Influence of Building Structure and Building Content on Residential Fires

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Abstract
In Europe, there are still a significant amount of residential fires. Particularly fires in the living room are a major threat to the occupants. Much research has been done to residential fires. However, there is still little known about the impact of the development of building structures and building content on the fire behaviour and room conditions. This report shows a clear view of how these developments affect the fire behaviour in residential buildings. A comparison is made between traditional, renovated and today's houses.

Due to several events in the past, building structures have changed dramatically. To keep heat longer inside the building, and therefore cost-saving, insulation structures and double glazing become common for the new building from the 1970s. In 1997, new buildings had to be even better insulated. At this time, better/thicker insulation material and better double glazing were introduced. By the application of more and/or better insulation materials, less heat will be lost. For the energy consumption and CO_2 emission, this is a positive effect. However, during a fire situation, this means that the heat which is generated by the fire, can not leave the enclosure quickly. As a result of that, higher temperatures and therefore a greater risk in the residential building will be reached.

Also, the building content has changed the last decades. Modern furniture is made of different materials than before the energy crisis. In the 50's mostly natural materials were used. Modern furniture is composed primarily of synthetics. This change has a major impact on the fire behaviour of furniture; natural products burn slower and produce less energy, than synthetics. When a building is furnished with modern furniture, and it ignites, this results in a very rapid fire development and smoke production. The safe evacuation time will be reduced dramatically in the case of modern furniture.

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Hilco Hiemstra
1 June 2016
"Read and Approved"

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Summary

In Europe still are a significant amount of residential fires. Particularly fires in the living room are a major threat to the occupants. Much research has been done to residential fires. However, there is still little known about the impact of the development of building structures and building content on the fire behaviour and room conditions. This report shows a clear view how these developments affect the fire behaviour in residential buildings. A comparison is made between traditional, renovated and today's building structures.

Due to several events in the past, building structures have changed dramatically. During the energy crisis in 1970, the fossil fuel price rose to a record level. To heat a building was more expensive than before. Poorly or not insulated buildings loss much heat through the building structure. To keep heat longer inside the building, and therefore cost-saving, insulation structures and double glazing become common for the new building. Due the Kyoto Protocol in 1997, new buildings had to be even better insulated. At this time, better/thicker insulation material and better double glazing were introduced. The Kyoto Protocol focused mainly on the CO_2 emission. Highly insulated materials have a positive effect on the CO_2 emission of buildings. New agreements such as the 2015 United Nations Climate Change Conference, which was held in Paris, 2015, may also affect the building structures in the future, but precise measures are not yet described.

The before mentioned development also affect the conditions in the building during a fire situation. By the application of more and/or better insulation materials, less heat will be lost. For the energy consumption and CO_2 emission, this is a positive effect. However, during a fire situation, this means that the heat which is generated by the fire, can not leave the enclosure quickly. As a result of that, higher temperatures and therefore a greater risk in the residential building will be reached.

Also, the building content has changed the last decades. Modern furniture is made of different materials than before the energy crisis. In the 50s mostly natural materials were used. Modern furniture is composed primarily of synthetics. This change has a major impact on the fire behaviour of furniture; natural products burn slower and produce less energy, than synthetics. When a building is furnished with modern furniture, and it ignites, this results in a very rapid fire development and smoke production. For occupants is the change of building content the biggest threat. In the first minutes of a fire situation, the occupants must have a safe evacuation route. The safe evacuation time will be reduced dramatically in the case of modern furniture. In a later stage of the fire, the influence of the building structure becomes clearer. When the fire is fully developed, higher temperatures will be reached in highly insulated buildings. This fact is particularly important for the firefighters and building designers since the structure must be calculated for these temperatures.

Samenvatting (in Dutch)

In Europa komen nog steeds aanzienlijk veel woningbranden voor. Met name branden in de woonkamer zijn een grote bedreiging voor de aanwezige personen. Veel onderzoek is al gedaan naar woningbranden, maar er is nog relatief weinig bekend over de invloed van de nieuwe gebouw-constructie en de moderne inrichting op het brandgedrag en de condities in een woning. Dit rapport schetst een duidelijk beeld hoe deze ontwikkelingen invloed hebben op het brandgedrag in woningen. Een vergelijking is gemaakt tussen traditionele, gerenoveerde en hedendaagse woningen.

Door verschillende gebeurtenissen in het verleden, zijn gebouw-constructies drastisch veranderd. Tijdens de energie-crisis in 1970 stegen de prijzen van fossiele brandstoffen naar recordhoogte. Om een woning te verwarmen moest dus meer betaald worden. Door slecht geïsoleerde woningen ging veel warmte verloren door de gebouw-schil. Om kosten te besparen en warmte langer in de woning te houden, werd vanaf deze tijd op grote schaal spouwisolatie en dubbel glas toegepast voor nieuwe woningen. Door de invoer van het Kyoto Protocol in 1997, moesten nieuwe woningen nog beter geïsoleerd worden. Hiertoe werd onder andere dikkere isolatie en beter isolerende beglazing geïntroduceerd. Het Kyoto Protocol richtte zich vooral op de uitstoot van CO_2. Door woningen nog beter te isoleren word de uitstoot van woningen verlaagd. Nieuwe overeenkomsten zoals het 2015 United Nations Climate Change Conference dat gehouden is in Parijs 2015, kunnen in de toekost ook invloed gaan hebben op de gebouw-constructie, maar precieze maatregelen zijn nog niet beschreven.

De voorgenoemde verandering beinvloed ook de conditie in een woning tijdens een brandsituatie. Door het toepassen van meer en/of betere isolatie materiaal, gaat minder warmte verloren. Voor het energieverbruik en de uitstoot van CO_2 is dit een positief effect, echter ten tijde van een brand betekent dit dat de warmte die gegenereerd wordt, ook moeilijk het gebouw kan verlaten. Dit resulteert in hogere temperaturen en daarmee een groter risico in de woning.

Ook de inrichting van de woning is sterk veranderd. Hedendaags meubilair is van ander materiaal samengesteld dan voor de energie-crisis. In de jaren 50 werden vooral natuurlijke producten gebruikt. Hedendaags meubilair is voornamelijk samengesteld uit kunststof onderdelen. Deze verandering heeft grote invloed op het brandgedrag van het meubilair; natuurlijke producten branden minder snel en minder heftig dan kunststof materiaal. Wanneer een woning voorzien is van “modern meubilair” en er ontstaat een ontsteking, resulteert dit in zeer korte tijd tot een uiterst heftige brand met snelle rook ontwikkeling. Voor aanwezige personen in de woning, is de verandering van het meubilair de grootste bedreiging. In de eerste minuten van een brand, moeten de aanwezige een veilige vluchtroute hebben. Door het brandgedrag van het moderne meubilair wordt de veilige vluchttijd aanzienlijke verkort. In een latere fase van de brand, wordt de invloed van de gebouw-constructie meer duildelijk. Wanneer de brand volledig ontwikkeld is, worden in beter geïsoleerde woningen hogere temperatuurwaarden gehaald. Dit gegeven is met name belangrijk voor de brandweer en gebouw-ontwerpers, aangezien de constructie daar wel op berekend moet zijn.

List of Symbols

A	Area (m^2)
A_o	Area of opening (m^2)
A_T	Total internal enclosure surface area (minus opening area) (m^2)
c_p	Specific heat at constant pressure (kJ/(kg K))
D	Diameter (m)
F	View factor (-)
g	Acceleration due to gravity (m/s^2)
H_o	Opening height (m)
h_k	Heat transfer coefficient (W/m^2K)
k	Thermal conductivity (W/mK)
L	Flame height (m)
$\dot{m}''$	Mass burning rate per unit area (kg/(s m^2))
m_p	Plume mass flow (kg/s)
$\dot{Q}$	Heat release rate, HRR (kW)
Q_f	Heat release rate of free-burning fuel item (kW)
$\dot{Q}_c$	Convective part of the heat release rate (kW)
$\dot{q}''_{fl}$	Radiative part of the heat release rate from flame (kW)
$\dot{q}''_U$	Radiative part of the heat release rate from upper smoke layer (kW)
r	Radius (m)
T	Temperature (K)
T_a	Ambient temperature (K)
t	Time (s)
z	Height above floor (m)
z_o	Height of virtual origin of fire plume (m)
α	Growth rate used in equation E1
α	Thermal diffusivity used in paragraph 3.3 (m^2/s)
ΔH_c	Complete heat of combustion (kJ/g)
δ	Thickness of the solid (m)
ε	Emissivity (-)
ρ_a	Density (kg/m^3)
σ	Stefan-Boltzmann Constant (W/m^2K^4)
χ_r	Fraction of total energy radiated (-)

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1 Introduction

1.1 Background

The properties of the fuel and the thermal properties of the boundaries will affect the conditions during pre-flashover in a building. According to tests, McCaffrey and colleagues developed an equation to determine the upper gas layer temperature in an enclosure (Equation 1). From this equation, it can be seen how fuel properties and boundary properties are related to the upper gas layer temperature in the enclosure. (Quintiere and Karlsson, 2000).

$$\frac{\Delta T}{T_a} = 1.63\left(\frac{\dot{Q}}{\sqrt{g}\rho_a c_p T_a A_o\sqrt{H_o}}\right)^{2/3}\left(\frac{h_k A_T}{\sqrt{g}\rho_a c_p A_o\sqrt{H_o}}\right)^{-1/3}$$

Equation 1

[Upper Layer Temperature] = [Fuel Properties] * [Boundary Properties]

During the last decades, fuel properties and the thermal properties of the boundaries have changed. Fuel properties are related to the materials in the room of fire origin. Materials of traditional and modern furniture have changed during the last decades. So is for example natural material changed for syntactic materials, what have different fuel properties. Thermal properties are related to the building structure. Several events have affected the building structure around the world. The main events are the Energy Crisis in 1970, the Kyoto Protocol 1997 and the most recent event is the 2015 United Nations Climate Change Conference (COP 21 or CMP 11) what was held in Paris.

1.1.1 Fuel Properties

Furniture went through significant changes over the last decades. This is a result of the change in manufacturing. In the early 20th century, most furniture was handcrafted of solid wood. The introduction of mass production of furniture, which has dramatically reduced the costs, made furniture more accessible to the general public. Also new materials such as plastic, made the production more efficient and lowered the cost of new furniture (“Furniture Design and Manufacturing - A Glance Into History,” 2016). Solid wood and plastic (syntactic) materials show totally different fire properties. The influence of the furniture change will affect the room conditions.

1.1.2 Boundary Properties

In the 1960’s started the increase of petroleum production in some of the world’s top producers. Though the production of petroleum increased, more pressure was created on the oil price. Oil supply for the countries as, Germany and the U.S. become a problem. The countries became increasingly dependent on foreign suppliers. At that time the member of Organization of Arab Petroleum Exporting Countries (OAPEC) proclaimed in 1973 an oil embargo against the U.S.. OAPEC limited or stopped oil shipments to the U.S. and other countries in Europe. For most of the parts, industrialized economies (Europe) relied on crude oil in the 1970s. The affected countries responded with a wide variety of new, and mostly permanent initiatives to contain their further dependency. (“1970s energy crisis,” 2016). A consequence of the energy crisis was that heating the buildings became more expensive than before. Most of the heating systems in the 1970s were based on oil, coal or gas (coal and gas can be seen as a by-product from oil), the prices of these products increased dramatically.

Another event is the Kyoto Protocol. The Kyoto Protocol is an international treaty, which extends in 1992 United Nations Framework Convention on Climate Change (UNFCCC) that commits State Parties to reduce greenhouse gases (CO_2) emissions, based on the premise that (a) global working exists and (b) man-made CO_2 emissions have caused it. The Kyoto Protocol was adopted in Kyoto, Japan, on 11 December 1997 and entered into force on 16 February 2005.

The Kyoto Protocol implemented the objective of the UNFCCC to fight global warming by reducing greenhouse gas concentrations in the atmosphere to "a level that would prevent dangerous anthropogenic interference with the climate system". The protocol is based on the principle of common but differentiated responsibilities: it puts the obligation to reduce current emissions on developed countries on the basis that they are historically responsible for the current levels of greenhouse gases in the atmosphere.

The Protocol´s first commitment period stated in 2008 and ended in 2012. A second commitment period was agreed on in 2012, known as the Doha Amendment to the protocol, in which 37 countries have binding targets: Australia, the European Union (also Sweden), Belarus, Iceland, Kazakhstan, Liechtenstein, Norway, Switzerland, and Ukraine. (United Nations Framework Convention on Climate Change, 2016).

Due to these events, buildings got more and more energy efficient (e.g. insulation in walls, roofs, double layer-glazing and energy generation became environmentally friendly). The more energy efficient buildings ensured that heat could longer stay inside the building, what led to energy savings (and therefore cost saving). The Kyoto Protocol commits State Parties to reduce greenhouse gases emissions, based on the premise that global warming exists and man-made CO_2 emissions have caused it. (United Nations Framework Convention on Climate Change, 2016). A way to reduce CO_2 emissions in residential buildings is by adding an insulation layer and make the building more airtight. As a result, that boundary properties change and therefore also the room conditions.

1.2 Objectives

The development of building content has a positive effect on cost saving, and building structure has a positive impact on the environment. Nevertheless, it is not entirely clear how this development affects the fire behaviour in residential buildings. Therefore, the primary objective of this report is to develop an overview how the building structure and the building content can affect the fire behaviour in a residential building.
Based on this overall research objective two research questions (RQ) are formulated.

With the better thermal performance of building boundaries, the energy consumption in buildings is reduced. This is good for the environment, however, how will this affect the behaviour of fires in those buildings? This forms the first research question:
RQ 1: Which influence has the change of building structure on the fire behaviour in an enclosure?

As the equation of McCaffrey (Equation 1) shows, not only the building structure has an influence on the fire behaviour, also the building content is an important factor (Fuel Properties). The building content is also changed during these decades; it has transitioned from being compromised of natural materials to dominate by synthetic material (Kerber, 2010). The second research question is, therefore:
RQ 2: Which influence has the change of building content on the fire behaviour in an enclosure.

These two research questions are considered to improve the knowledge about the impact of the change in building structure and building content on fire behaviour in residential buildings over the last decades.

1.3 Methodology

The methodology used in this report is based on a "Case-Study" (fixed geometry). By using this Case-Study, a good comparison can be made for the different building structures and building contents. The report can be divided into four steps, and these are explained below:

1. Determine the change in building structure and building content
2. Set parameters for a fire model
3. Use fire model to generate results
4. Sensitivity analyse

In the first step is investigated how the building structure and building content changed during the last decades. In this step, three typical building structures are taken, these typical structures are:

1. Traditional, structure before the oil/energy crisis (before the 70s)
2. Renovated, modified traditional structure (insulation added)
3. Today's structure, structure that is used today

For the building content two types are analysed, namely:

1. Traditional (before the 70s)
2. Modern (today's furniture)

In the second step, the main parameters that have an influence on the fire behaviour in the room of fire origin and adjacent room are set. By using literature, parameters for thermal properties of the building material for the different building structures are gained. A Case-Study with a fixed geometry will be performed to find out what influence the development of building structure has on the fire behaviour and room conditions. For the building content in the living room, several tests are used to determine the fire behaviour of each item. To analyse the conditions in the enclosure, a fixed set-up of furniture is used. This ensures that the geometry and the place of the furniture do not play a role in the fire behaviour.

In step three, the data that is generated in step two is used. Different scenarios are analysed with a fire model and compared with each other, also the time to reach critical conditions for life safety is analysed. This comparison should answer the "objective" of this report.

In the final step, a sensitivity analysis is done to determine what influence different (fixed) parameters have on the results of step three.

1.4 Limitations

This report focused on residential fires; this means that the work only focuses on small and medium-sized enclosures. For the results of this report, the focus will be on the heat release rate in the room of fire origin, the hot gas layer temperature and interface height. The hot gas layer temperature and the interface height will also be analysed in the adjacent room. The last two parameters are commonly used as criteria for life safety in fire safety engineering. Toxicity is not specifically taken into account, it is assumed that the hot smoke layer will harm the occupants (a possibility for that is toxicity), when the hot gas layer reached critical conditions. The report is based on previous literature, and a fire model is used, what will not give 100% realistic values to reality, but in the 5 months that are set for this report a full-scale test is not possible. Therefore, the data that is obtained in this report gives only a general impression of the fire behaviour and conditions in the rooms. There are three different building structures, and two types of building content analysed. These structure types are based on West-European building structures. It is possible that other building structures or materials are used around the world. Another limitation is that the fire starts in one of the items in the living room. The items in the living room are considered as typical in living rooms.

2 The Change of Building Structure and Building Contents

In this chapter, the way how the building structure and building content is changed over the years is described. Three building structures are determined what will be used as “Typical” structure. A brief description is given about the change in building contents.

2.1 Development of Residential Houses during the Last Decades

As written in the previous chapter, several events have affected the building structures around the world. Building structures changed to become more independent of oil (or other fossil fuels), plus countries are more aware of environment damages. New residential buildings are more sustainable than before.

A sustainable building means; the building is designed with respect for human and environment. It is not only energy saving but also (U.S. Environmental Protection Agency, 2016):

- Energy efficiency and renewable energy
- Water efficiency
- Environmentally preferable building materials and specifications
- Waste reduction
- Toxics reduction
- Indoor air quality
- Smart growth and sustainable development

House-users use energy to heat-up their houses, heat-up the water and for electricity. The more energy is used, the more oil (fossil fuels) is used (a relation to that is the more CO_2 is emitted).
Heating of spaces in buildings is necessary to get a comfortable temperature. Space heating asks the most of the energy. The figure below shows the Energy Consumption in the average consumption in the European Union.

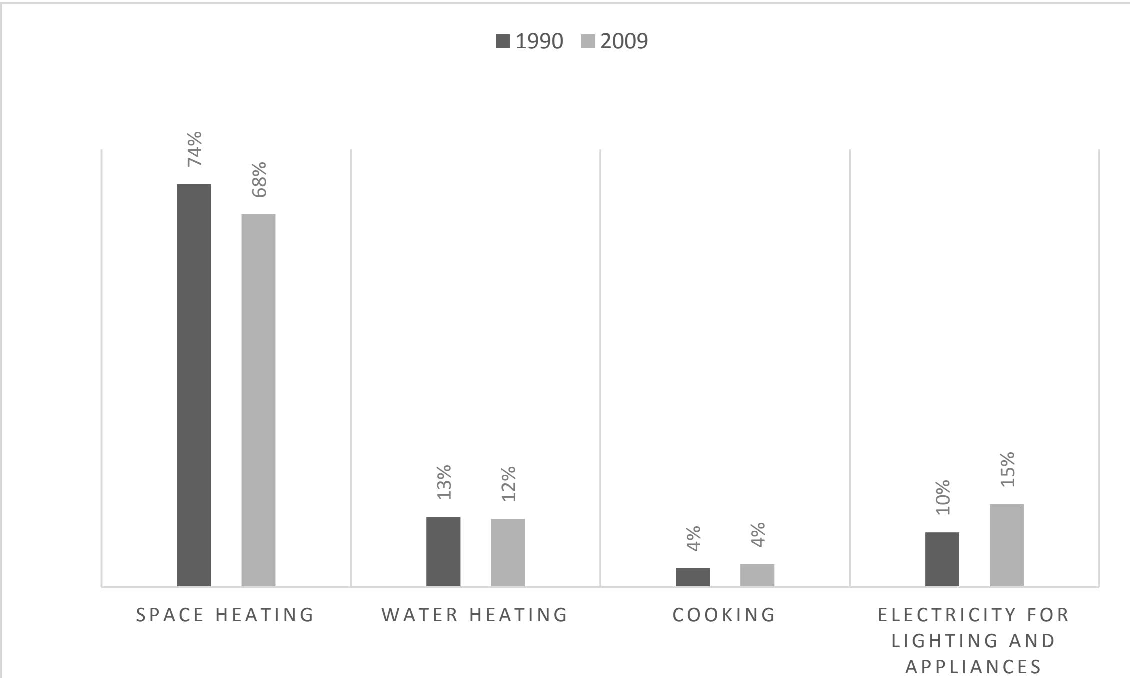

Figure 1 Energy Consumption in the European Union in 1990 and 2009 (European Environment Agency, 2012)

Space heating represented 68% of total household consumption in 2009 compared to 74% in 1990 and is the by far the biggest energy consumption in the household sector in Europe. Better insulating capabilities in building materials represent a measure in order to reduce the heat losses or gains through the external partitions of the building. Other features and concepts for sustainable buildings are:

- Increase the level of air tightness
- Efficient heat recovery of the ventilation in order to improve the performance of heating and cooling system
- Reduction of thermal bridging
- Use of more efficient windows (can also see as insulation measure)

By improving the thermal properties of buildings, ventilation becomes an important factor. Ventilation in buildings is necessary to replace the used/dirty air for fresh air. When no ventilation system is installed, condensation can build-up in the building. A good ventilation system is needed to provide a healthy and comfort environment in a building. During the decades, ventilation systems are improved. In regard to the development of residential buildings and its effect on fire safety in buildings, only the influence of insulation measures (as structure change) is analysed in this report.

2.1.1 Wall Insulation

In the west of Europe, it is only relatively recently that external walls of buildings have been insulated. Before this, walls were largely uninsulated, and a typical wall was structured by a solid brick (Energy Saving Trust, 2016) or with an extremely narrow cavity (in this report called: "Traditional Structure"). A solid brick wall insulates a building, however by adding an extra insulation layer the thermal properties will be improved. The widespread introduction of insulation for new buildings began in the 1970's (energy crisis), and it became compulsory in building regulations during the 1990's in west Europe. ("Cavity wall," 2016).

2.1.1.1 Today's Building Structure

After the energy crisis of 1973, cavity filling with insulation was introduced in the west of Europe. A cavity wall is a two 'skin' layer separated by a hollow space where insulation can be placed. The cavity wall is not totally filled with insulation. The insulation is attached to the inner 'skin' of the building; an air layer is needed to in order to prevent water penetration through the structure and condensation problems.

