optimum effect if measures to reduce the production of smoke are taken as well. So, in line with this metaphor: we can mop up as much as we like, but unless we turn off the tap, the new measures in the future Dutch Building Decree will only have positive effects for an average group of occupants. If we also want the measures to have positive effects for vulnerable occupants, such as the elderly, something must also be done to limit smoke production.

One might wonder whether it would be sufficient to limit these efforts to products that produce a lot of smoke, such as sofas and mattresses? Because, if no or hardly any smoke is produced, there is no need to reduce or prevent smoke propagation. Tackling fire growth and smoke development as closely to the source as possible has the greatest effect. This is theoretically correct, but not feasible in practice. There are too many flammable fixtures and fittings that can cause smoke to develop. Although they are likely to develop less smoke than sofas and mattresses, this will still be substantial, requiring measures to limit smoke propagation to be taken for them as well.

10.2.4 People's personal responsibility behind the front door

One of the principles of policy makers is to minimise the number of regulations regarding fire safety behind people's front doors. It is the government's policy to minimise any invasion of people’s privacy. In itself, this is a sound and justifiable goal. However, this assumes that if occupants are careless about fire safety in their own residence, the consequences of a possible fire will remain limited to that residence. However, the many real-life incidents where smoke quickly propagated to outside the residence have shown that this is no longer true. And these experiments have demonstrated something else that has a close bearing with this: a burning sofa in a residence can be fatal for the occupants of other residences in the residential building. The justified question that should therefore be asked is whether the principle of people's personal responsibility behind their front doors can still be maintained in its entirety. Or should legal requirements be set on the flammability and smoke development of mattresses and sofas (i.e.: upholstered furniture in general) in residences?

10.2.5 Vulnerability of facilities

The experiments have shown which facilities or measures, or which combinations of facilities and/or measures, are the most effective and which are the least effective. The vulnerability of the actual facility or measure was not taken into account. The facility remaining intact is, of course, one of the factors that decide its proper functioning in practice over a long period. In practice, failing to close a door or deactivating the self-closing function is often a decisive factor for the extent of smoke propagation and for the possibility of escape and survivability. And it is not only a lack of knowledge or maintenance that prevents people from making sure that a facility is kept operational. It is often also the inconvenience of the facility in daily use. The reconstruction of the July 2017 Grenfell Tower fire in London showed that the quality of the facility had a significant impact on the extent of smoke propagation. Therefore, it is important that the probability of failure of the facility is also considered when deciding about what to include in building regulations. Although the risk is the product of the probability and the effect, the effect is also determined by the quality of the facility and its acceptance by occupants.

10.2.6 Escape or stay-in-place

The increasing ageing of the population in residential buildings makes it increasingly difficult to continue to achieve the basic starting point from the Dutch Building Decree that people should be able to safely leave the building in good time in the event of a fire. As a result, a search for alternatives has been ongoing for some time; shorter corridors, the use of lifts and staying in place in those residences where there is no fire. For this reason, this research not only considered the possibility of escape, but also survivability. In the past, the Fire Service Academy had established that, in order to apply this 'stay-in-place' principle, measurements would - as a minimum - have to be taken in order to:

- limit smoke production
- prevent smoke from propagating from the residence on fire
- promote that the occupants of residences where there is no fire should stay in their residence and should not open their front doors during the entire fire.

The experiments have shown that a fire suppression system is not sufficient to reduce smoke production. What is also required is that the burning household produce less smoke. It has also been found that opening the access door to the residence with the fire room leads to extensive smoke propagation to the corridor, followed by visible and non-visible smoke propagation to the other residences. This means that the experiments do not yet provide conclusive advice as to the circumstances under which the stay-in-place principle can be safely applied. Furthermore, this research did not consider the occupants' behaviour, although we know that their behaviour is a factor that also plays a role. A little smoke in a residence still enables good survivability, but it is quite likely that people will then still open the entrance door to the residence which would cause conditions to deteriorate rapidly. The fire in the Grenfell Tower in London also demonstrated how vulnerable the stay-in-place system can be. At present, the Fire Service Academy is conducting PhD research into influencing the behaviour of the elderly.

10.3 Significance for incident response

10.3.1 Smoke propagation in relation to incident response

Many factors influence smoke propagation. Examples are wind pressure, the (outside) temperature, the presence of any shafts and conduits, doors being open or closed, and the airtightness of the residence and the building. The activities of the fire service also influence the smoke propagation through the building. Most of these factors are difficult to control. This makes it very hard to predict how the smoke will propagate in a certain building and whether, and to what extent, this will have any effects in other residences and escape routes in the building. The predictability of the smoke propagation decreases further as the smoke propagates further through the building. In addition, the experiments also showed that, even if no smoke is visible, there can still be hazardous concentrations of toxic gases (mainly CO).