The width of the cavity but also the insulation is increased during the years. After the energy crisis, the insulation layer was around 25 till 50 mm thick, nowadays thicknesses of 240 mm are reached. The insulation materials that can be used for this kind of insulation are a rigid polyurethane foam, rigid polyisocyanurate foam, phenolic foam, expanded polystyrene foam and stone wool ("Spouwmuur," 2016). The thermal performance of the materials can vary. In Figure 2 a schematic view is given of the "Today's Structure".

2.1.1.2 Renovated Building Structure

It is possible to improve the "Traditional structure"; this type will be called "Renovated Structure." There are two ways of improving the traditional structure. It can be done by adding an insulation layer on the outside of the external wall or by adding the insulation on the inside of the wall. (Energy Saving Trust, 2016)

Internal wall insulation can be done by fitting insulation boards to the wall, or by building a stud wall filled in with an insulation material. An advantage of this method is that it is generally cheaper to install than external wall insulation. (See middle figure in Figure 2).

External wall insulation involves fixing a layer of insulation material to the wall, then covering it with a special type of render (plasterwork) or cladding. (Energy Saving Trust, 2016)

Figure 2 shows how the wall details changed during the last decades (schematically).

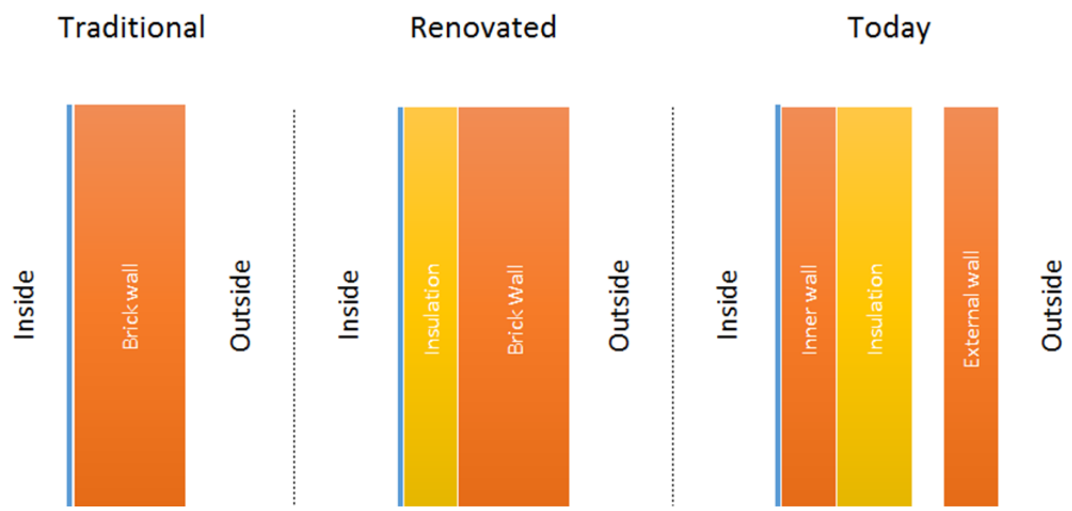

Figure 2 Development of Wall Details (schematic)

2.1.2 External Windows

As the walls, all buildings lose heat through their windows. The development of more energy efficient windows also started after the energy crisis. Before the energy crisis, one layer of glass was normally used (Traditional).

2.1.2.1 New Building Method

After the energy crisis, double-glazing became more common in central Europe. The introduction of double-glazing meant that energy could be reduced, and houses inside kept warmer (as cavity wall). More recently, the gap between the glass panels is in a vacuum or filled with a heavy inert gas as Argon, Krypton or Xenon. Both methods are trying to create a more effective insulating barrier, known scientifically as increasing the R-value (which is the measure of thermal resistance). Nowadays even triple layer glass can be used. (The Green age, 2016).

2.1.2.2 Renovation Method

To reduce the energy losses in traditional buildings different ways can be chosen. The entire window can be replaced by a new window (with double-glazing) or a "secondary-glazing" can be applied. Secondary-glazing works by fitting a secondary plane of (double) glass and frame, inside the existing window reveal.

Figure 3 shows schematically the development of the window/glass detail for buildings.

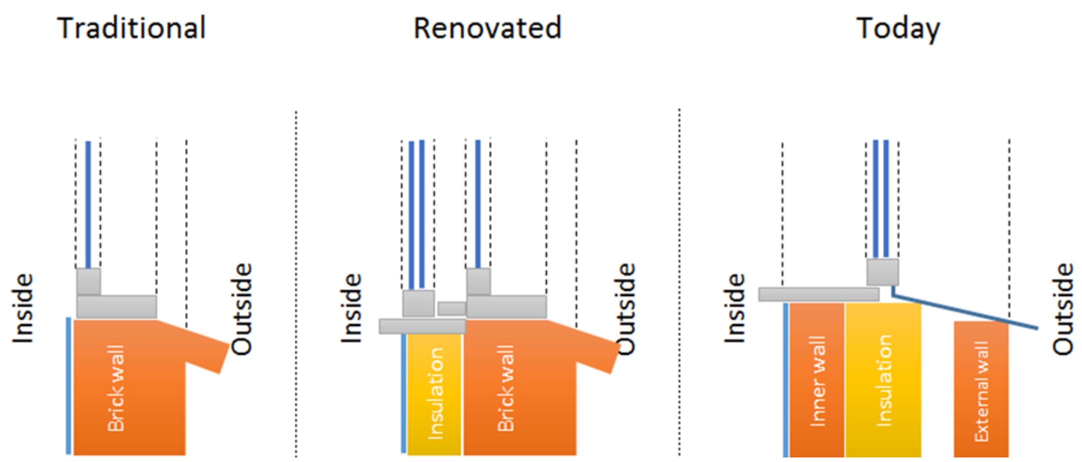

Figure 3 Development of Window/Glass Detail (bottom detail, schematic)

2.2 Building Content

This report is written in a fire safety context. According to NFPA research, after the kitchen and bedroom, the most common fires are in the living room, and these incidents caused 24% of home fire deaths and 10% of the home fire injuries. These numbers are from the U.S. between 2009 and 2013 (NFPA, 2015). Swedish statistics shows that almost 25% of the deaths in residential fires are found in the living room, this is most frequent for residential fires in Sweden between 2004 and 2014. (Myndigheten för samhällsskydd och beredskap, 2016). From these numbers, it can be stated that the living room is a potential risk to the safety of residents. From this point of view, this report will only focus on the building content in the living room.

The IKEA Museum, Älmhult (Sweden) shows 20 different living room settings with IKEA furniture and objects from the 1940’s until today. Each setting shows a living room from a specific period. The “1970’s room” shows, for example, solid pine furniture. Darker furniture and vivid colours, metal and colourful fabrics with prints are used to describe the 1980’s. In the last years (from 2000) much focus was on the social initiative and sustainability, strong design gave the living room extra focus on detail and quality. (IKEA, 2016a).

Figure 4 Change in Furniture in the living room during the years (left: 1960, right 2000+) (IKEA, 2016a)

Although the function of the living room has not changed, materials have certainly changed over the years. Over the time, it has transitioned from being compromised of natural materials to dominated by synthetic materials. In terms of a fire safety perspective are the changes in general (Kerber, 2010):

- The increased use of more flammable synthetic material such as plastics and textiles.
- The increased quantity of combustible materials.
- The use of goods with unknown composition and uncertain flammable behaviour.

The materials that are used in furniture have changed dramatically over the last 30 or 40 years. Furniture in the 1940’s or 1950’s was often made of bare wood. Upholstered furniture was usually made of cotton velour over mohair or leather over horsehair. Such furnishings were combustible. Most of the materials were susceptible to smouldering ignition sources such as a dropped cigarette but, with a few exceptions, would not be readily ignited by a short-lived flame source such as a common match. Ignition of all but latex foam and kapok took many seconds or even minutes of exposure, and often reluctantly, producing small flames, preferring to smoulder instead. (Dehaan, 2016)

By the 1960’s and 1970’s, things were changing, furnishings were often polyurethane foam or cotton padding covered by cotton on cotton/synthetic upholstery fabric. As a result, fire behaviour began to change. Synthetic fabrics and PU foam added smoulder resistance to furnishings but made them more susceptible to ignition by even short-lived-open flame sources. This causes fires in residential buildings to be hotter and the heat release rates to increase as more synthetics are involved. The fire growth in this type of furniture is also faster than the previous types from the 40s or 50s. (Dehaan, 2016)

By the 1980's furnishings became almost exclusively polyurethane foam with synthetic covering very difficult to ignite with a smouldering cigarette but readily ignited by even a small flame. Once ignited, flames could spread quickly, and engulf all of the large chair or sofa flames in less than 10 minutes. Synthetic upholstery materials with their low melting points, melt as they burn, producing molten, burning droplets of materials that fall to the base of the furniture and institute rapidly growing vertical-face fires on the sides of the furniture, as well as "drop-down" damage to floors and carpets beneath. (Dehaan, 2016)

Today's furniture markedly improved its resistance to the most common type of accidental ignition, for example in the United Kingdom, upholstered furniture should pass flammability tests according to BS5852 Parts 1, 2 or BS7177/BS6807. These standards include cigarette and small flame ignition tests. In the United States, there are voluntary standards for cigarette ignition of upholstered furniture. Both tests are based on accidental ignition sources, but the trade-off is much worse resistance to flaming sources. Once alight, such furnishings can be completely involved in 3 to 5 minutes and be reduced to a charred frame in 10 minutes, while producing very high temperatures and high heat release rates. (Dehaan, 2016)

3 Case-Study – Input Data to Fire Model

A Case-Study will be performed to find out what influence the development of building structure and building content presented in chapter 2 have had on fire safety. For three structure types (Traditional, Renovated and Today's) the most important parameters that have an influence on fire safety are written and discussed in this chapter. The same is done for the building content (Traditional and Modern furniture). These parameters are used as input for a fire model.

3.1 Fire simulation model

There are different computational methods that can be used to determine the conditions in an enclosure during a fire. There are two major categories of fire models available, zone models and CFD models.

Zone models normally divide the room(s) into two vertically uniform zones; the hot upper gas layer due to the fire and the cool layer below. The layers are assumed to be well mixed; that means that the conditions in each layer are constant. Most zone models are based on the same fundamental principles and assumptions that a zone model uses conservation equations for mass and energy applied to each layer. (Jason, 2009)

CFD models (Computational Fluid Dynamics) split the enclosure up into a large number of small sub-volumes. The models are based on the basic physical principles of energy, mass, and momentum conservation. The model can calculate the movement of heat and smoke between the sub-volumes over time. At any point in time, it is possible to find the temperature, velocity, and gas concentration within each of the cells. (Quintiere and Karlsson, 2000)

In this report, a comparison is made of different building structures and building content. The data that will be analysed in the different cases are the Heat Release Rate (HRR), hot gas layer temperature and the interface height (smoke layer height). To get a general idea, a zone model is suitable for this. As written before, there are many different models available. In this report the zone model B-RISK Design Fire is used, to determine the conditions in the enclosure. B-RISK is used because, it is possible to simulate an item-to-item ignition, irradiation from the hot layer, combining various fire scenarios and multiple rooms can be modelled.

3.1.1 B-RISK Design Fire

B-RISK is developed by BRANZ and the University of Canterbury. The software is intended for evaluating the performance and hazard associated with room fires. Central to B-RISK is an underlying deterministic fire zone model previously developed and known as BRANZFIRE. In B-RISK the physics of the core BRANZFIRE model is extended, and the model provides the user with a better description of the uncertainty and risk associated with fires in building enclosures. The B-RISK model may be used for both single deterministic runs as well as for multiple iterations of a scenario for the purpose of sensitivity analysis or for producing probabilistic descriptors of fire risk under defined conditions (Wade et al., 2013). B-RISK DESIGN FIRE TOOL version 2015.07 is used.

3.1.2 Limitations of B-RISK

B-RISK is a computational tool used to determine the flow of smoke and gases and its properties through a building. B-RISK is based on a set of equations that predicts variables by using enthalpy and mass flux over a time step. These equations are derived from the conservation of energy and mass, and the use of the ideal gas law. By using these simplifying equations, errors or differences can occur compared to real life or full-scale experiments. Also flame impingement is not considered in B-RISK, this can significantly affect the irradiation to the fuel.

It is important to know what the underlying physics and assumptions are which the program is based on, in order to be able to evaluate critically the results. Further on in this a couple of the assumptions are described, for more detailed information the user guide of B-RISK can be used.

3.1.3 Scenarios

The influence of the structure types and building content on fire behaviour is determined by analysing twelve different scenarios. Each structure type (Traditional, Renovated and Today's) is analysed with traditional and modern building content. The influence of opening the windows is also taken into account (all openings to the outside air open or closed). In total, this gives twelve different scenarios. By analysing these scenarios, it can be seen what the influence is of the different type of structure and building contents. The scenarios are given in Table 1.

Table 1 Analysed Fire Scenarios

	Scenarios											
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Structure												
Traditional [Tr]	X	X	X	X								
Renovated [Re]					X	X	X	X				
Today's [To]									X	X	X	X
Furniture												
Traditional [Tf]			X	X			X	X			X	X
Modern [Mf]	X	X			X	X			X	X		
Windows												
Closed [Wc]	X		X		X		X		X		X	
Open [Wo]		X		X		X		X		X		X

3.2 Geometry of the Case-Study

For the geometry, a typical floor plan is taken of a single floor apartment. A typical apartment has a hallway that connects the living room with the bedrooms. This geometry is used for all scenarios. With a fixed geometry a better comparison can be made for the different scenarios. Figure 5 shows the floor plan where the geometry is based on. The floor-plan is also given in appendix A (scale 1:100).

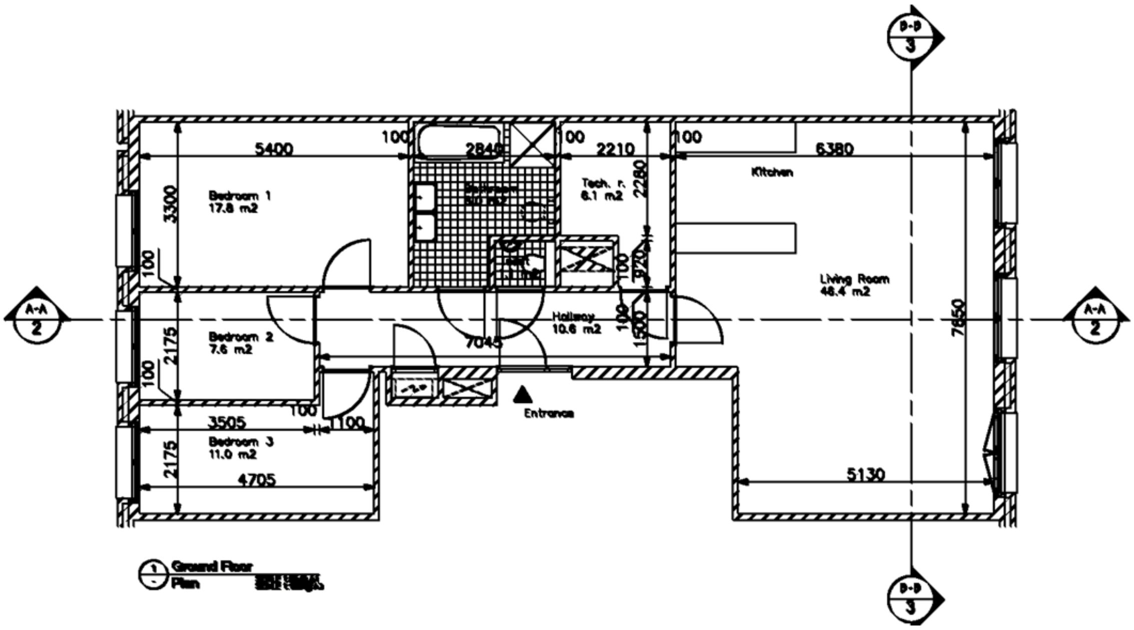

Figure 5 Case-Study Floor Plan (not on scale)

An assumption is made that; above and below the apartment other apartments are situated. The apartment has an open kitchen with a connection to the living room. The area of the kitchen-living room is 46.4 m^2. Two windows are installed and one double door that gives access to outside (balcony). The openings have the following dimensions:

- Windows (L x H): 1.55 x 1.30 meter (2x)
- Double door (L x H): 1.65 x 2.14 meter.

There are three bedrooms; each bedroom has a window of (L x H) 1.55 x 1.30 meter. The area of the bedrooms are, bedroom 1: 17.8 m^2, bedroom 2: 7.6 m^2, and bedroom 3: 11.0 m^2. In between the bedrooms and the living room, a hallway is situated. The hallway has a floor area of 10.6 m^2. The hallway also gives access to a technical room and the bathroom/toilet (not taken into account in the simulations, doors are closed to these rooms). The technical room is 6.1 m^2, the bathroom is 8.0 m^2 and the toilet 1.1 m^2.

The internal height in the apartment is 2.5 meter. The internal height of residential buildings vary in Europe; the Netherlands is the normal ceiling height 2.6 meters for new buildings and 2.4 meters for existing buildings. (BRISbouwbesluit online, 2016). For Sweden, it is 2.4 meter (Boverket, 2014).

As written in paragraph 3.1.2, B-RISK has some limitations. One of the limitations is that the spaces that are modelled need to be rectangular. As shown in Figure 5, the rooms are not rectangular. Therefore, the floor plan is simplified, the kitchen-living room is rectangular, and the bedrooms are (considered as one room).This simplification will not have an affect the conditions in the apartment. Beside that, this is a relative study where the influence of the structure types and building content are of interest and not the exact conditions in the apartment presented in Figure 5. Even with this simplifications, a general idea of the conditions in the fire room and the hallway can be generated. Figure 6 shows the floor plan that is modelled in B-RISK.

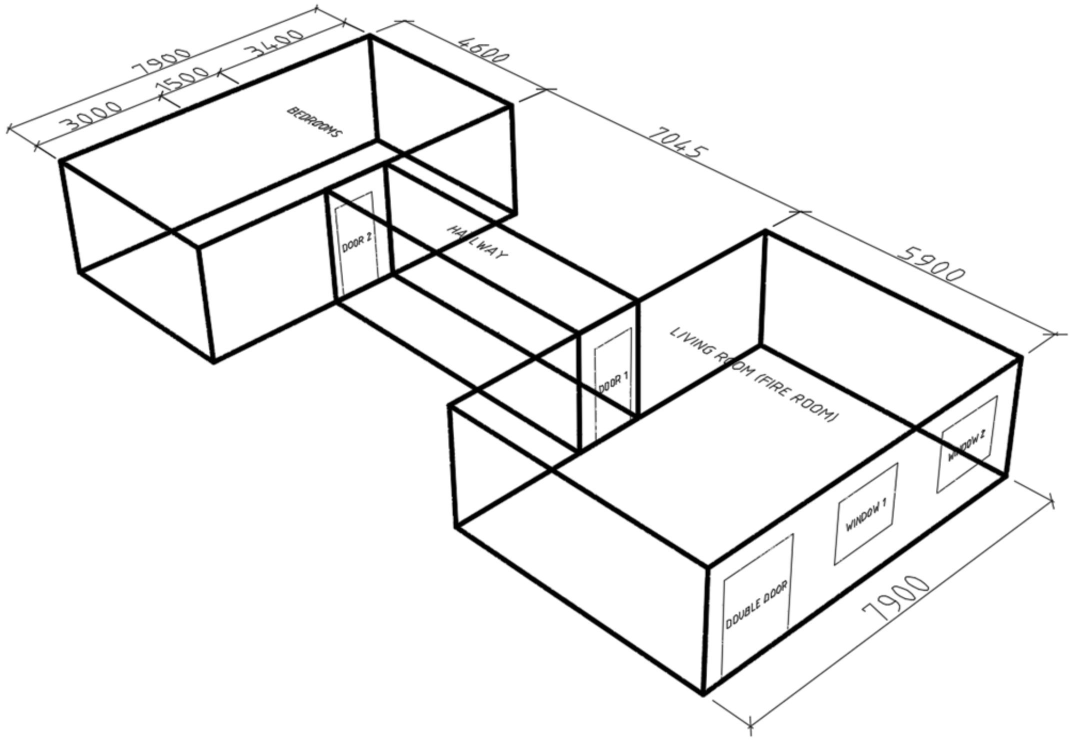

Figure 6 Modelled Floor Plan in B-RISK (perspective, not on scale)

3.3 Building Materials

As written in chapter 2, the building structures have changed during the last decades in Western Europe. In this paragraph, the structures of the building that will be analysed are further described in the following paragraphs. For each structure type (Traditional, Renovated, and Today) specific materials are taken. Other material types are possible, but to narrow down the research, these parameters will be used. For the conductivity an assumption is made: as thermal conductivity is dependent on temperature, a typical value is taken for the building materials. These values are referred to a specific temperature of 20 ˚C.

3.3.1 Traditional Structure

As written in paragraph 2.1.1 traditional buildings have a solid wall or have an extremely narrow cavity. The walls were built of brick.

In this report, the assumption is made that; the traditional structure has a double brick structure. In appendix B, a detail of the wall/window connection is given. The windows are carried out in a single glass plane in a wooden frame. As written before, the apartment is assumed to be located in between other levels of apartments. The floor and ceiling are therefore carried out in a concrete structure.

The following values for thermal properties are used for the materials. These values are important for the heat transfer in the enclosure.

Table 2 **Thermal Properties Traditional Buildings (Quintiere and Karlsson, 2000), (Clarke, 2007)**

		Thickness [mm]	k [W/m K]	Cp [J/kg K]	ρ [kg/m³]	α [m²/s]
External Wall						
	Brick	210	0.69	840	1 600	$5.2*10^{-7}$
Internal Wall						
	Concrete	100	1.2	880	2 100	$6.5*10^{-7}$
Window						
Frame	Wood	60	0.23	3 050	650	$5.2*10^{-7}$
	Glass	6	0.80	840	2 600	$3.7*10^{-7}$
Floor – Ceiling						
	Concrete	200	1.2	880	2 100	$6.5*10^{-7}$

3.3.2 Renovated Structure

For the renovated structure, an insulation layer is placed on the inside of the "traditional wall" as given in paragraph 2.1.1.2. As an insulation material, mineral wool is used. A traditional window is placed with a "secondary" (double layered) window on the inside of the house. In Appendix C, a detail of the wall/window connection is given (based on detail (Isover, 2016a)).

For choosing insulation on the inside of the building is done, because in the "today's structure" insulation in placed in the cavity. By doing this, more information about the effect of the insulation layer will be generated. In Table 3 the structure materials for the renovated structure are listed with their thermal properties.

Table 3 **Thermal Properties Renovated Buildings (Quintiere and Karlsson, 2000), (Clarke, 2007)**

		Thickness [mm]	k [W/m K]	Cp [J/kg K]	ρ [kg/m³]	α [m²/s]
External Wall						
Int.	Gypsum Pl.	13	0.48	840	1 440	$4.1*10^{-7}$
	Insulation	190	0.041	800	100	$5.1*10^{-7}$
Ext.	Brick	210	0.69	840	1 600	$5.2*10^{-7}$
Internal Wall						
	Concrete	100	1.2	880	2 100	$6.5*10^{-7}$
Window						
Frame 1	Wood	60	0.23	3 050	650	$5.2*10^{-7}$
	Glass	6	0.80	840	2 600	$3.7*10^{-7}$
	Argon	15	0.016	520	1 400	$2.2*10^{-8}$
	Glass	6	0.80	840	2 600	$3.7*10^{-7}$
	Air layer	220	0.026	1 005	1.2	$2.1*10^{-5}$
Frame 2	Wood	90	0.23	3 050	650	$5.2*10^{-7}$
	Glass	6	0.80	840	2 600	$3.7*10^{-7}$
Floor – Ceiling						
	Concrete	200	1.2	880	2 100	$6.5*10^{-7}$

3.3.3 *Today's Structure*

For the today's structure, a cavity wall with insulation is taken for the structure, based on paragraph 2.1.1.1. For the windows, a double-glazing system with Argon in between the double layer of glass is taken. In Appendix D, a detail of the wall/window connection is given (based on detail (Isover, 2016b), table 4 gives the thermal properties of the used materials.

Table 4 Thermal properties Today's Buildings (Quintiere and Karlsson, 2000), (Clarke, 2007)

		Thickness [mm]	k [W/m K]	Cp [J/kg K]	ρ [kg/m^3]	α [m^2/s]
External Wall						
Int.	Concrete	100	1.2	880	2 100	6.5*10^{-7}
	Insulation	240	0.041	800	100	5.1*10^{-7}
	Air layer	40	0.026	1 005	1.2	2.1*10^{-5}
Ext.	Brick	100	0.69	840	1 600	5.2*10^{-7}
Internal Wall						
	Concrete	100	1.2	880	2 100	6.5*10^{-7}
Window						
Frame	Wood	90	0.23	3 050	650	5.2*10^{-7}
	Glass	6	0.80	840	2 600	3.7*10^{-7}
	Argon	15	0.016	520	1 400	2.2*10^{-8}
	Glass	6	0.80	840	2 600	3.7*10^{-7}
Floor – Ceiling						
	Concrete	200	1.2	880	2 100	6.5*10^{-7}

3.3.4 *Wall Properties in Fire Model*

Input in the fire model, B-RISK uses an implicit one-dimensional, finite-difference scheme to calculate heat conduction through the ceiling, upper walls, lower walls and floor. The walls and ceiling can be specified as a single layer or as a two-layer system, the floor is specified as a single layer. For the opening only one layer can be specified.

By calculating the penetration time of each material layer it can be found which layers will be heated during a fire situation. The penetration time is calculated by the following equation:

$$t_p = \frac{\delta^2}{4\alpha}$$

Equation 2

Where, δ is the thickness of the material layer and α the thermal diffusivity. In Table 5 the penetration times of each (wall) structure type is given.

Table 5 Calculated Penetration Time Different Structure Types

		Thickness [mm]	α [m^2/s]	t_p [s]	Cumulative t_p [s]
Traditional Structure					
	Brick	210	$5.2*10^{-7}$	21 202	21 202
Renovated Structure					
Int.	Plaster Board	13	$4.1*10^{-7}$	103	103
	Insulation	190	$5.1*10^{-7}$	17 696	17 799
Ext.	Brick	210	$5.2*10^{-7}$	21 202	39 001
Today's Structure					
Int.	Concrete	100	$6.5*10^{-7}$	3 846	3 846
	Insulation	240	$5.1*10^{-7}$	28 235	32 081
	Air	40	$2.1*10^{-5}$	19	32 100
Ext.	Brick	100	$5.2*10^{-7}$	4 808	36 908

From this table, the material layers that will be used in the fire model can be determined. With the fire duration time, the time is determined till which layer the heat will reach during a fire scenario in the enclosure. The layers that are heated-up during the fire, are used in the fire model. The fire duration is determined in paragraph 3. 4.

3.3.1 Window Properties in Fire Model

The same approach is used for the windows. The penetration time for the windows is given in Table 6.

Table 6 Calculated Penetration Time Different Window Types

		Thickness [mm]	α [m^2/s]	t_p [s]	Cumulative t_p [s]
Traditional Window					
	Glass	6	$3.7*10^{-7}$	25	25
Renovated Window					
Int.	Glass	6	$3.7*10^{-7}$	25	25
	Argon	15	$2.2*10^{-8}$	2 559	2 584
	Glass	6	$3.7*10^{-7}$	25	2 609
	Air layer	220	$2.1*10^{-5}$	561	3 170
Ext.	Glass	6	$3.7*10^{-7}$	25	3 195
Today's Window					
Int.	Glass	6	$3.7*10^{-7}$	25	25
	Argon	15	$2.2*10^{-8}$	2 559	2 584
Ext.	Glass	6	$3.7*10^{-7}$	25	2 609

As written before, for the openings, only one layer can be specified in B-RISK. For the traditional window this is not a problem, for the renovated and today's window it is. Therefore a simplification is made for these window systems. An average value for thermal conductivity and thermal diffusivity is taken till the layer that is penetrated by heat.

Another assumption is made for the heat transfer in the window systems. Only conduction is taken into account. Convective heat transfer only occurs within a small temperature range. In this case temperature differences a relatively high, what results in a low convection and is therefore neglected.

3.4 Building Contents

It is assumed that the fire starts in the living room (as written in paragraph 2.2, a plausible assumption). As written before, the function of the living room is not considered to have changed over the years. To get an idea of the fire development in the living room, the "standard" items are placed. The standard items are:

1. Sofa 1
2. Sofa 2
3. Armchair
4. Coffee table
5. Side table

The items are placed on a possible place in the living room and will be fixed for all the scenarios from Table 1. Figure 7 shows the position of the furniture in the living room.

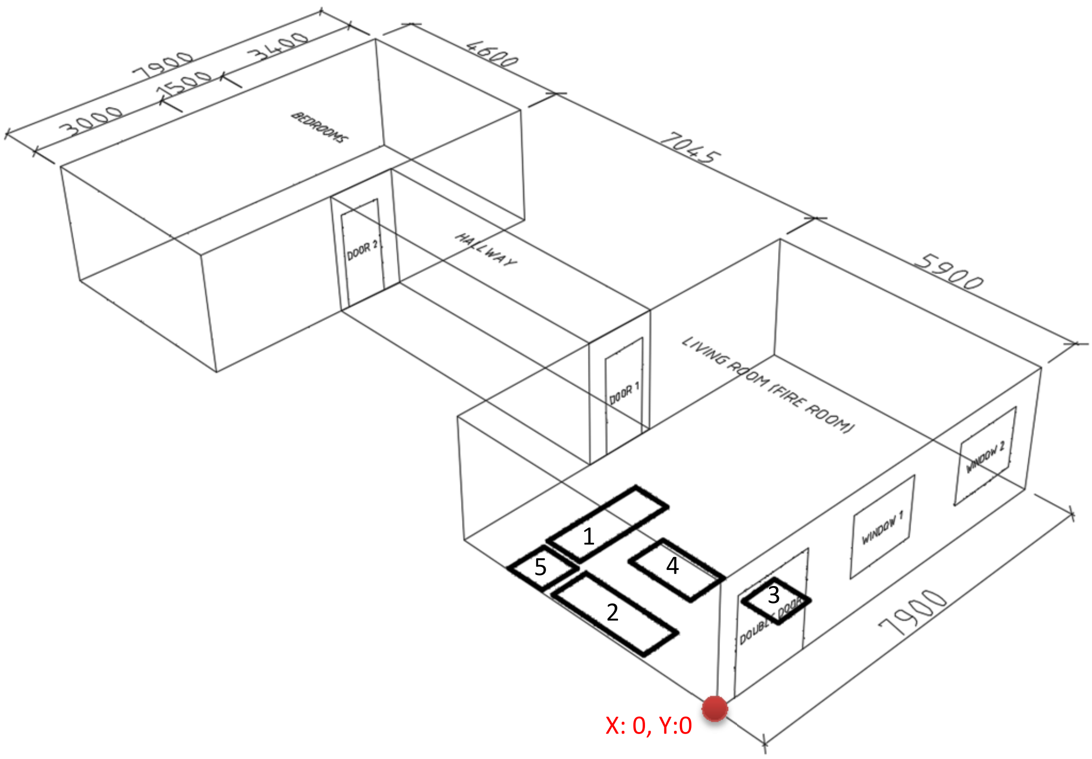

Figure 7 Floor plan with Furniture (Perspective, not on scale)

3.4.1 Fuel Packages

In the living room, different items are placed with different fire loads. It is hard to use the right data for smoke filling or fire spread models, every living room is differently furnished. To get a general idea of the fire load in a living room, experimental data is used for the furniture. It is possible that there is an inaccuracy in the HRR. There are also more factors what can influence the HRR, like ventilation, where the item is ignited, and how the item is located with respect to the walls. However, to get a general idea about the development of a living room fire, this data is used as reference data. In appendix E, the determination of the HRR for the used building content is given. The next paragraphs, gives a short summary about this.

3.4.1.1 Modern Furniture

For the modern furniture, test data is used. Four tests are done with chairs and two for sofas. For the chair and sofa HRR-curves, an average value is taken from these tests. With the average values, a general idea of the HRR of each item is generated. The peak HRR for the chair is approximately 1 500 kW and for the sofa 3 000 kW. The fire duration is for both items 1 200 seconds. Another property that has an influence on the fire behaviour that the HRR, is the area of the fire. In B-RISK the Heat Release Rate Per Unit Area (HRRPUA) can be set. The HRRPUA for the chair and sofa are set on 1 020 kW/m^2, this is equal to Moderate-weight type B upholstered furniture (Quintiere and Karlsson, 2000). For the sofa- and side table, an approximate curve is made. This approximate curve is based on the T-Square equation and experimental data, the HRRPUA is set to be 350 kW/m^2. In Figure 8 the HRR-curves for the modern furniture is given.

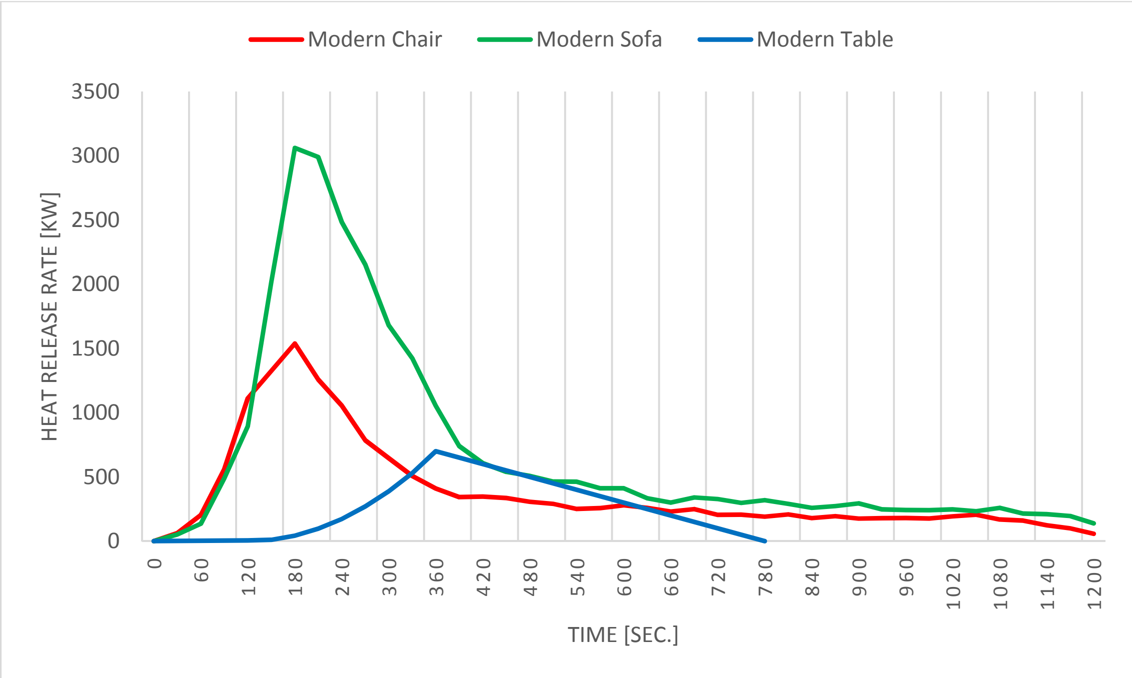

Figure 8 Input Heat Release Rate vs. Time curves Modern Furniture

The tests were done in a room calorimeter, radiation of the hot smoke layer had therefore influence on the HRR of the items. The sub-mode “Enhance Burning Rate due to Hot Layer Effects” is therefore turned off in B-RISK.

3.4.1.2 Traditional Furniture

For determining the HRR of traditional furniture, a theoretical approach is used. From theory, the peak HRR of a traditional sofa is around 400 kW. Once ignited, they would burn slowly often reluctantly, producing small flames, preferring to smoulder instead. (Dehaan, 2016).
For the chair and sofa, the same peak HRR is used and the HRRPUA is assumed to be 400 kW/m^2. The HRRPUA is equal to Moderate-weight type C upholstered furniture (Quintiere and Karlsson, 2000). The duration of the fire is based on the total energy release rate of the modern furniture; 80% of the total energy release rate of the chair and the sofa is used for the traditional furniture. This gives almost a double duration time of the fire for traditional furniture. The HRR for the tables, is assumed to be similar to the modern case. Figure 9 shows the HRR-curves for traditional furniture. In Appendix E, the development of the HRR-curves is presented more detailed.

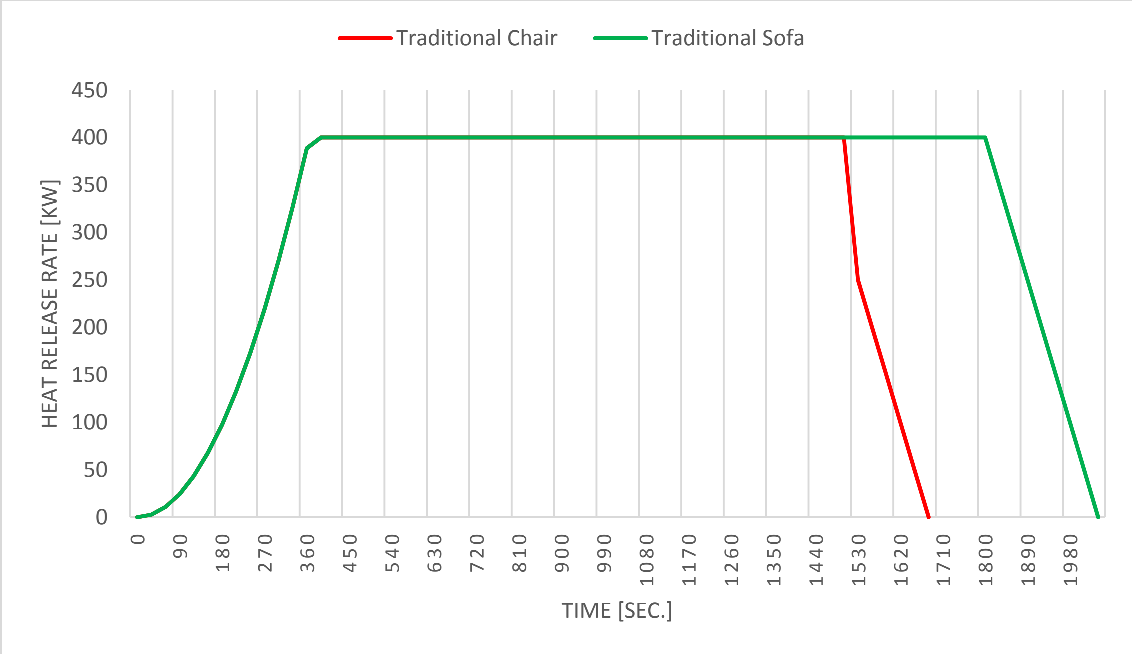

Figure 9 Input Heat Release Rate vs. Time curves Traditional Furniture

Other properties that are used in the fire model are given in the following tables. These properties are used for traditional and modern furniture.

Table 7 Material Properties Chair

Geometry		**Unit**
Width	0.85	m
Depth	0.88	m
Height	0.85	m
(Fire location) Height	0.44	m
Coordinates in B-RISK (left edge of item)	X: 2.2, Y: 0.7	m
Chemistry		
Heat of Combustion	24.2 (Polymethylmethacrylate)	kJ/g
Soot Yield	0.022	g/g
CO_2 Yield	1.690	g/g
Radiant Loss Fraction	0.3	-

Table 8 Material Properties Sofa

Geometry		Unit
Width	1.97	m
Depth	0.93	m
Height	0.81	m
(Fire location) Height	0.45	m
Coordinates in B-RISK	X: 1.0, Y: 4.1 – Sofa 1	m
(left edge of item)	X: 0.1, Y: 1.7 – Sofa 2	m
Chemistry		
Heat of Combustion	24.2 (Polymethylmethacrylate)	kJ/g
Soot Yield	0.022	g/g
CO_2 Yield	1.690	g/g
Radiant Loss Fraction	0.3	-

Table 9 Material Properties Wooden Table

Geometry		Unit
Length	0.8	m
Width	0.8	m
(Fire location) Height	0.5	m
Coordinates in B-RISK	X: 1.6, Y: 2.1 – Coffee table	m
(left edge of item)	X: 0.05, Y: 4.0 – Side table	m
Chemistry		
Heat of Combustion	12.4 (Wood)	kJ/g
Soot Yield	0.015	g/g
CO_2 Yield	1.19	g/g
Radiant Loss Fraction	0.3	-

3.4.2 *Fire initiation*

The fire initiation can significantly affect the initial characteristics of the fire. In this report five items are placed in the fire room, each of them can be the first item ignited. When an item is ignited, it can spread to the other items in the fire room (item-to-item fire spread). The ignition of a "secondary" item in B-RISK is based on the radiation from the flames of a burning item and radiation from the hot upper gas layer in the fire room.

For each scenario (Table 1) five different runs are done. Each run, another item ignites first, what results in five fire curves for one scenario. From these five curves, an average curve is made, the average curve is used to determine the enclosure conditions for each scenario. In Figure 10 is this shown for the HRR of scenario 2, the same method is used for the hot gas layer temperature and interface height.

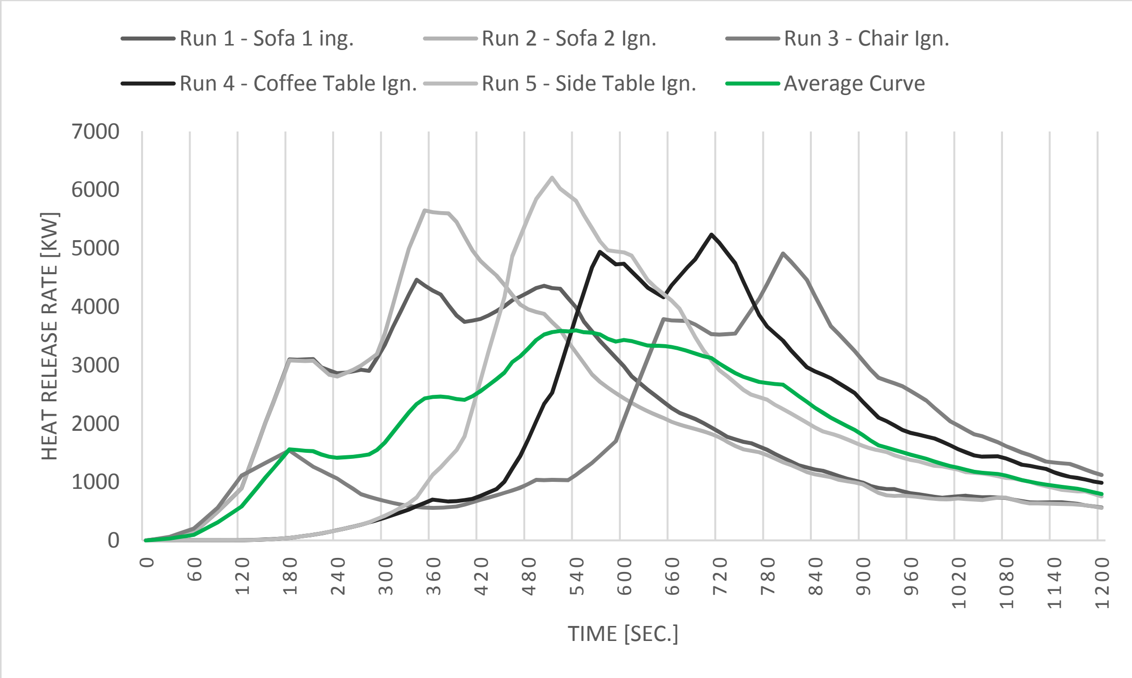

Figure 10 Determination of HRR-Curve for 5 Items in the Room of Fire Origin for Scenario 2

3.5 Ventilation/Openings

After ignition and during the initial fire growth phase, the fire is considered to be fuel-controlled. Because there is sufficient oxygen available for combustion in the compartment in the initial phase, the fire entirely depends on the characteristics of the fuel and its geometry. As the fire grows it may become ventilation-controlled, when there is not enough oxygen available to combust all the pyrolyzing fuel. The energy release rate of the fire can then be determined by the amount of oxygen that enters the enclosure openings (Quintiere and Karlsson, 2000).