This confronts the first crew commander(s) to arrive and the fire operation commander with a difficult task. When they arrive at the scene of the fire, it is not immediately clear where the fire is located and how extensive it is. Even a minor fire can cause a lot of smoke to propagate, and the smoke can come from any opening. Because smoke can propagate both into the escape routes and into other residences, it is more likely than before that occupants will leave their residence on their own and try to escape. The first crew commander is faced with a difficult dilemma: go and look for the fire first and extinguish it, or evacuate the building first. This also has its implications for the manpower required if a fire in a residential building is reported: this should be planned to enable evacuating the residences on the floor where there is a fire, while also finding the fire and assessing other floors. Given the unpredictability of smoke propagation, preventive evacuation of sections of the building where no smoke is visible (yet) might be worth considering as well. Given the results of this research, a relatively minor fire in a residential building with internal corridors calls for a considerable deployment of personnel and equipment. It is recommended that guidelines be prepared for this.

10.3.2 The numbers tell the tale

The extent of smoke propagation and the locations in the building where there can be hazardous concentrations are highly unpredictable. All of this makes gathering the facts of a fire in a residential building with internal corridors extremely important. The experiments also showed that, even if no smoke is visible, hazardous concentrations of toxic gases (mainly CO) can still be present. This is new information which means that it is no longer the visible smoke which determines the danger area during and after a fire in a residential building, but that measurements (for CO) should be conducted everywhere.

From a practical point of view, specifically measuring the CO concentration in the entire building is the only way to enable an objective assessment of whether evacuation is required and of when the building is sufficiently safe again.

10.3.3 The deployment method

The experiments have shown that every fire service deployment leads to an improvement of the situation compared to the tests where there was no attack. Society expects the fire service to take action and fortunately the fire service is also able to make a difference with its actions under these circumstances.

However, it has been found to be very difficult to properly assess what the best deployment method will be from outside the building. The best way of action inside the building can actually only be decided once the interior situation is known. That is why the assessment is very important. Which routes are still sufficiently smoke-free? Is the door to the residence open or closed? Are there any other escape routes? The commanding officers and the crew members, particularly when on the floor with the fire room, have to know these factors in order to be able to conduct an appropriate deployment.

The fire service action is one of the factors that influence smoke propagation. Opening doors, particularly the doors to staircases, and even moving through smoke-filled corridors, influences the smoke propagation. More than ever before, fire crews will have to pay attention to keeping escape routes free from smoke by preventing unnecessary actions and keeping doors closed.

The operation and application of smoke stoppers was not examined as part of these experiments. Several sources indicate that smoke stoppers can be a possible (partial) solution. However, a smoke stopper does not eliminate the root cause: in most cases, there will have been smoke propagation before the arrival of the fire service. This means that the smoke stopper would only help to reduce further propagation.

10.3.4 Evacuation

As stated above, the experiments have shown that smoke propagation is much more extensive that former experience suggested. It is also unpredictable and, even if there is no visible smoke, the situation can still be insufficiently safe, specifically for the most vulnerable people.

This finding also calls for attention to be paid to the safety of unprotected emergency responders, such as in-house emergency responders and the police, who help to evacuate occupants. They will no longer be able to automatically assume that if there is no visible smoke, they can work safely. Also for unprotected emergency responders, measuring (for CO) is the only way to make an objective assessment of the safety risks.

It is important that the evacuation routes are kept as clean as possible. Opening any partitions should be minimised. However, it is not ruled out that horizontal evacuation is no longer possible for the most vulnerable groups. That is why measurements should be conducted in the evacuation route. An alternative route or protecting the occupants might be a solution here. Identifying and separating escape and deployment routes should therefore also be part of the deployment plan.

Vertical evacuation and evacuation via the outside, if possible, is a good alternative to horizontal evacuation. Whilst awaiting their evacuation, occupants can be advised to stand at the open window or on the balcony. If this is not possible, the use of escape masks can be a solution in many cases, but this depends on the measurement readings along the escape route.

10.3.5 Ventilation

At present, extinguishing the fire quickly and then ventilating is a frequently used method. The experiments have resulted in some interesting information about ventilating after a fire. It was found that ventilating can have an unexpected adverse effect. In the past, positive pressure ventilation was always assumed to be a good and workable method to expel smoke from escape routes and residences. It has now been found that, where no smoke is visible, there can still be a relevant CO concentration and this use of fans can actually propagate this further through the building and into residences which were initially clean. Therefore, simply ventilating is not recommended.

In fact, ventilating is a complex activity and the flow profiles can be just as unpredictable as the actual smoke propagation. Preparing a ventilation plan might be a solution, but this calls for subject-matter knowledge. Further research into the effect of flow in buildings caused by positive pressure fans might provide input for such a plan.

In any event, simply using a positive pressure fan will no longer do. Opening as many rooms as possible and windows in those rooms whilst measuring the effects looks like a possibility which, for now, beats doing nothing in order to remove the smoke. These results are not sufficient to determine whether the application of hydraulic ventilation is a solution as well, but ventilating by creating negative pressure can, in theory, lead to unpredictable flows.