The effects of the ventilation on the fire behaviour is analysed by, opening or closing the windows in the fire room. To get an idea of the effects of the ventilation, all openings are closed in one case, and in another case all windows and doors are open. The breaking of glass due to heat exposure and pressure build-up is not taking into account (it should be noted: glass breaking can have a big influence on the fire behaviour in an enclosure). In the living room two windows and a double balcony door that will supply air (oxygen) from the outside are present. The openings have the following dimensions:

- Windows (L x H): 1.55 x 1.30 meter
- Double door (L x H): 1.50 x 2.10 meter.

The windows have an offset of 0.8 meters from the floor. The following figure (Figure 11) shows the ventilation openings. The doors to the adjacent rooms are in all cases opened. The inner doors have a height of 2.1 meters and a width of 0.9 meters. The openings are assumed to have a discharge coefficient of 0.68.

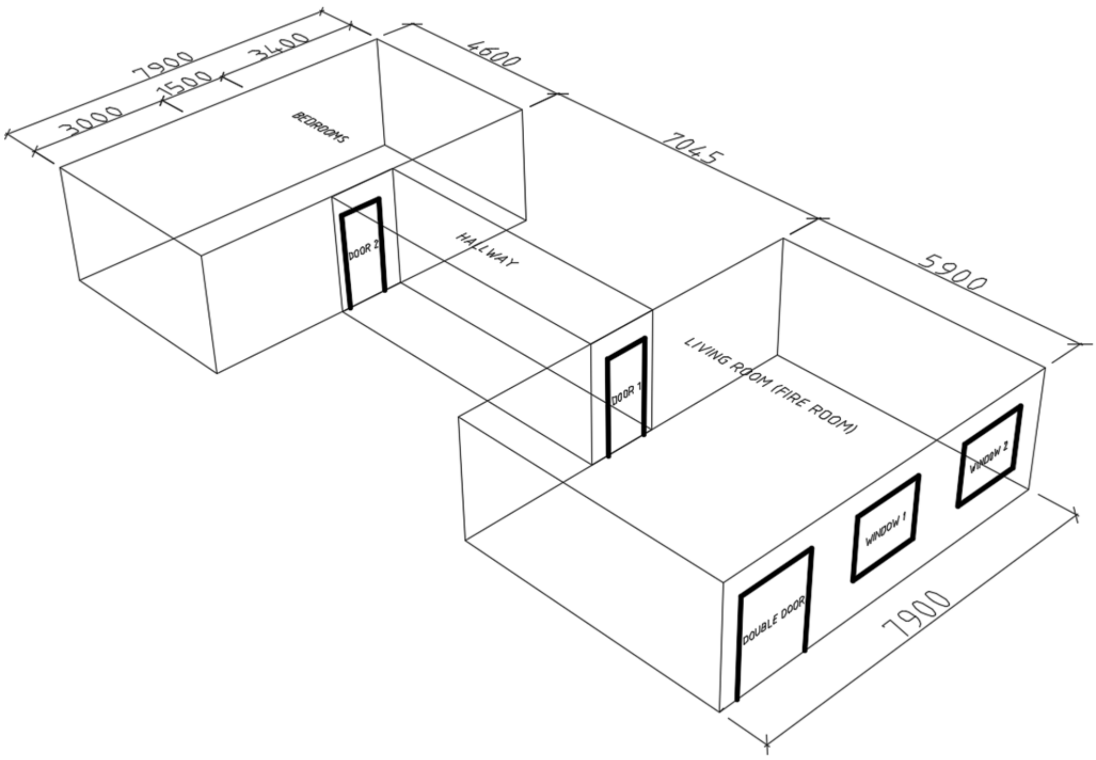

Figure 11 Floor Plan with Openings (perspective, not on scale)

The interior temperature is set to be 24 °C and for the exterior temperature is 15 °C with a relative humidity of 50% in all the simulations.

4 Case-Study - Fire Model Results

In chapter 3 the input data is given, that is used in the fire model B-RISK Design Fire. The results of the fire model are presented in this chapter. The data that have been analysed is, the Heat Release Rate (HRR), the hot gas layer temperature in the room of origin and adjacent room (hallway), the interface height in the room of origin and the adjacent room for the different scenarios from Table 1. The analysed data is related to the critical conditions of life safety.

Because different items are presented in the living room that can ignite, an average value is taken as the result for each scenario (see paragraph 3.4.2). In all comparison, the three structure types are presented to compare the influence of the structure types. This is done by the use of different colours. Red is presenting the Traditional structure, Green the Renovated structure and Blue is used for Today's structure.

4.1 Structure Effects

The comparison of the structure influence is assessed only by the use of modern furniture. The influence of structure will have the same results for traditional furniture. In this paragraph also, the influence of windows (open or close) is given.

4.1.1 Window Open-Case

When all openings are opened the fire grows to a fully developed fire, with a peak HRR of approximately 3 600 kW at 540 seconds. The fire is burning until all fuel is consumed. In this case, there is enough oxygen available for total combustion. Secondary items are ignited by radiation from the hot upper gas layer or by flame spread from another item. This results in a quick increase in HRR and temperature. When the fuel almost is consumed the HRR and temperature decrease quickly.

The hot upper gas layer descends slow to 1 meter above floor level, due to the openings (hot air can leave the enclosure through the openings). Also, the smoke layer does not descend fully toward the flame region, the openings keep the smoke layer at a steady height. This means that the mass loss what is released from the flames into the smoke layer is at least equal or lower that the mass loss rate through the openings.

4.1.2 Window Close - Case

As expected, in the cases where is no opening in the enclosure are presented, the total energy that is released is much lower than the "Window Open-Case", the same counts for the peak HRR (580 kW at 120 seconds). This is because less oxygen entrains the fire. The oxygen that is available is coming from the enclosure. When all oxygen from the enclosure is consumed, no more oxygen is available (there is no supply of fresh air). The available oxygen controls the burning in the enclosure, also the smoke layer descend soon toward the flame region and covered the flame, this also gives less oxygen into the flame region. Both lead to lower energy release rates and gas temperature in the "Window Closed-Cases". In contrast to the quick increase in temperature in the beginning, the temperature decreases slowly when the fire become limited by under-ventilated conditions. This is due to the lack of openings; the heat cannot escape the enclosure through the openings. The only heat loss in this case is to the enclosure boundaries.

4.1.3 Results Structure Effects

As written before, one of the main parts of this report is to analyse the influence of structure types on the fire behaviour in an enclosure. In the following figures, the conditions in the room of fire origin are given for the three different structure types. As Figure 12 and Figure 14 show, the HRR and smoke layer height are equal for the analysed structure types (this is also a cause of the sub-model: Enhance Burning Rate due to Hot Layer Effects). The main difference is in the upper gas layer temperature.

From Figure 13 it can be seen that the traditional structure has the lowest temperature for the hot gas layer. This is due to the conductivity and the density of the structure. The structure takes more heat into the structure. This results in more heat losses into the building structure, and lower hot gas temperatures.

For the renovated structure, the insulation layer is placed to the walls, at the side of the fire. The insulation layer has a low conductivity (convection is not taken into account, this only occurs when temperature differences are not significant), what means that less heat will be taken into the material. With as a result, less heat will be lost through the boundary layer and therefore the temperature increased in the enclosure.

Today's structure has an inner concrete layer with insulation. As the traditional structure, the inner layer will take some heat. However the combination of a high conductivity, and higher density of the structure, less heat will be conducted into the structure. What results in a slightly higher temperature in the today's structure compared to the traditional structure.

As the traditional structure is taken as base-model, the renovated structure produces a 8% higher peak value for the temperature in the enclosure and today's structure 2% higher.

When the windows are closed, a 16% higher peak value is presented for temperature in the enclosure for the renovated structure and 6% for today's structure. This is a result of the building structure and the highly insulated windows. The surface of the glass is relatively big, the one layer system in the traditional case will lose heat easily to the outside of the enclosure (the penetration time of one layer of glass is only 25 seconds). In the renovated and today's windows system the penetration time is at least 2 609 seconds, this causes less heat losses through the glass surface.

The following figures show the HRR (Figure 12), Hot gas layer temperature (Figure 13) and Interface height (Figure 14) vs. Time in the room of fire origin.

Where Tr: Traditional, Re: Renovated, To: Today's structures are and Mf: Modern furniture, Wc: Windows closed and Wo: Windows open.

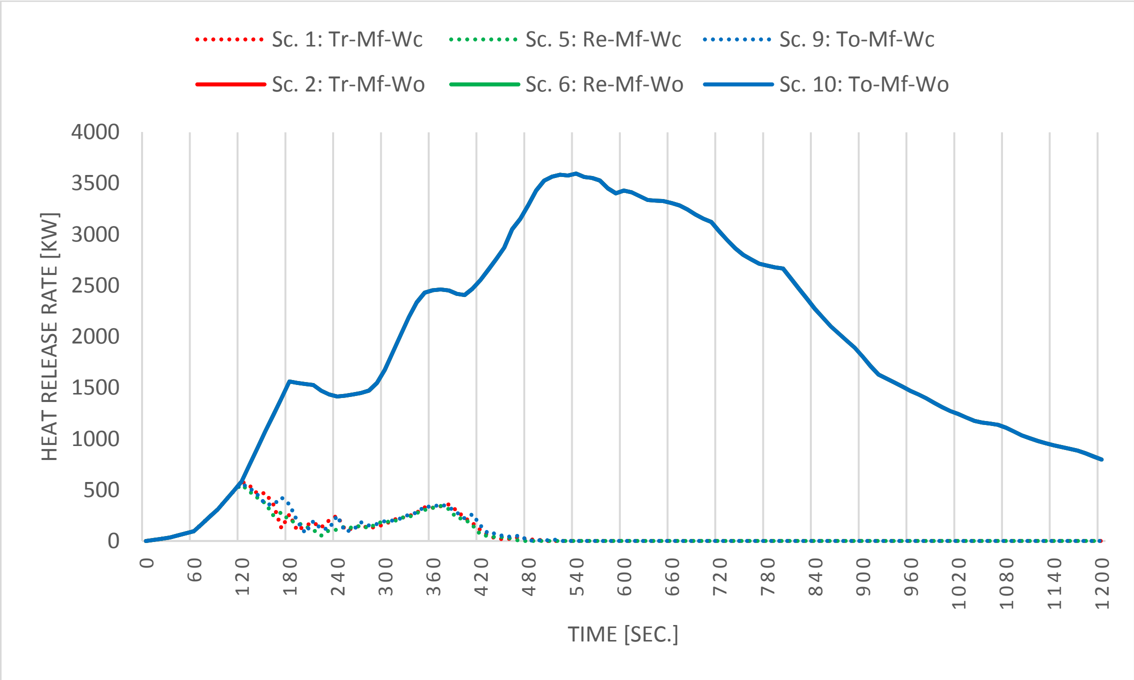

Figure 12 Heat Release Rate vs. Time Curves, Ventilation/Structure Effects

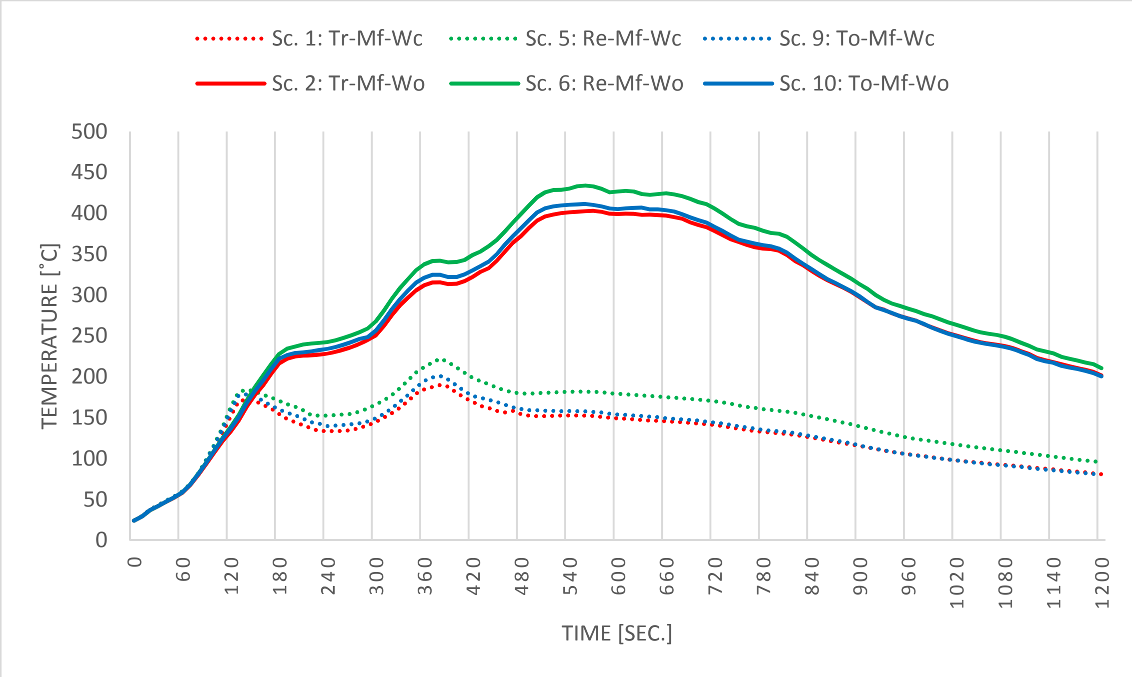

Figure 13 Hot Gas Layer Temperature vs. Time Curves, Ventilation/Structure Effects

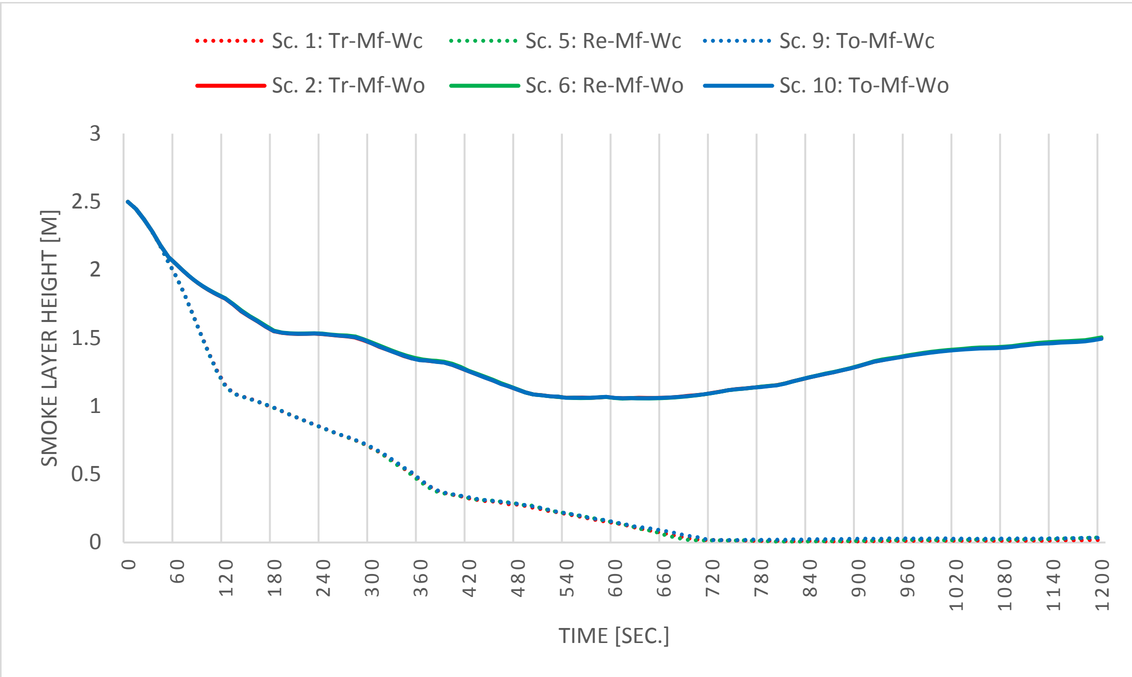

Figure 14 Interface Height vs. Time Curves Ventilation/Structure Effects

4.2 Building Content Effects

To determine the effects of the building content on the fire conditions in the enclosure, the traditional and modern furniture are compared. As mentioned before, when there is no opening in the enclosure, the fire will be ventilation-controlled and go out in a early stage.To get a better idea about the effects of changing building contents on the fire behaviour in the enclosure, the “Window Open-Case” is used.

4.2.1 *Traditional Furniture*

In the scenarios with the traditional furniture (see Table 1), the fire growth rate is slow (α: 0.003 kW/s^2), and the Peak HRR of approximately 700 kW is reached at approximately 1 140 seconds. After the Peak HRR is reached, a slow decay is presented. All the energy is released in 2 400 seconds. The total energy that is released does not result in a flashover situation in the studied compartment; there is not enough fuel burning at the same time. Flame spread from item-to-item does not occur in all situations; in some situations, the fire in the initial burning object is too small to ignite adjacent objects. The maximum temperature in the room of fire origin is between 178 °C for the traditional structure and 190 °C for the renovated structure.

4.2.2 *Modern Furniture*

In the scenarios with modern furniture, the fire development is faster and the Peak HRR higher than the traditional scenarios. At 540 seconds a Peak HRR of approximately 3 600 kW is reached. At this time, the temperature of the hot upper gas layer is reaching at least 400°C. After 720 seconds the fire decays and at approximately 1 200 seconds all fuel is consumed.

4.2.3 *Results Furniture Effects*

Traditional furniture and modern furniture show different fire behaviours. From the figures 15, 16 and 17, it is very clear to see that traditional furniture burns slower and produces less energy, than the modern furniture. With as result that, modern furniture reaches much higher temperatures in the room of fire origin.

A result of the higher HRR, more energy is released in a shorter time, this results in a higher mass loss rate from the fire into the smoke layer. In this comparison influence of the HRR on the hot gas layer is clear. In the modern furniture scenario, the smoke layer descends quickly to 1 meters above ground floor instead of 1.6 meters in the traditional scenario. However, after decaying the HRR the hot upper gas layer increases fast in the modern furniture case.

In Table 10 an overview is given how the peak values for the traditional furniture differ from the modern furniture.

Table 10 The Deviation for Traditional Furniture

	Modern Furniture	Traditional Furniture	Deviation
Heat Release Rate	3 595 kW	700 kW	-80.5%
Hot Gas Layer Temp.			
Traditional	403 ˚C	177 ˚C	-56.1%
Renovated	434 ˚C	190 ˚C	-56.2%
Today’s	411 ˚C	181 ˚C	-56.0%
Smoke Layer Height	1.06 m	1.60 m	50.9%

The following figures show the HRR (Figure 15), hot gas layer temperature (Figure 16) and smoke layer height (Figure 17) vs. time in the room of fire origin.

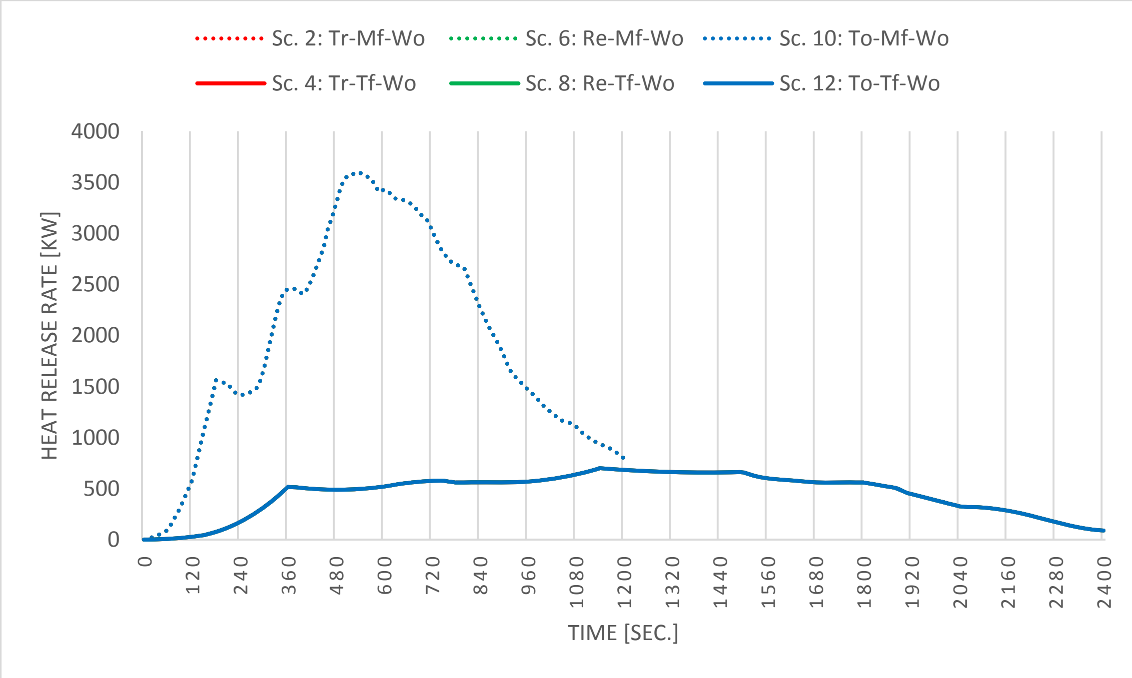

Figure 15 **Heat Release Rate vs. Time Curves, Furniture/Structure Effects**

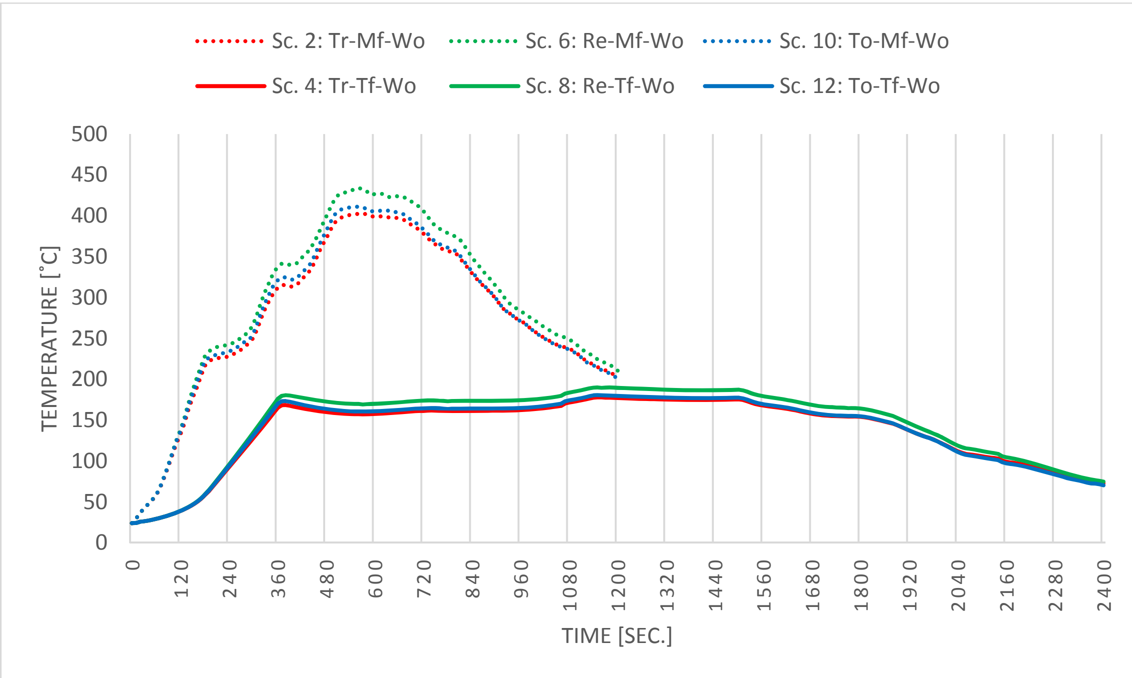

Figure 16 **Hot Gas Layer Temperature vs. Time Curves, Furniture/Structure Effects**

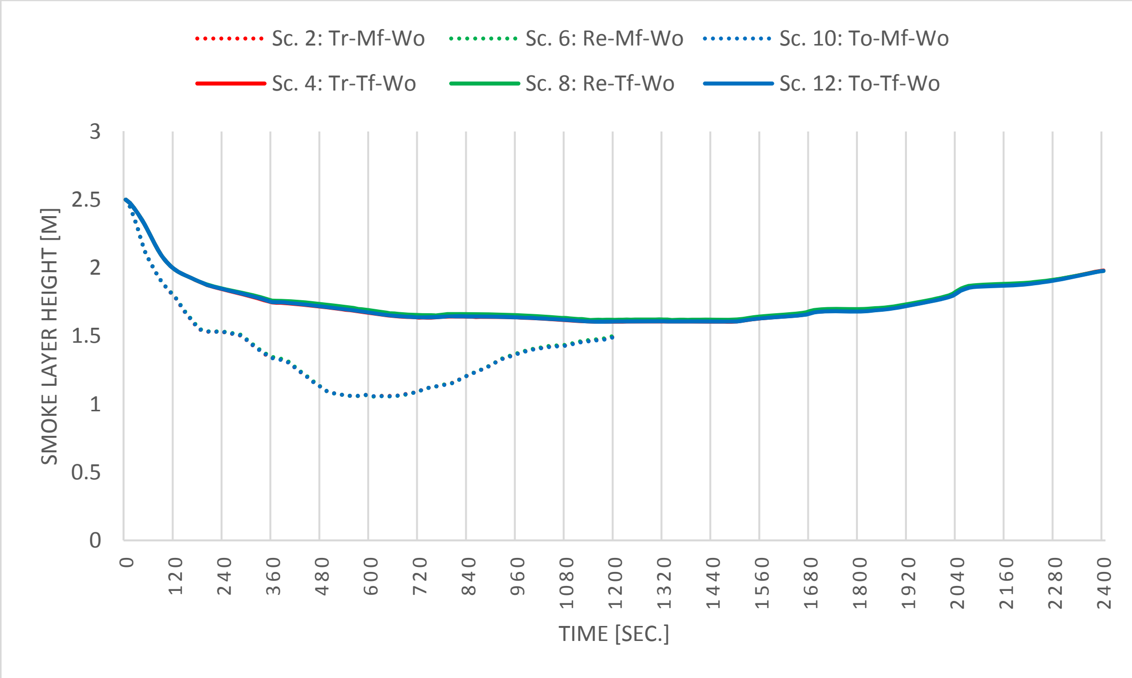

Figure 17 Interface Height vs. Time Curves, Furniture/Structure Effects

4.3 Conditions in Adjacent Room

B-RISK is able to generate the conditions in the adjacent room. In this paragraph, the conditions in the adjacent room (hallway, see Figure 6) are given. In all scenarios the internal doors are open. The conditions that are analysed are temperature and smoke layer height.

4.3.1 Temperature

The temperature in the adjacent room (hallway) will increase when hot smoke enters the room. The hot gas can enter the adjacent room by the opening between the room of fire origin (living room) and the adjacent room. In all scenarios the temperature in the adjacent room is lower than the room of fire origin. The hot gas layer will lose heat by flowing to the adjacent room. Heat will be lost to the interior surface in the room of fire origin and radiation through openings to the outside, what results in lower hot gas layer temperatures in the adjacent room. However, the influence of the structure is still visible. The temperature in the adjacent room in the renovated and today's structure are higher than the traditional structure.

Figure 18 shows the hot gas layer temperature in the adjacent room and the temperature in the room of fire origin for scenario 2, 6 and 10. These scenarios are based on the scenario with modern furniture and windows open. In general, the same results apply to the other scenarios.

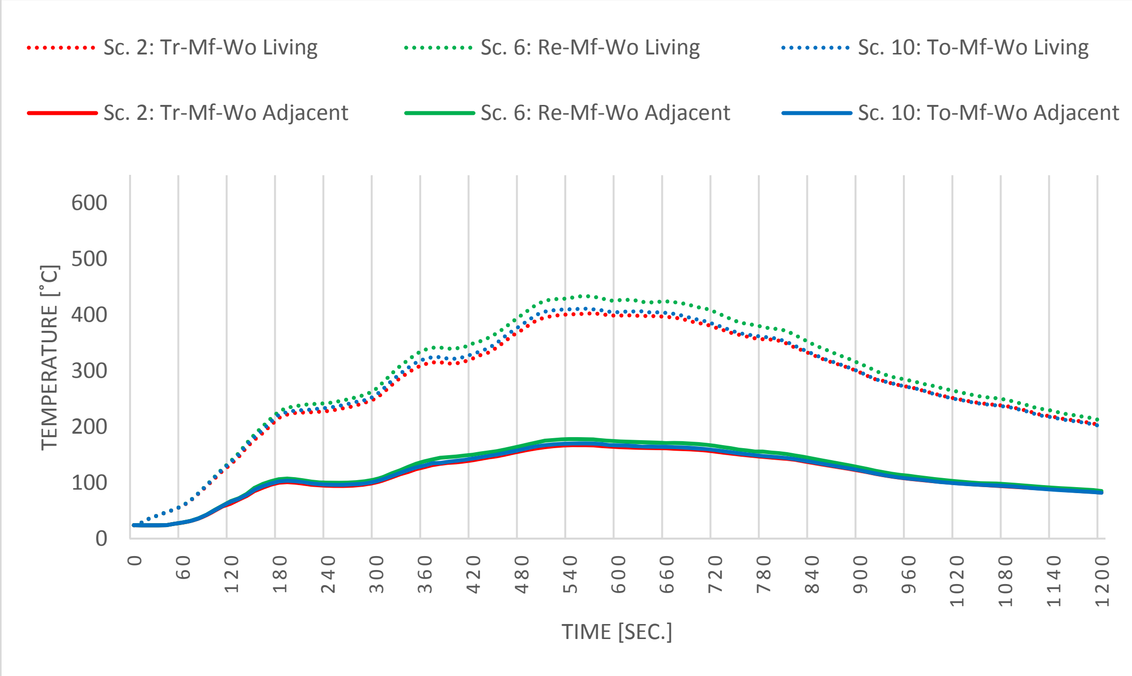

Figure 18 Hot Gas Layer Temperature vs. Time Curves, Fire Room – Adjacent Room/Structures

4.3.2 Smoke Layer Height

When the hot gas layer reaches the opening between the room of fire origin and the adjacent room, the gas layer will flow into the adjacent room. After the height of the gas layer equals in the adjacent room to the room of fire origin, the gas layer in the adjacent room will decrease faster than in the room of fire origin. At a certain point, the hallway is almost totally filled with smoke. Differences in structure types are minimal, but clearer in the adjacent room than in the room of fire origin. The gas layer decent lower with the renovated structure.

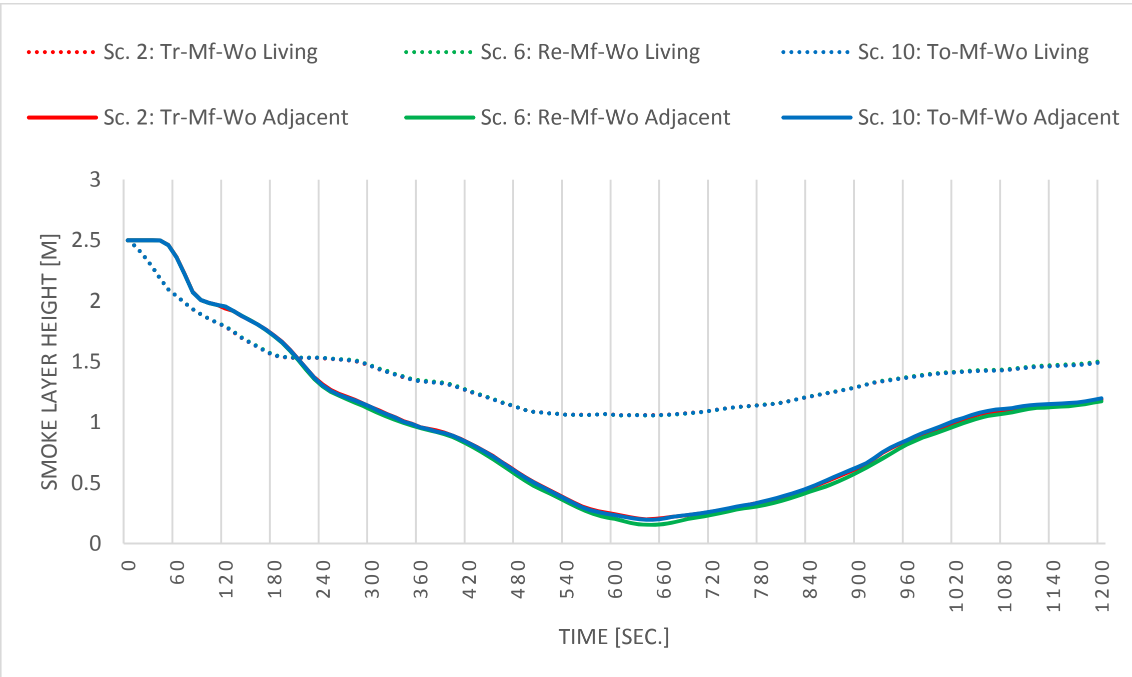

Figure 19 Interface Height vs. Time Curves, Fire Room – Adjacent Room/Structure

4.4 Critical Conditions (Life Safety of the Occupants)

Building fire regulations commonly require two main objectives: Life safety of the occupants and structural stability of the building. Two distinctly different design procedures are applied in each case, the former to do with the pre-flashover stage of the fire, the latter with the post-flashover stage. With the previous data, the critical conditions for each scenario can be checked.

Heat poses is a significant physical danger to humans, both when skin or lungs are in direct contact with heated air and when heat is radiated from a distance. Building regulations therefore typically specify a certain maximum temperature to which humans may be exposed, as well as some maximum radiative heat flux from the hot gas layer. These critical criteria can vary over Europe, in this report, the critical conditions are taken from the British Standards Institution. The conditions are given in Table 11.

Table 11 Critical Conditions that Prevent Evacuation (Christian, 2003)

Critical Conditions that Prevent Evacuation	
Smoke layer height	< 2 m
Smoke layer temperature	> 200 ˚C
Visibility	< 10 m

In Table 12, the time until critical conditions are reached is given. From this table, the “worst-case” scenario for the Case-Study can be determined. Visibility is not taken into account, the maximum distance in a room is 7.9 meter, 10 m will not be reached.

Table 12 Time to Reach Critical Conditions for Each Scenario

Time to Reach Critical Conditions [sec.]						
		Criteria	Smoke Layer 2 m		Smoke Temp. 200 ˚C	
Structure	Content	Windows / Location	Fire Room	Adjacent Room	Fire Room	Adjacent Room
Traditional	Modern	Closed	60	70	-	-
		Open	70	100	170	-
	Traditional	Closed	100	140	-	-
		Open	120	210	-	-
Renovated	Modern	Closed	60	70	350	-
		Open	70	100	160	-
	Traditional	Closed	100	140	350	-
		Open	120	210	-	-
Today’s	Modern	Closed	60	70	380	-
		Open	70	100	170	-
	Traditional	Closed	100	140	370	-
		Open	120	210	-	-

From Table 12 can be seen that, the temperature of the gas layer is not the most critical aspect for occupants during an escape. The gas layer height is a greater aspect for the occupants. In all scenarios, the smoke layer descends lower than 2 meters from the floor.

The scenarios with no opening have the fastest decrease of the gas layer. With traditional furniture, the critical conditions are reached after 100 seconds in the fire room and after 140 seconds this is reached for the adjacent room. The scenarios with modern furniture, have the fastest decrease of the smoke layer. So, in regard to time to critical conditions, this is worst-case of the studied scenarios. After 60 seconds the critical conditions are reached in the room of fire origin and 70 seconds for the adjacent room. This is similar for all structure types.

5 Sensitivity Analysis

The results of this report are based on literature, a 2-zone fire model, and assumptions (as the Case-Study). The chosen “fixed” values that can have an impact on the results, are evaluated in this sensitivity analysis.

The effect of input variables is tested through a sensitivity analysis in order to get results that can be used to discuss the external validity of the results. Sensitivity analysis is done by, determining possible intervals for inputs and testing how changes in input affect the output. As reference input, the Case-Study is taken with the windows open and modern furniture (Mf-Wo) as “Base-Model”. For the effects of geometry and maximum heat release rate, all structure types are analysed. For the effects on fire location and the ventilation, the traditional structure (Tr) is analysed. However, the same results of the influence of structure type can be used from the previous chapter. With the scenarios with open windows, there is enough oxygen supply and differences can be better determined in HRR, hot gas layer temperature and interface height.

5.1.1 Geometry Effects

The results that are gained, are based on a fixed geometry; the living room has an area of 46.4 m^2. Based on United States Census data, houses have over the years increased in average area and incorporate open floor plans (Kerber, 2010). As the Case-Study shows (Figure 5), the living room is directly connected to the kitchen. It can be said that the Case-Study is a modern floor plan. This result in a larger volume, thus more oxygen is available. To determine the effects of the geometry on the results, a living room with an area of 23 m^2 and 69.6 m^2 is studied. This is 50% and 150% of the living room area that is used for the Case-Study. The geometry of the hallway and bedrooms are not changed. For the openings, the same ‘opening factor’ is used.
In the Base-Model, the openings have an area of 7.2 m^2. For the 50% living room the area of the openings will become 3.6 m^2 and for the 150% living room 10.8 m^2. The opening area is divided as follows:

Living room area 50% of the Base-Model:
- Window (L x H): 1.145 x 1.30 meter
- Double door (L x H): 1.00 x 2.10 meter

Living room area 150% of the Base-Model:
- Windows 1 and 2 (L x H): 1.145 x 1.30 meter
- Window 3 (L x H): 2.79 x 1.30 meter
- Double door (L x H): 1.50 x 2.10 meter

The window has an offset of 0.8 meters from the floor, and all the openings have a discharge coefficient of 0.68, this is equal to the Base-Model. In Figure 20 the geometry of the 50% and the 150% living room is given.

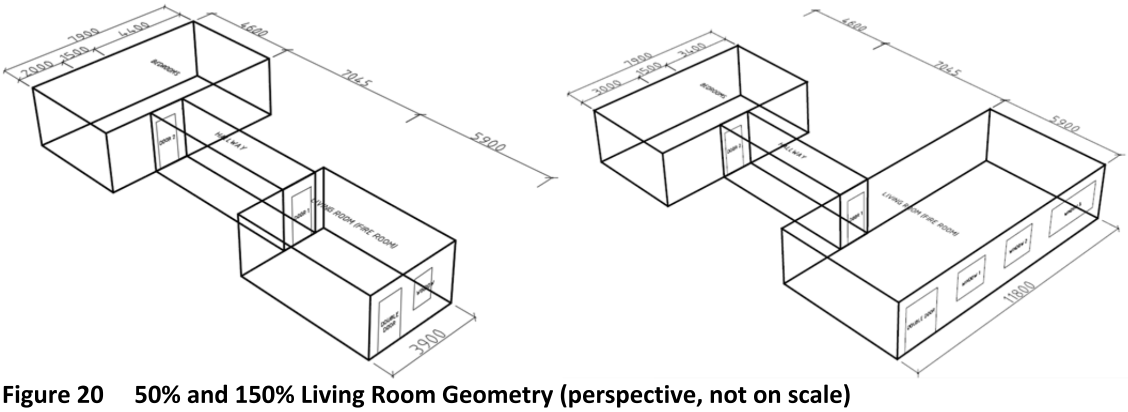

Figure 20 50% and 150% Living Room Geometry (perspective, not on scale)

Figure 21, 22 and 23 shows; the results of the Base-Model, the results of the 50% and 150% living room area, with opened windows. The 50% renovated-case had an error in the simulations and quitted after 330 seconds, therefore the line stops at this time. However, from the other cases a trend can be sketched for this case. From these figures, it can be seen that the geometry has an influence on the fire conditions. The HRR is growing slightly faster when the geometry becomes smaller.

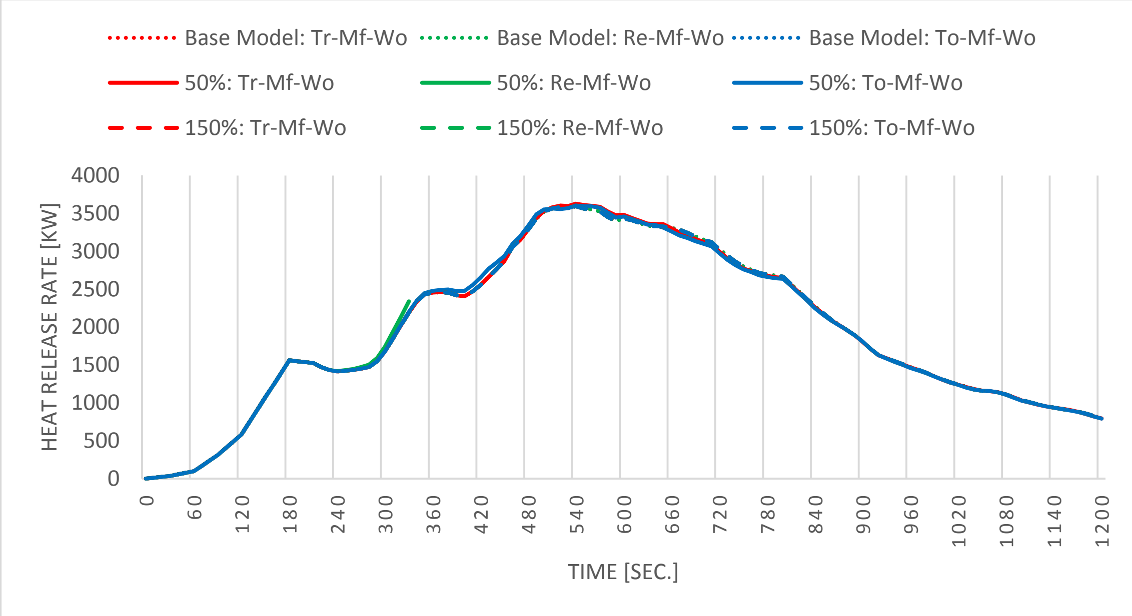

Figure 21 Heat Release Rate vs. Time Curves, Base-Model vs. 50% and 150% living room area

The temperature in the enclosure is significantly higher and the smoke layer decent quicker when the geometry becomes smaller, as a result that critical conditions will be reached earlier. The geometry has a smaller surface area, so fewer losses are presented through the boundary. Also, the fire is relatively big in contrast to the other cases (same fuel properties in a smaller enclosure). When the enclosure becomes bigger, critical conditions are reached later in time. The different structure types exhibit the same results on the influence of the geometry, the renovated structure reached the highest values and the traditional structure the lowest.