Further research into flows in buildings is necessary in order to gather more knowledge about this.

10.4 In conclusion

In 2014, the Fire Service Academy conducted field experiments in single-family homes in Zutphen. An important conclusion of that research was that that the exact fire development and smoke propagation depended on many factors. The same conclusion applies to the current experiments. Opening the door later or earlier, opening the door for a period longer or shorter than 30 seconds, opening the window a little less or a little further, a different fire load composition: these are all factors that help to determine the fire development and smoke propagation. And, just like in 2014, it can now also be established that the conclusions about smoke propagation are universally valid.

The findings of this research deepen our knowledge and help the fire service to act more safely and effectively. They support elements that had already been observed in practice, but for which no general firefighting principles had yet been developed. In this respect, we have progressed.

The Dutch national government has indicated that it is not in favour of separate fire safety measures for vulnerable people (such as the elderly), but that it prefers to apply universally applicable fire safety regulations. The results of this research into smoke propagation justify the question of whether, although improving fire safety in a general sense, the government's policy may actually not, or insufficiently, improve fire safety for vulnerable occupants, since the research has shown that individual (effect) measures do lead to a better possibility of escape and survivability for average occupants, but not, or to a limited extent, for vulnerable and highly vulnerable occupants. And it is precisely these groups that are overrepresented in the statistics of fatal residential fires. And furthermore, their number will only increase in the next few years.

It is therefore about time we ‘close the tap before we start mopping up’.

Glossary

Glossary	
ASET	Available Safe Escape Time: the time available to escape or to survive in the event of a fire.
Baseline scenario	A fire that starts in a sofa without any measures for risk management, no deployment, and a fictitious person escaping who leaves the door to the residence open.
BBL	The future Dutch Building Decree [*Besluit bouwwerken leefomgeving*].
Fire conditions	Conditions to which people are exposed in the event of a fire: toxic gases, heat and visual obscuration caused by smoke (visibility).
Fire object	Object in which the fire started.
Fire room	Residence in which the fire started.
Crib no. 5	Crib no. 5 was ignited according to the protocol in British standard BS 5852:2006.
Sensitivity factor (sf)	The degree of vulnerability to irritant and asphyxiant gases, heat and visual obscuration for the three groups: general group (sf = 1), vulnerable group (sf = 0.3), and highly vulnerable group (sf = 0.1).
Group	This research assumes three groups (sub-populations): a general group, a vulnerable group, and a highly vulnerable group.
Deployment phase	Phase during which the deployment takes place. This phase follows immediately after the escape phase, from t = 20 minutes until the end of the test (t = 55 minutes).
Mechanical ventilation	Ventilating the building by means of electric fans during the deployment phase (after extinguishing).
Natural ventilation	Ventilating a building or part of a building by using the flow that is created by the pressure and temperature differences caused by the fire.
Safe escape	Escape which is not impaired. See figure 1.3 for an explanation.
Operational time of the fire service	The time from the start of the fire until the moment the fire service can start their initial action.
Field experiments	All the nineteen tests that have been conducted.
Measures for risk management	Fire or smoke limiting facilities. In this research: a closed door, a mobile water mist, an organic fire load, and a smoke resistant partition.

Smoke	A mixture of soot particles, drops of liquid (such as water) and gases. The gases in the smoke can consist of decomposition gases, combustion gases, and ambient air.
Smoke resistant partition	Two smoke resistant partitions were tested as part of the research: a smoke resistant partition that was already in the building in accordance with the existing building regulations and a smoke resistant partition in accordance with new, future requirements in the *BBL*; a smoke resistant door was installed (S200) and seams and air leaks in both the internal and external partition/structure were sealed.
RSET	Required Safe Escape Time: the time needed to escape or to survive in the event of a fire.
Sa or S200	The smoke resistance of a partition (Ra or R200 criterion) between rooms depends on the smoke leakage (Sa or S200 criterion) of the various components in this partition (e.g. gaps and openings around doors, penetrations, connections and ventilation ducts).
Deployment method	This research distinguishes between two methods: an offensive interior attack (the fire is extinguished before the fire service starts evacuating people) and a defensive interior attack (the door to the fire room is closed and people are evacuated / rescued, after which the fire is extinguished). If there was no attack, the fire was extinguished after the end of the test.
Test	Each individual test conducted (with a total duration of 55 minutes).
Ventilation profile	The extent to which oxygen can reach the fire through openings (doors, windows, gaps, seams and ventilation ducts) in the fire room and the residential building.
Possibility of escape and survivability	This research considered four situations in relation to the possibility of escape and survivability: safe escape, impaired escape, a life-threatening situation, and a fatal situation.
Escape phase	From the start of the test, t = 0 minutes up to t = 20 minutes; from the ignition until the start of the deployment.
Progress	To advance towards the fire / to move through the smoke (and darkness) towards the fire room.

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