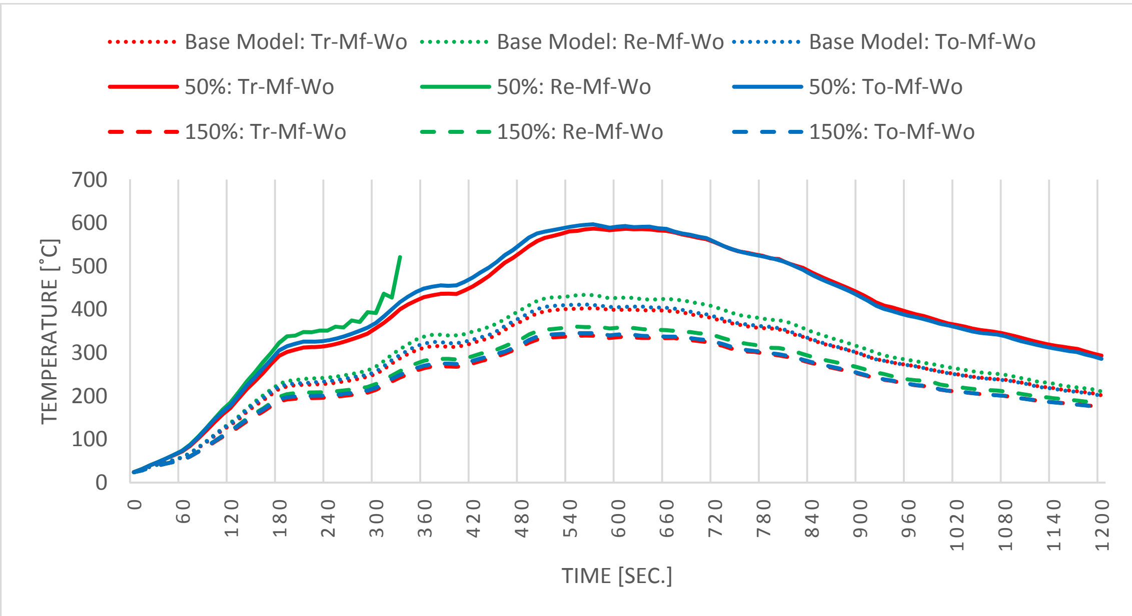

Figure 22 Hot Gas Layer Temperature vs. Time Curves, Base-Model vs. 50% and 150% living room area/Structure

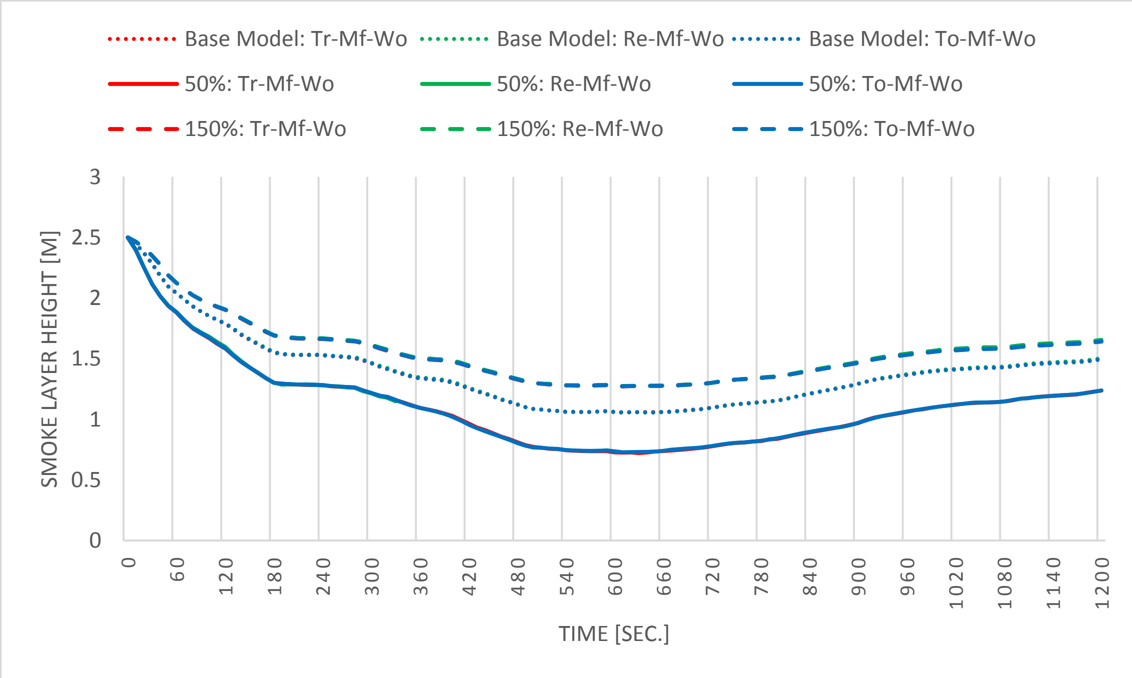

Figure 23 **Interface Height vs. Time Curves, Case-Study vs. 50% and 150% living-room area/Structure**

5.1.2 Heat Release Rate Effects

Living rooms are furnished differently, it is possible that one room has more fuel load than the other. Therefore, it is analysed what the effects is when the HRR per item increases. The comparison is made with the average curves, that are used in the Case-Study and furniture with 50% and 150% of the peak HRR value of the Case-Study (for the Chair and Sofa). In Figure 24 are the HRR-curves showed for the chair and in Figure 25 the HRR-cures for the sofas.

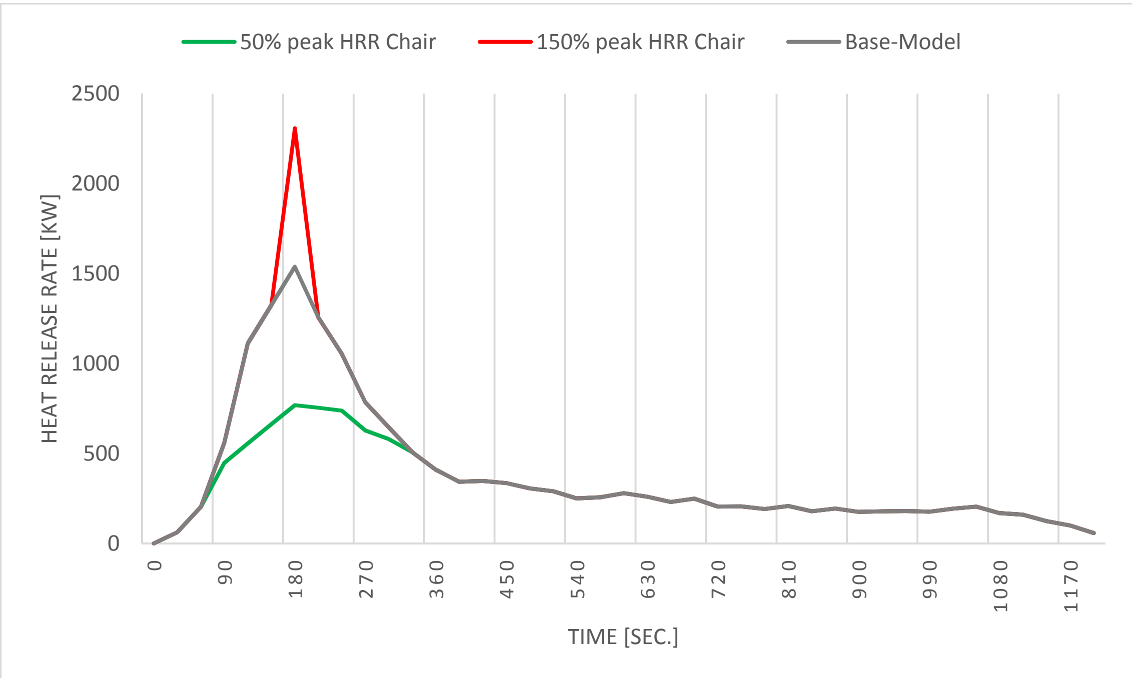

Figure 24 **Heat Release Rate vs. Time Curves Chair, Base-Model, 50% peak HRR and 150% peak HRR**

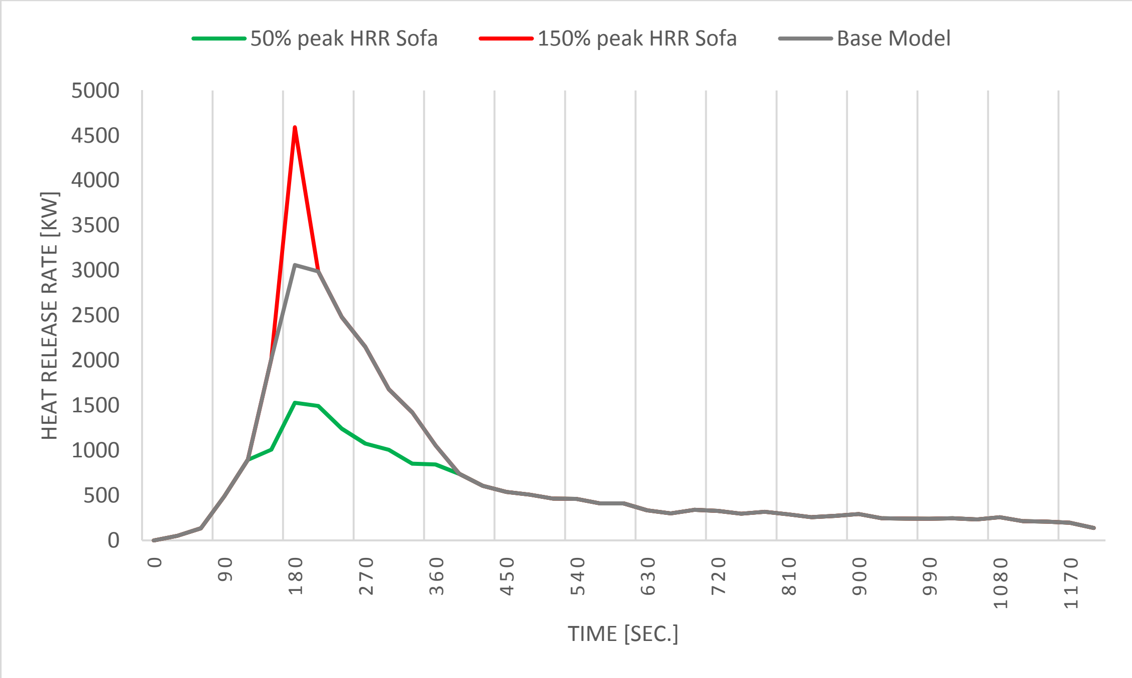

Figure 25 **Heat Release Rate vs. Time Curves Sofas, Base-Model, 50% peak HRR and 150% peak HRR**

For the coffee- and side table the same values are used as the Case-Study. Figure 26 shows the HRR-curves in the living room. In this figure, it can be seen that the growth rate of the 150%-case is faster than all other cases. This is because, a higher peak HRR of the chair and sofa is used. In the same time higher values for the peak HRR is reached.

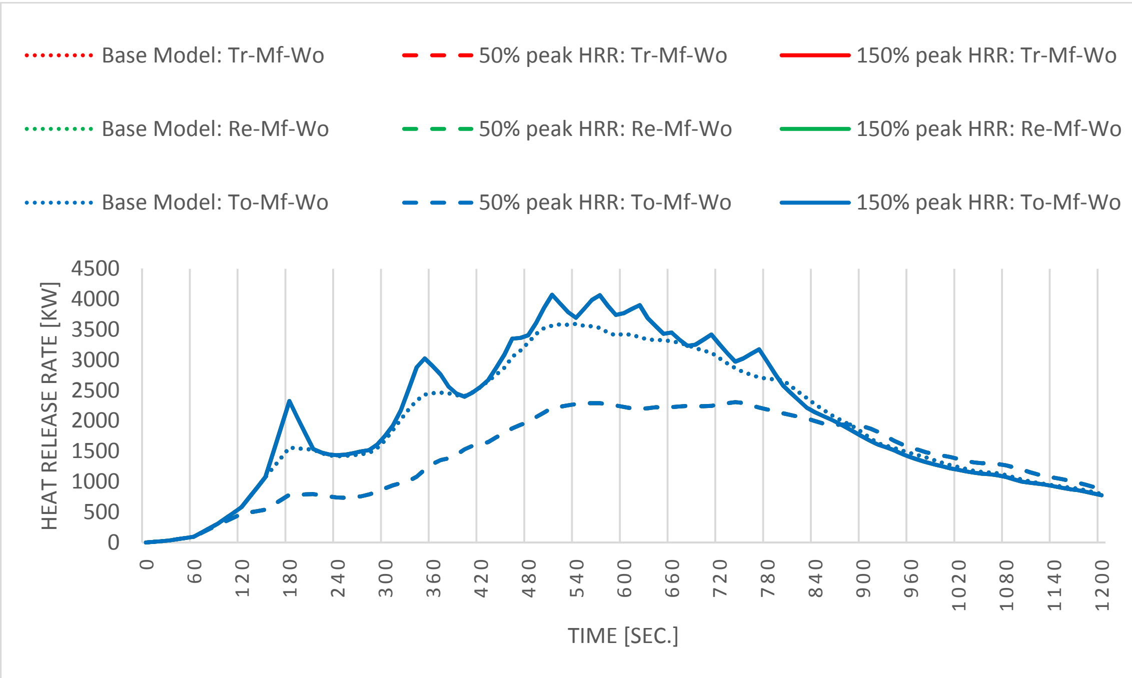

Figure 26 **Heat Release Rate vs. Time curves, Fuel Load/Structure Effects**

As Figure 27 and Figure 28 show, the same applies to the hot gas layer and interface height. Critical conditions will be reached earlier, when the growth rate is faster.

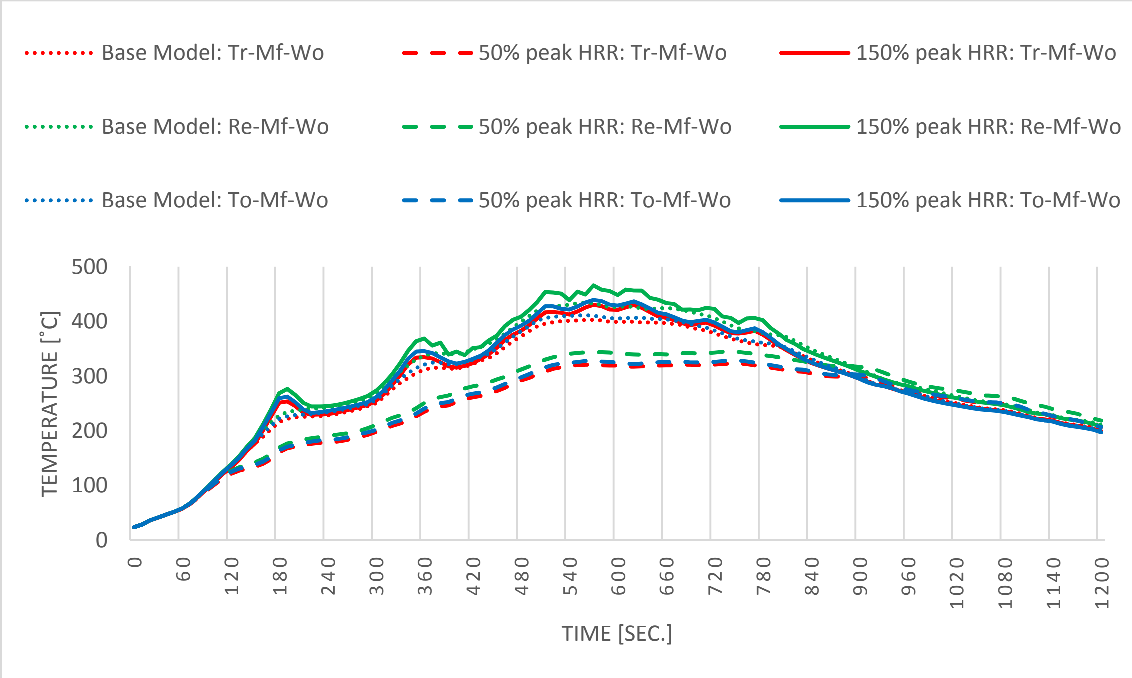

Figure 27 **Hot Gas Layer Temperature vs. Time curves, Fuel Load/Structure Effects**

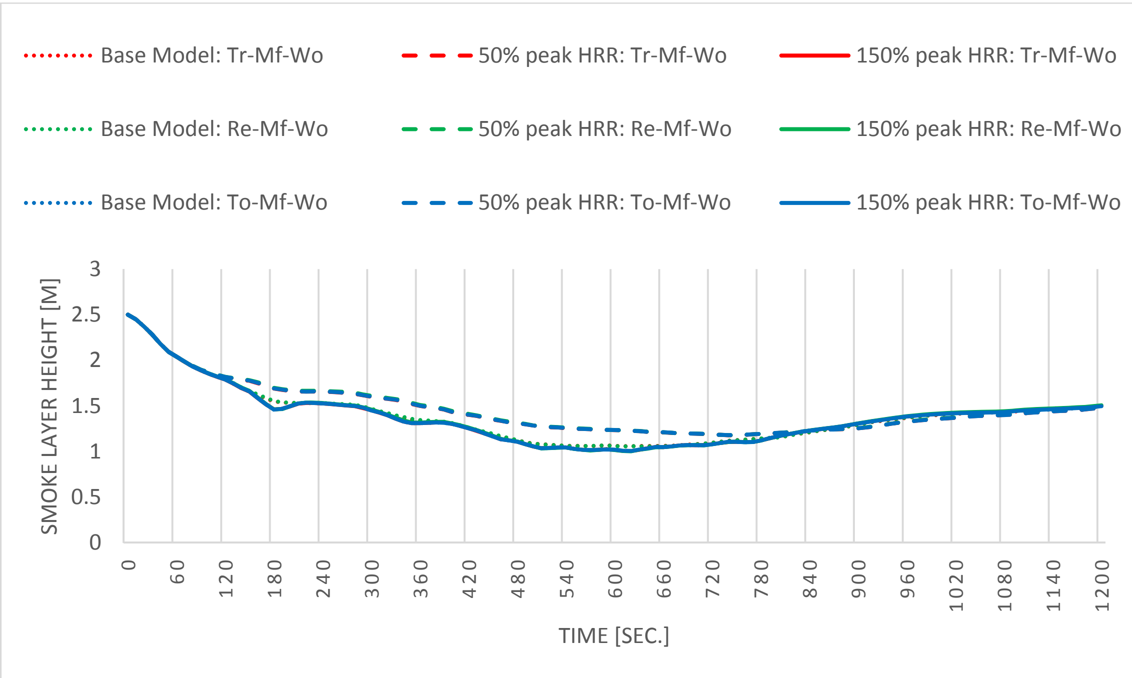

Figure 28 **Interface Height vs. Time curves, Fuel Load/Structure Effects**

5.1.3 Place of the Fire Location Effects

With B-RISK Design Fire Tool, different configurations can be analysed. The program can generate randomly configurations for the furniture placement. By using this tool, the effects of the location of the furniture on the fire behaviour is determined. Five randomly configurations are taken. In Appendix F, the five configurations are shown. Only the results are shown for structure type traditional, the other structure types will generate the same effects, but with slightly higher temperatures in the living room. The smoke layer would give similar results for all structure types.

From figure 29, 30 and 31 it can be seen that, the place of furniture has influence. When objects are placed closer to each other, the chance of flashover situation is getting bigger. The peak HRR for the different configurations are in between 2 672 kW and 4 287 kW. However, the differences in HRR, the temperature of the hot gas layer and the smoke layer height are not significant affected. The hot gas layer temperatures are in between 333 °C and 456 °C, for the smoke layer height is this, 1.06 m and 1.24 m. A result of this relative small chance in temperature and smoke layer height is; the opening factor is in all cases similar. This cause heat losses through the openings, also the hot gas can escape the enclosure. The critical conditions are therefore also minimal affected. In Figure 29 can be seen, that at approximately 1 500 kW the place of the furniture effect has on the fire behaviour. At this point, secondary items can receive enough radiation (from the first burning object) to ignite.

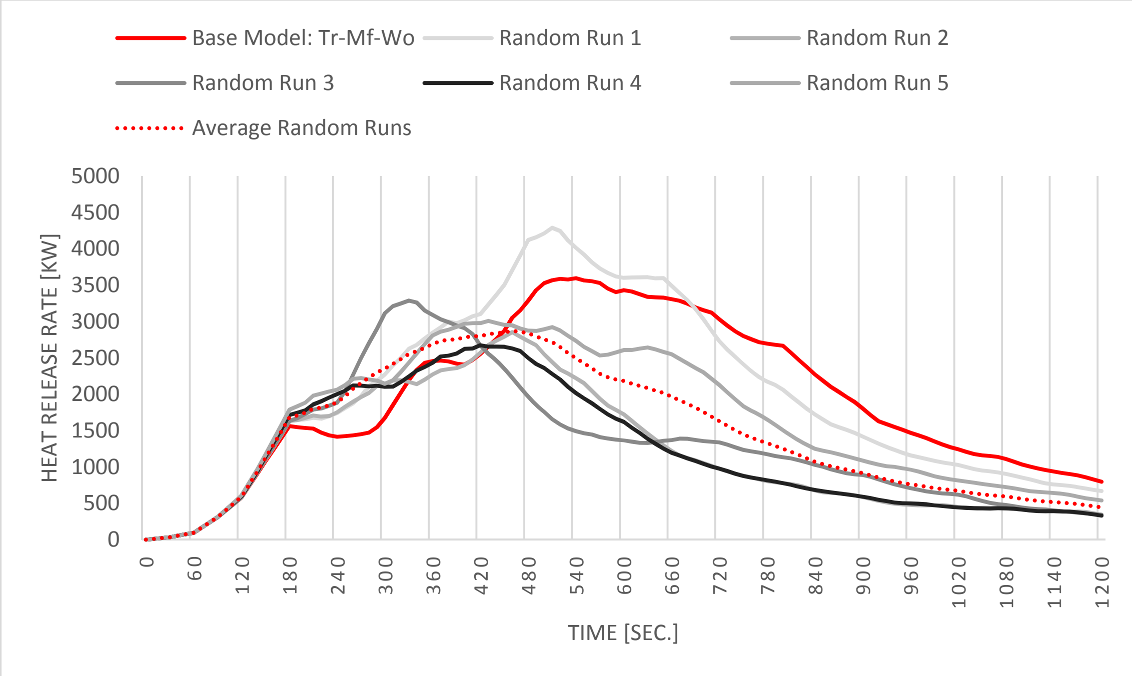

Figure 29 **Heat Release Rate vs. Time Curves, Randomly Configurations**

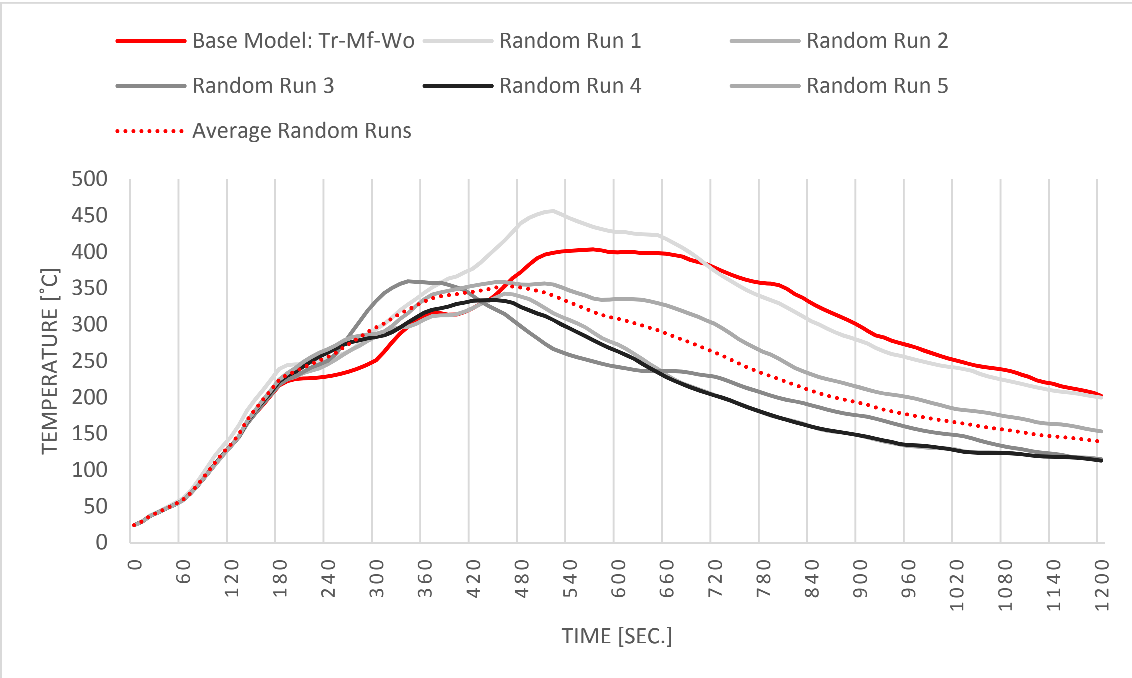

Figure 30 **Hot Gas Layer Temperature vs. Time Curves, Randomly Configurations**

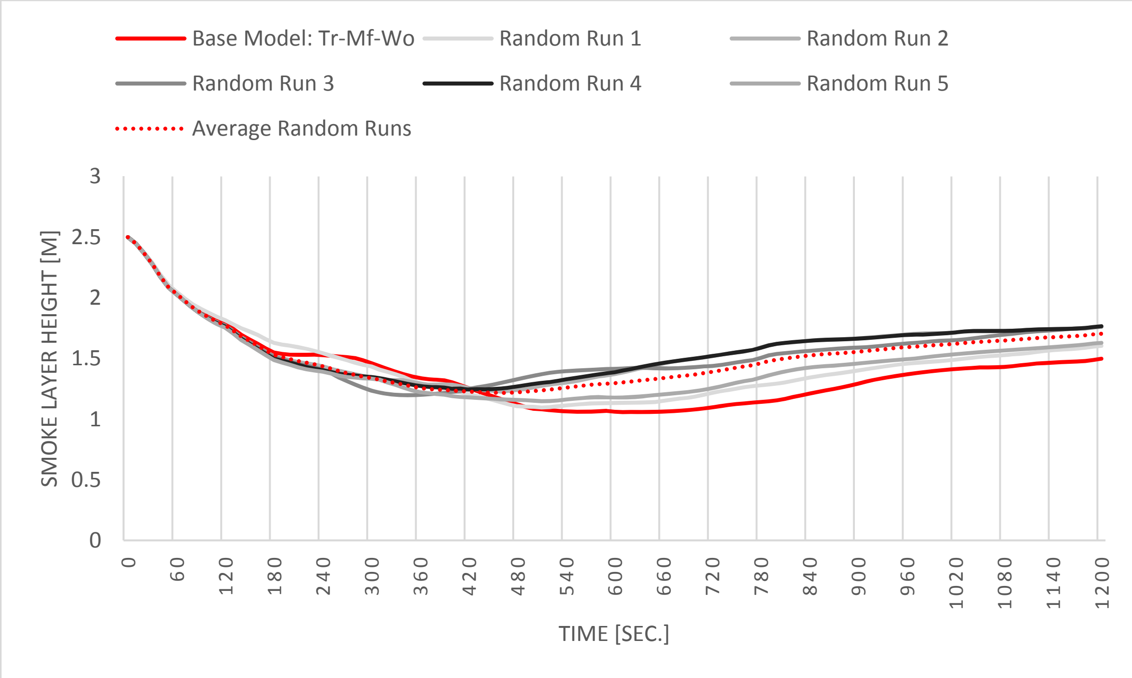

Figure 31 **Interface Height vs. Time Curves, Randomly Configurations**

5.1.4 Ventilation Opening Effects

The Case-Study has three openings (2 windows and a double door) to the outside. It is possible that openings are closed or opened. Even glass can break during a fire in the enclosure. Therefore, the influence of the openings has been analysed in this paragraph.

As written before in the scenario 1 (Table 1) is no openings in the enclosure, the energy that is released is lower than where the openings are opened. In Figure 32 a comparison is made with different opening sizes. The Base-Model has three openings, in the comparison four possibilities are presented, namely:

1. Scenario 1 – No openings open (Tr-Mf-Wc)
2. Scenario 2 – All openings open (Tr-Mf-Wo: Base-Model)
3. Scenario 2a: 1 window open (1.55 x 1.30, sill height 0.823 meter)
4. Scenario 2b: Double door open (1.50 x 2.10, sill height 0.0 meter)

By closing openings the HRR will be controlled by the oxygen supply, the less oxygen, the lower the HRR. As the figure shows, in the case no openings open (Sc. 1: Tr-Mf-Wc) and Window Open, the HRR is controlled by the oxygen supply. In these cases the openings are too small to supply enough oxygen for full combustion of the fuel.

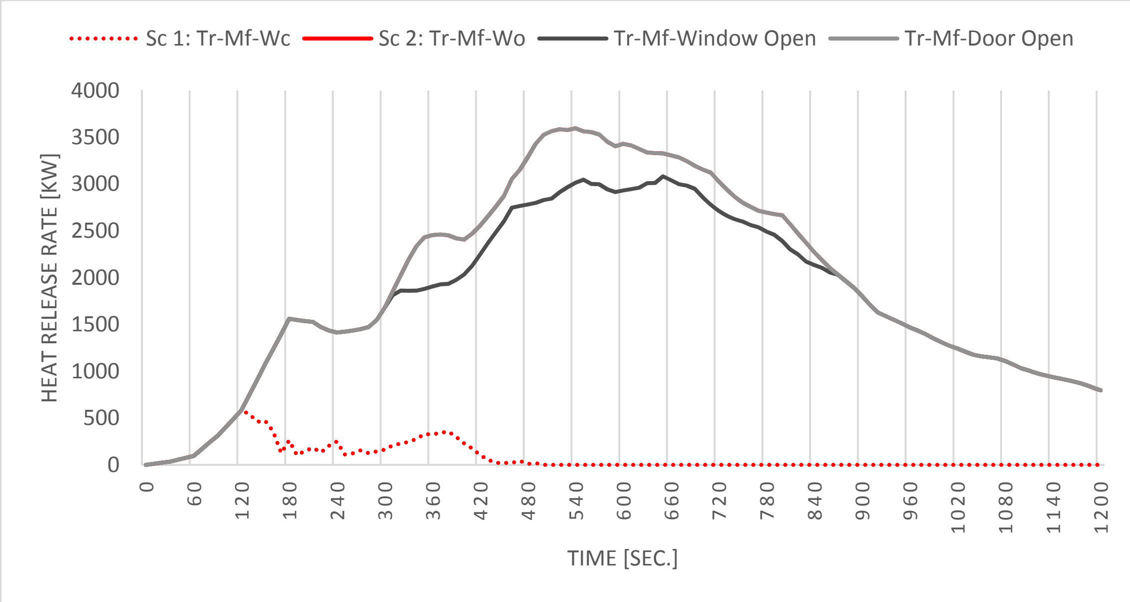

Figure 32 Heat Release Rate vs. Time Curves, Opening Effects

Contradiction to the HRR is, when the opening area is less, there are less heat losses through the opening. In Figure 33 it can be seen that even when the HRR is lower or equal to the case where all openings are open, still temperatures above 450˚C can be reached. Most of the heat will stay in the enclosure what results in relatively high temperatures compared to the HRR. When the conditions are precisely matched (with just enough oxygen supply), it is even possible with a relatively low HRR to reach higher temperatures than the Base-Model.

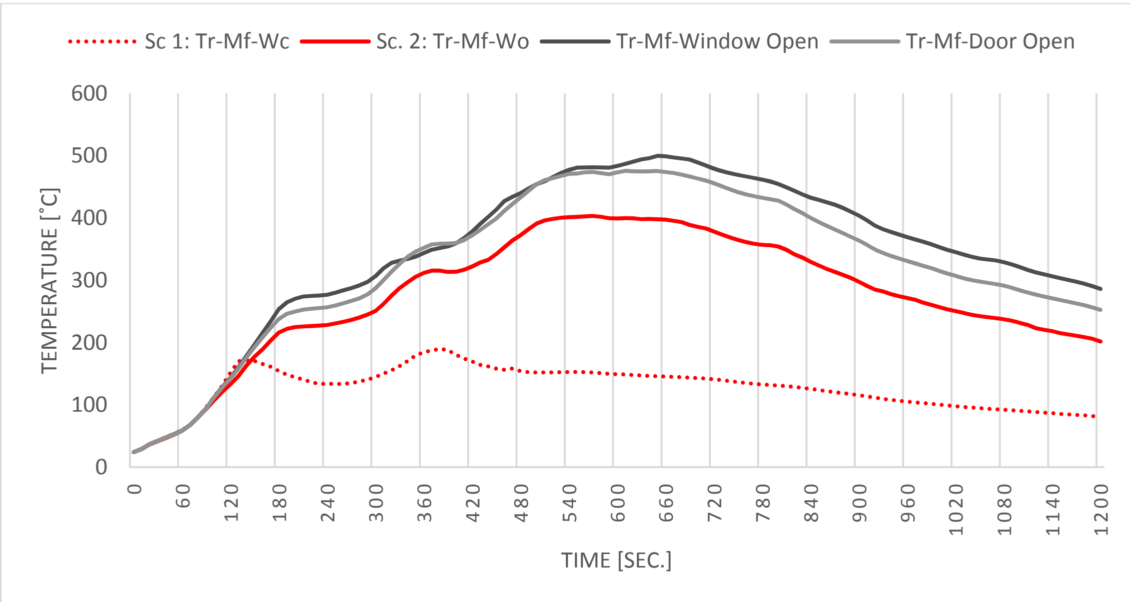

Figure 33 Hot Gas Layer Temperature vs. Time Curves, Opening Effects

In the case of the smoke layer height, when the openings become smaller the smoke layer decreases quicker. This is a result of the mass flow rate through the openings; when the mass flow rate through the openings is less, the mass that is released from the flame will stay in the enclosure and transported into the hot gas layer. This creates a thicker smoke layer, and critical conditions will be reached earlier.

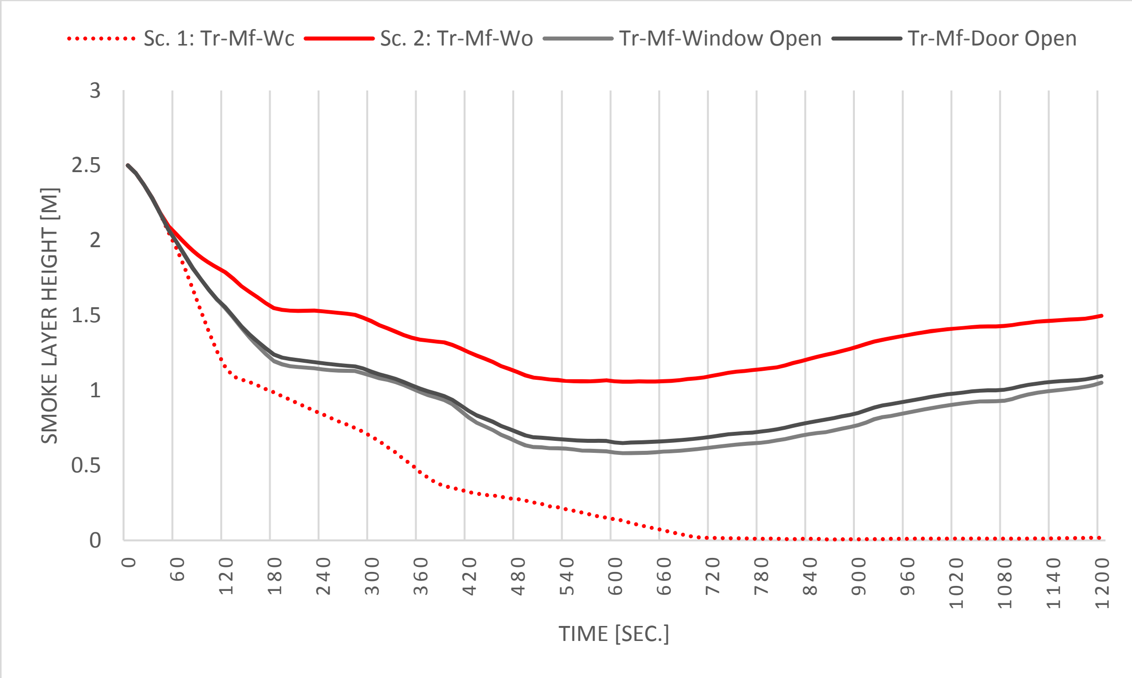

Figure 34 Interface Height vs. Time curves, Opening Effects

5.2 Overview of Effects

The previous paragraphs have shown, that the fixed values have an influence on the fire behaviour in the enclosure. In this paragraph an overview is given how much these parameters differ from the Base-Model. Table 13 shows the results, taken from the peak values.

Table 13 Sensitivity Overview – Deviation from Base-Model

	Heat Release Rate	Temperature	Smoke Layer Height
Place of the Fire Location Effects			
Run 1	19%	13%	4%
Run 2	-21%	-15%	16%
Run 3	-9%	-11%	13%
Run 4	-26%	-17%	18%
Run 5	-16%	-11%	9%
Ventilation Openings Effect			
Window Open	-14%	24%	-45%
Double Door Open	0%	18%	-39%
Traditional			
Geometry 50%	0.9%	45.6%	-31.8%
Geometry 150%	0.0%	-15.8%	20.3%
Renovated			
Geometry 50%	Error	Error	Error
Geometry 150%	0.0%	-17.0%	20.7%
Todays			
Geometry 50%	0.3%	45.0%	-31.1%
Geometry 150%	0.0%	-16.0%	20.4%
Traditional			
Peak HRR 50%	-35.8%	-19.7%	11.3%
Peak HRR 150%	13.3%	6.8%	-4.9%
Renovated			
Peak HRR 50%	-35.8%	-20.6%	11.7%
Peak HRR 150%	13.3%	7.4%	-5.0%
Today's			
Peak HRR 50%	-35.8%	-20.1%	11.5%
Peak HRR 150%	13.3%	6.8%	-4.9%

6 Discussion

This report is based on a fire model and assumptions (as input for the fire model). The focus of this report is to investigate the influence of the development of the building structure and building content on residential fires. The building structure and building content have changed rapidly across Europe the last decades. This report gives a better understanding how this change has influenced the fire behaviour in residential fires. Residential fires are becoming relatively big in a short time, due new materials in furniture. The building structure also contributes to higher temperatures in the building enclosure. However, these effects are less evident.

The used assumptions of the fire model, the research results, and the applied methodology in this report are discussed in this chapter.

6.1 Internal Validity

Internal validity is the extent to which it can be said that a cause and effect relationship can be established. The results of this report are generated by the fire-model B-RISK. Therefore, it is necessary to discuss the assumptions in B-RISK and how well it can represent some actual fire conditions.

B-RISK is a 2-zone model and uses assumptions to calculate the conditions in an enclosure. The main assumption of a 2-zone model is that the model the room divides in two homogenous zones, a hot upper layer and a relatively cool lower layer. This gives not exactly the temperatures in the room. However, this gives a good approximation. Beside this assumption, B-RISK uses sub-models for;

- Heskestad plume entrainment
- Flame spread
- Convective wall flows
- Radiation exchange
- Burning rate enhancement (not used, in this research)

The most important sub-model that has an influence on the results of this report is the Flame spread model and Burning Rate Enhancement model. These models have an influence on the HRR-curves. All conditions in the enclosure are related to the HRR-curves.

The ignition of secondary items is based on the radiation that is received by the secondary item, which occurs in one of two ways and based on the item-to-item fire spread model developed by Baker (Baker et al., 2011):

1. Radiation from the flames of burning items
2. Radiation from the underside of the hot upper layer

The radiation from the flames of burning items is modelled by using the Point Source Model (Modak's point source model), represented mathematically as:

$$\dot{q}"_{fl} = \frac{\dot{Q}\chi_r}{4\pi r^2}$$

Equation 3

Where, *r* is the distance of the target from the "centre" of the flame, and χ is the fraction of total energy radiated.

Baker investigated six flame radiation models (Baker et al., 2011), a series of free-burning radiation experiments with propane gas burners were done, to determine which of the six flames radiation models was best suited for the radiation and ignition sub-model. The Modak's point source model gave the best match to the actual experimental heat flux values that were measured. From this, it can be stated that the radiation model from the flames of burning items to an item, that is used in B-RISK gives a good approximation.

The radiation from the underside of the hot upper layer, which is treated as a planar, uniform, isothermal “surface”. The surface is also assumed to be both “diffuse”, and “grey”. The heat flux from the hot upper layer to the top of the object is therefore calculated as:

$$\dot{q}"_U = \varepsilon_U \sigma T_U F$$

Equation 4

B-RISK assumes that the secondary object is located in the centre of the compartment. In most cases the secondary object will not be located in the centre of the compartment, as a result of that higher values will be used for the heat flux, a slightly over prediction of the fire curve can occur.

Another important sub-model is the, Enhance Burning Rate due to Hot Layer Effects. B-RISK recommend this sub-model, when data is gained from a free-burning test. In this research test data is used from a room calorimeter, therefore this sub-model is not used. However, from the results it can be seen that the HRR for the different structure types is equal to each other, this is unreasonable (In the renovated-case the temperature of the hot gas layer is higher, what results in more radiation to the fuel). By using the sub-model, differences will appear for the different structure types. In Figure 35 is this shown.

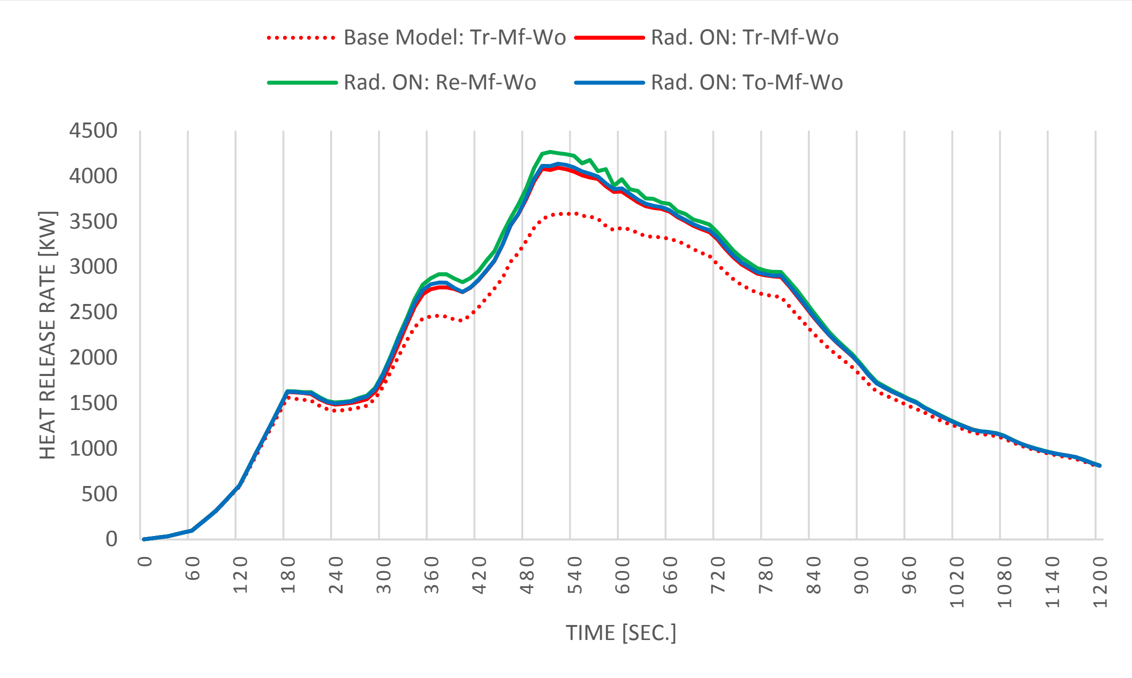

Figure 35 Comparison Enhance Burning Rate due to Hot Layer Effect OFF/ON

When using the sub-model (Enhance Burning Rate due to Hot Layer Effects) in this research, this will present an over-prediction. In order to get a good approximation, it can be expected that the HRR of each structure type is within the range of the Base Model HRR-curve and the curve of the structure type (with the sub-model ON).

6.2 External Validity

External validity is, the extent to which the results of this report can be generalized in other situations. In this report, a Case-Study is used to analyse the impact of the development of building structure and building content on the fire behaviour and room conditions in a residential building. Data that is used for the structures types is based on literature, this data may be slightly different from reality. Nevertheless, it gives a good approximation for the different structure types.

6.2.1 *Case-Study Boundary Parameters*

The fire behaviour and room conditions will depend on many factors. The most important parameters for the boundary on the fire behaviour in a building is the enclosure dimensions of the geometry, material properties and the 'openings-factor'.

The geometry that is used is more likely for modern buildings. The living-room is connected directly to the kitchen, and internal height is 2.5 meters, this is typical for new residential buildings. Traditional residential buildings generally have smaller spaces and a less height. Therefore, is in the sensitivity analysis the influence of the geometry determined. From this analysis, it can be seen that if a traditional house is smaller the hot gas layer is hotter and the smoke layer height decent lower.

Regarding the material properties, data is used from literature. This may differ from reality. However, to limit the research, some estimations need to be done.

The other main factor that has an influence on the fire behaviour and room conditions is the opening factor. New residential buildings are better insulated and more air-tight than traditional buildings. It is conceivable that a new residential building has a smaller opening factor than traditional buildings. This results in a quicker under-ventilated fire situation for new buildings (see paragraph 4.1.3). However, windows/doors can be opened by the users all the time. This means that the opening factor is very depended and hard to predict the exact situation during the fire. Therefore, different cases are analysed in this report.

It is also possible to calculate a more accurate result. By adding pressure build-up, a ventilation system and breaking of glass more accurate results can be gained. In the case of a closed enclose, failure of glass can cause a sudden oxygen supply, resulting in a rapid fire development. However, these factors are not believed to have an influence on the results of this report. The renovated case will still lead to higher values in the enclosure.

The results that are gained give a clear overview of the fire development and room conditions in residential buildings. The results from the Case-Study and sensitivity analysis shows a clear trend of what will happen if different parameters are changed. Therefore, the results can be seen as representative of the different residential buildings types.

6.2.2 *Case-Study parameters Fuel Properties*

Data that is used for the HRR for modern furniture came from tests done in laboratories. Conditions can be different compared to this particular Case-Study. Material properties, ventilation openings, and the geometry are not totally equal to each other. However, by lack of better date, this information is used.

For the traditional furniture, it is difficult to find experimental data. Before the 70's few fire experiments have been done. Much of the data that is used in this report is based on theory from Dr. Dehaan. Dr. John Dehaan has been done fire and explosion investigations for over 30 years. This is not a hard reference, and this can be an uncertainty what needs to take in mind.

Another uncertainty can be, the starting point of the fire. It is hard to say which item ignites first. Therefore, an average value is taken in this report. It is possible that in a specific situation the fire-curve reach higher HRR's than used. In additional to this, only the "standard" items are taken into account. Electro devisers, floor covering, etc. are not. The total HRR-curves that are generated are indicative and likely undervalued compared to reality. If other HRR-curves would have been used, it is still considered to be very likely that the same general influence of fire behaviour and fire conditions, as identified in this report, would have been identified.

6.3 The Applied Method

The method that is used in this report will influence the results. Therefore, in this paragraph, the used method is discussed.

To generate results of the influence of the development of the building structure and building content a fire model is used. For this report, B-RISK is used. B-RISK is a 2-Zone model, 2-zone models normally split the room into two vertically uniform zones; the hot upper gas layer due to the fire and the cool layer below. The hot upper gas layer and the cool layer below are uniform zones, it is an average temperature of that layer. The input-data that is used is collected from literature. Therefore, the results cannot be seen as a reference for all residential buildings. Instead, this report focused on the influence of the development of building structure and building content. To get a general idea how this development has influenced the fire behaviour and room conditions in residential buildings, an approximation of the fire load and building structure is used.

Other ways of generating results for this type of research can be done by doing experiments or by advanced fire-models (CFD-models). A disadvantage of these type of methods is that they are time demanding. An advantage; the results will be detailed and precise. Nevertheless, the fire model that is used in this report gives a good approximation, from the results a clear trend can be seen, more detailed and precise methods are believed to have generated the same conclusions on the research questions.

7 Conclusion

The topic of this report was to analyse the influence of building structure and building content on residential fires. By using a Case-Study and a fire-model, an overview is created how the developments affect the fire behaviour and room conditions. Two research questions were formulated for this report, namely:
RQ 1: *Which influence has the change of insulation on the fire behaviour in a living enclosure.*
RQ 2: *Which influence has the change of building content on the fire behaviour in an enclosure.*

The most valuable outcomes are listed below:

- Residential buildings become more and more energy efficient with more insulation; more energy efficient buildings are good for the environment. However, more insulation cause fewer energy losses through the enclosure boundaries in a fire situation. Traditional structures are commonly built in brick without insulation. A part of the heat that is produced by the fire will be conducted in the solid structure, what results in more heat losses through the structure and lower temperatures in the enclosure than the Renovated and Today's structure.

- The renovated structure reach the highest peak values for temperature and smoke layer height. The structure is built with an insulation layer on the inside of the enclosure. The insulation on the inside matters more than if it the insulation was placed on the outside because the heat wave reached the insulation layer earlier. By reaching the insulation layer first, heat is relatively slow conducted into the structure. This results in less heat losses through the structure.

- When the smoke layer reaches a height of 2 meters above floor level, critical conditions for occupants are reached according to the British Standard Institute. When windows are closed, the critical condition is reached earlier than when windows are opened. After 60 seconds critical conditions are reached for all structure types by using modern furniture. This scenario is the most critical scenario for occupants.

- Traditional furniture and modern furniture show different fire behaviours. Traditional furniture burns slower and produces less energy than modern furniture. Therefore, modern furniture reaches higher HRR's and higher temperatures very rapidly in the enclosure.

- Temperatures in the adjacent room are lower than the room of fire origin. The hot smoke layer loses heat by flowing to the adjacent room. The temperature in the adjacent room is higher in the renovated and today's structure than the traditional structure. The differences are not as obvious as in the fire room itself.

- In general, the development of the building structure and building content results in more dangerous fire situations in a residential building. For life safety in a residential building, the change of the material in the furniture is the biggest threat. When the fire becomes fully developed, the effect of insulated structures become more evident, renovated and modern structures increase the temperatures in the enclosure.

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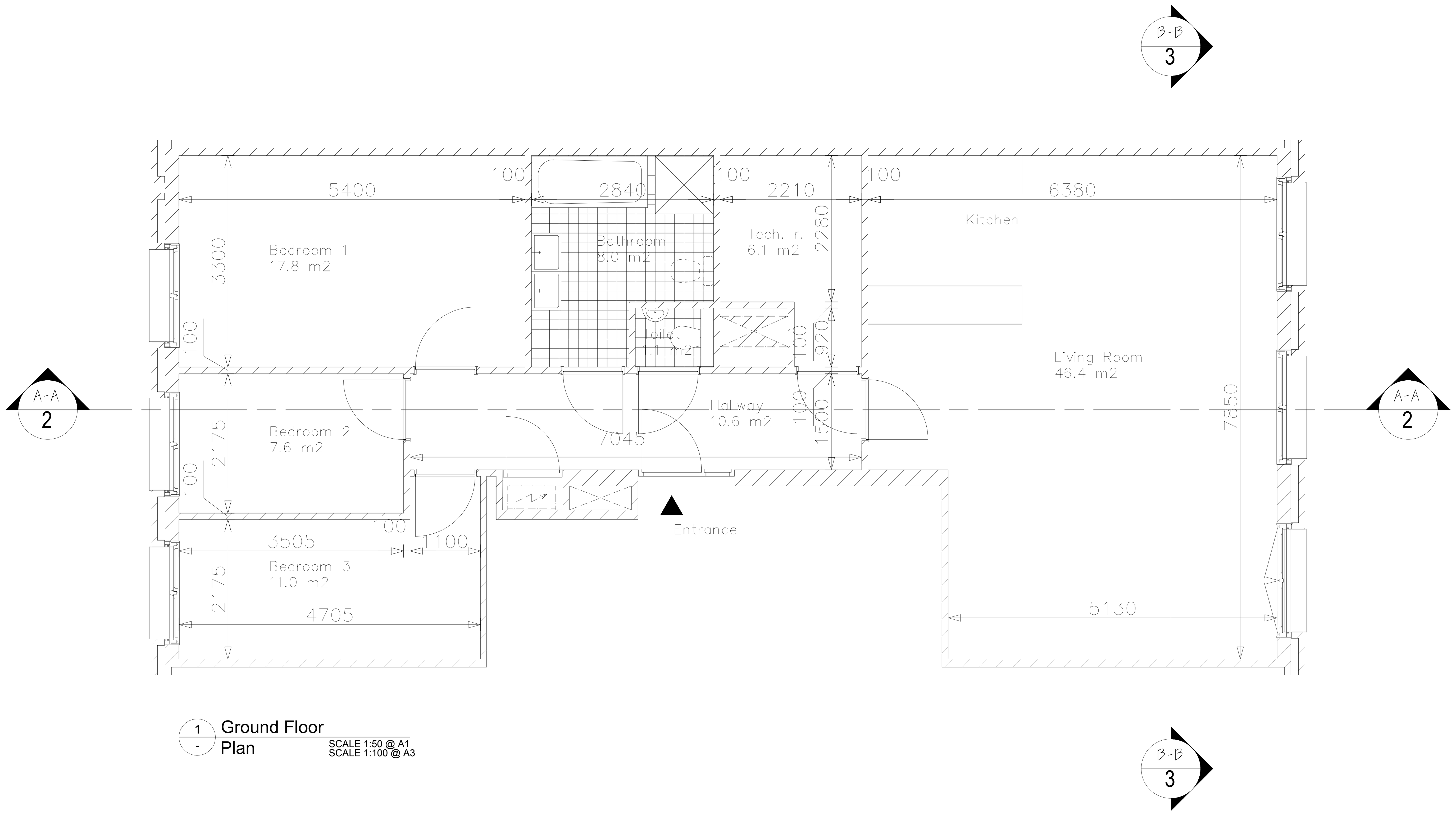
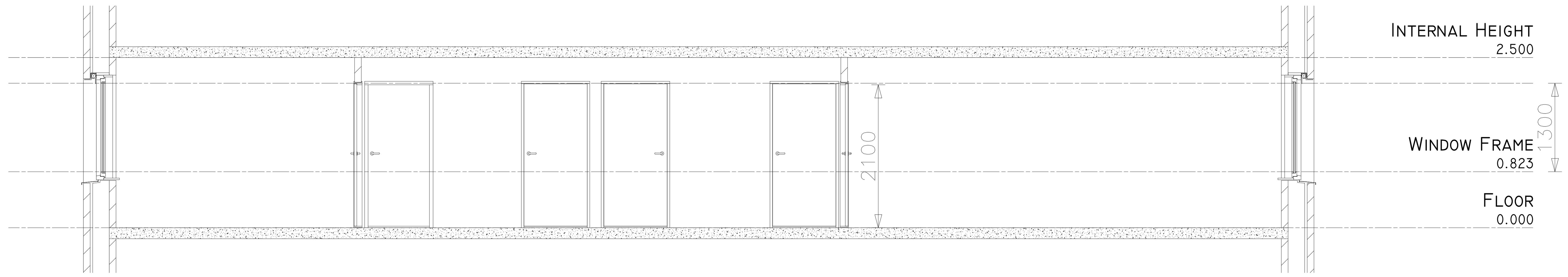
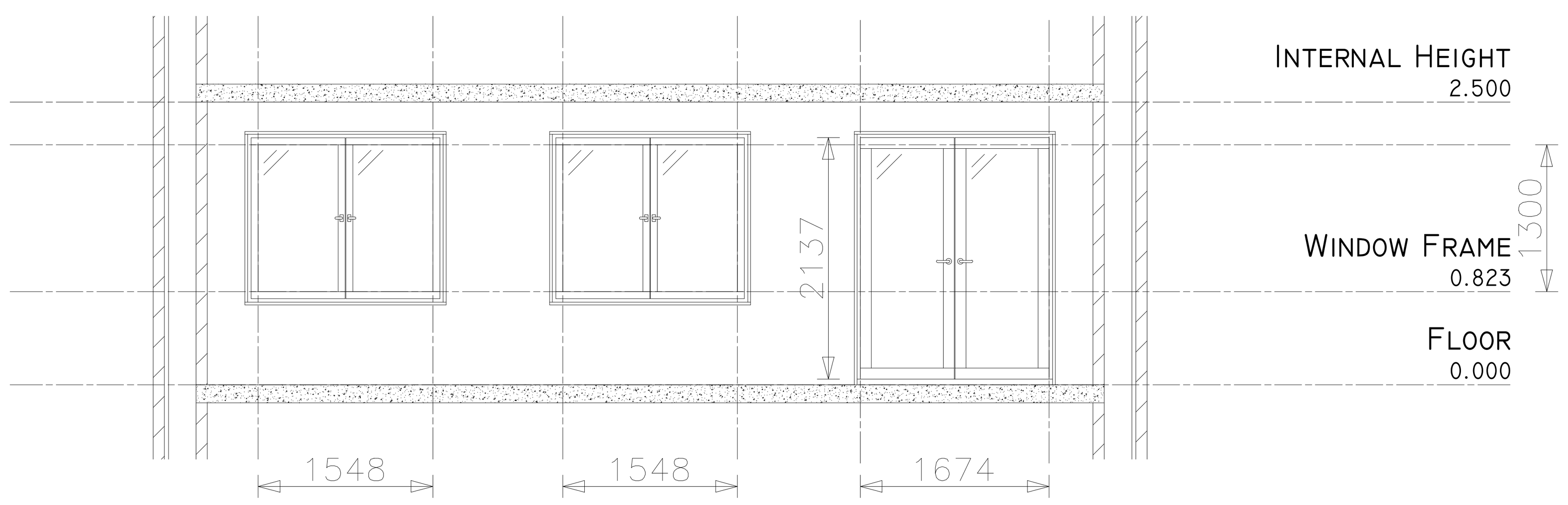
Appendix A: Floor-Plan – Case Study Apartment



1 Ground Floor Plan
SCALE 1:50 @ A1
SCALE 1:100 @ A3



2 Standard House Section A-A
SCALE 1:50 @ A1
SCALE 1:100 @ A3



3 Standard House Section B-B
SCALE 1:50 @ A1
SCALE 1:100 @ A3

DRAWING NOTES

REV	DATE	DESCRIPTION	DRAWN	CHECK
00	06-03	Thesis design	HH	NJ

DRAWING REVISIONS

PROJECT

Influence of Building Structure and Building Content on Residential Fires

Hilco Hiemstra

DRAWING TITLE

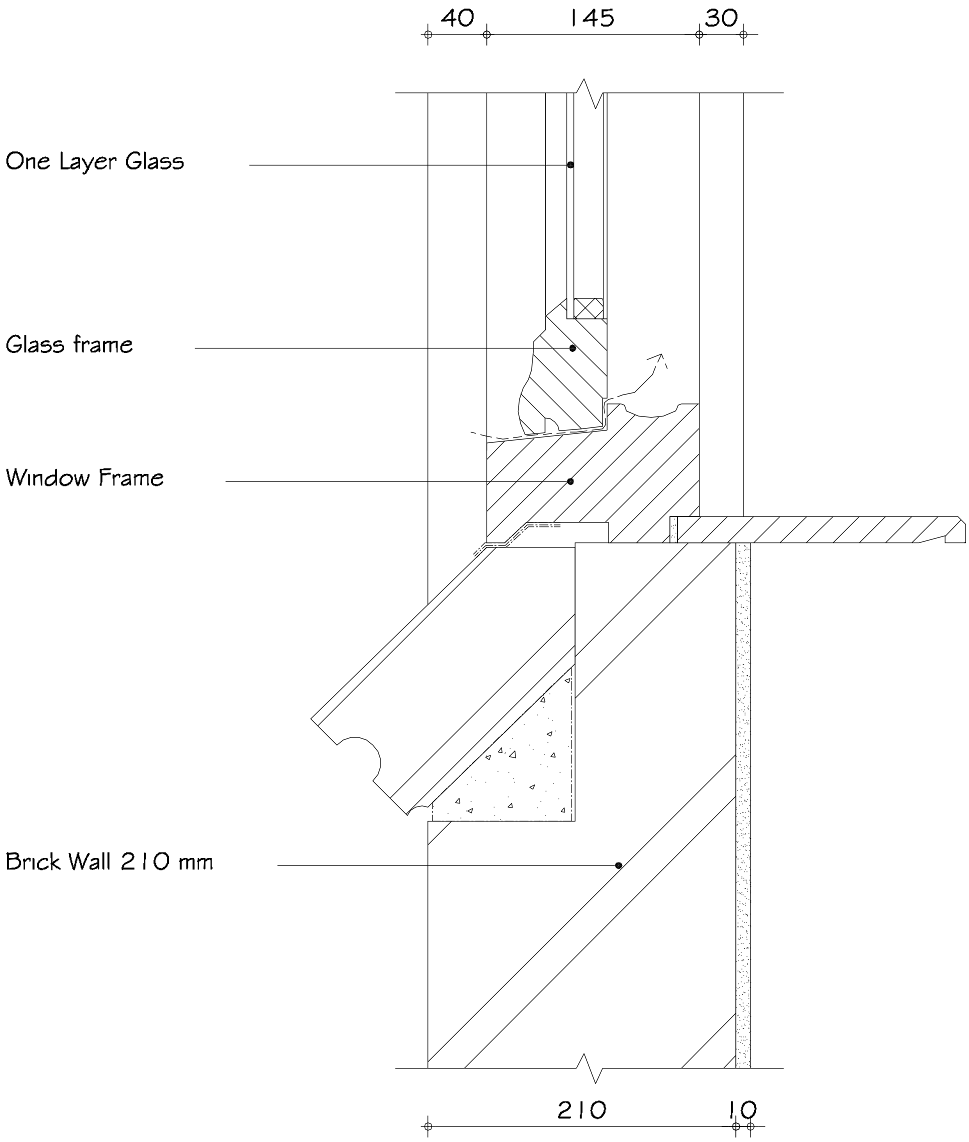
Case-Study Apartment

Floor plan - Sections

SCALE (A1)	SCALE (A3)
1:50	1:100

Report	DRAWING NUMBER	REVISION
31XX	F100	00

Appendix B: Wall/Window Detail Traditional Case



1 - WINDOW JAMB TRADITIONAL DETAIL TYPICAL

A4 @ Scale 1:5

DRAWING NOTES

DRAWING TITLE

REV	DATE	DESCRIPTION	DRAWN	CHECK
00	28-1	Thesis design	HH	NJ

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Influence of Building Structure and Building Content on Residential Fires

Hilco Hiemstra

DRAWING TITLE
Case-Study

Window Detail

SCALE (A4)
1:5

Report
31XX

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F200

REVISION
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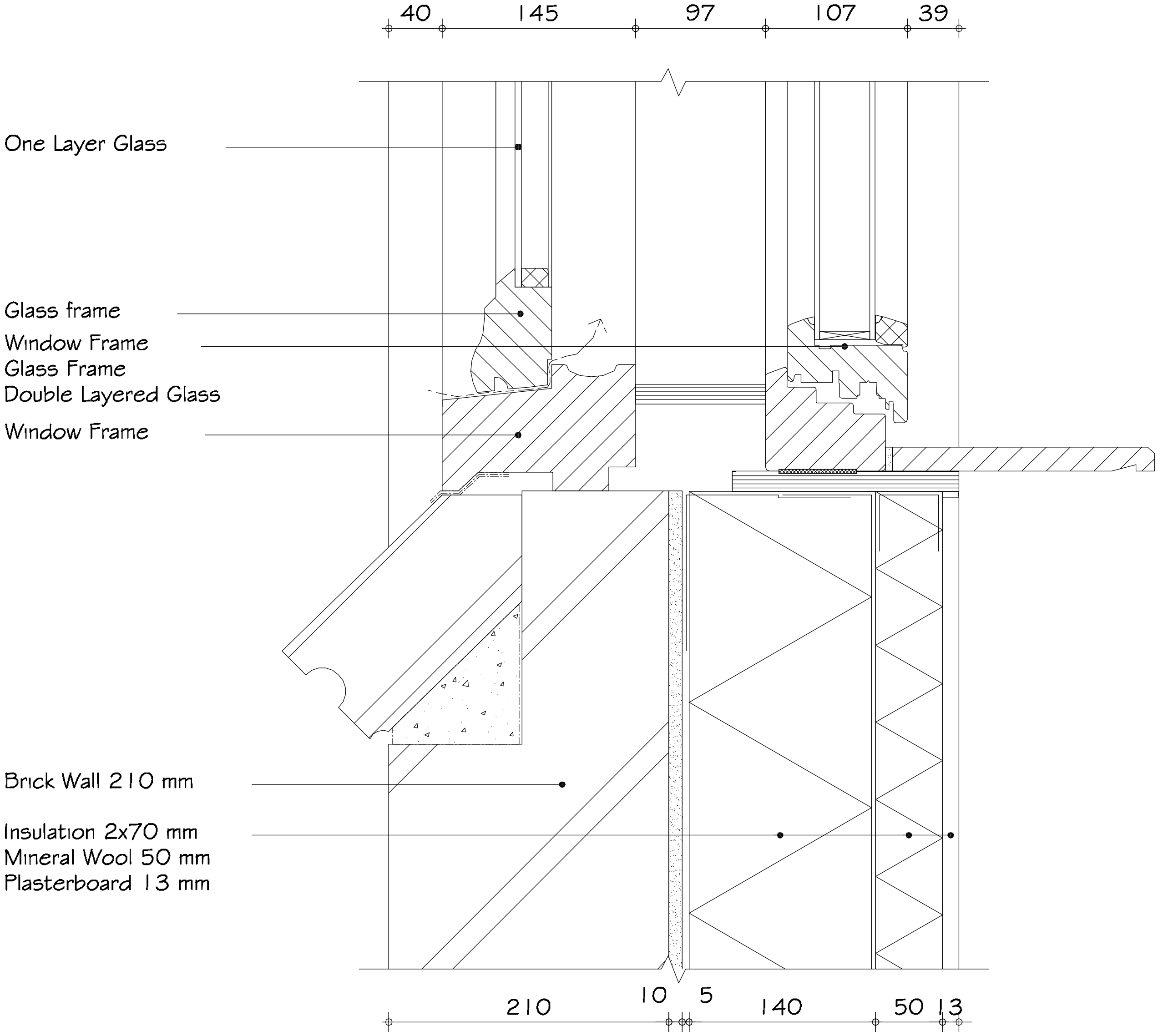
Appendix C: Wall/Window Detail Renovated Case



2 - WINDOW JAMB RENOVATION DETAIL TYPICAL

A4 @ Scale 1:5

DRAWING NOTES

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REV	DATE	DESCRIPTION	DRAWN	CHECK
00	28-1	Thesis design	HH	NJ

PROJECT

Influence of Building Structure and Building Content on Residential Fires

Hilco Hiemstra

DRAWING TITLE

Case-Study

Window Detail

SCALE (A4)

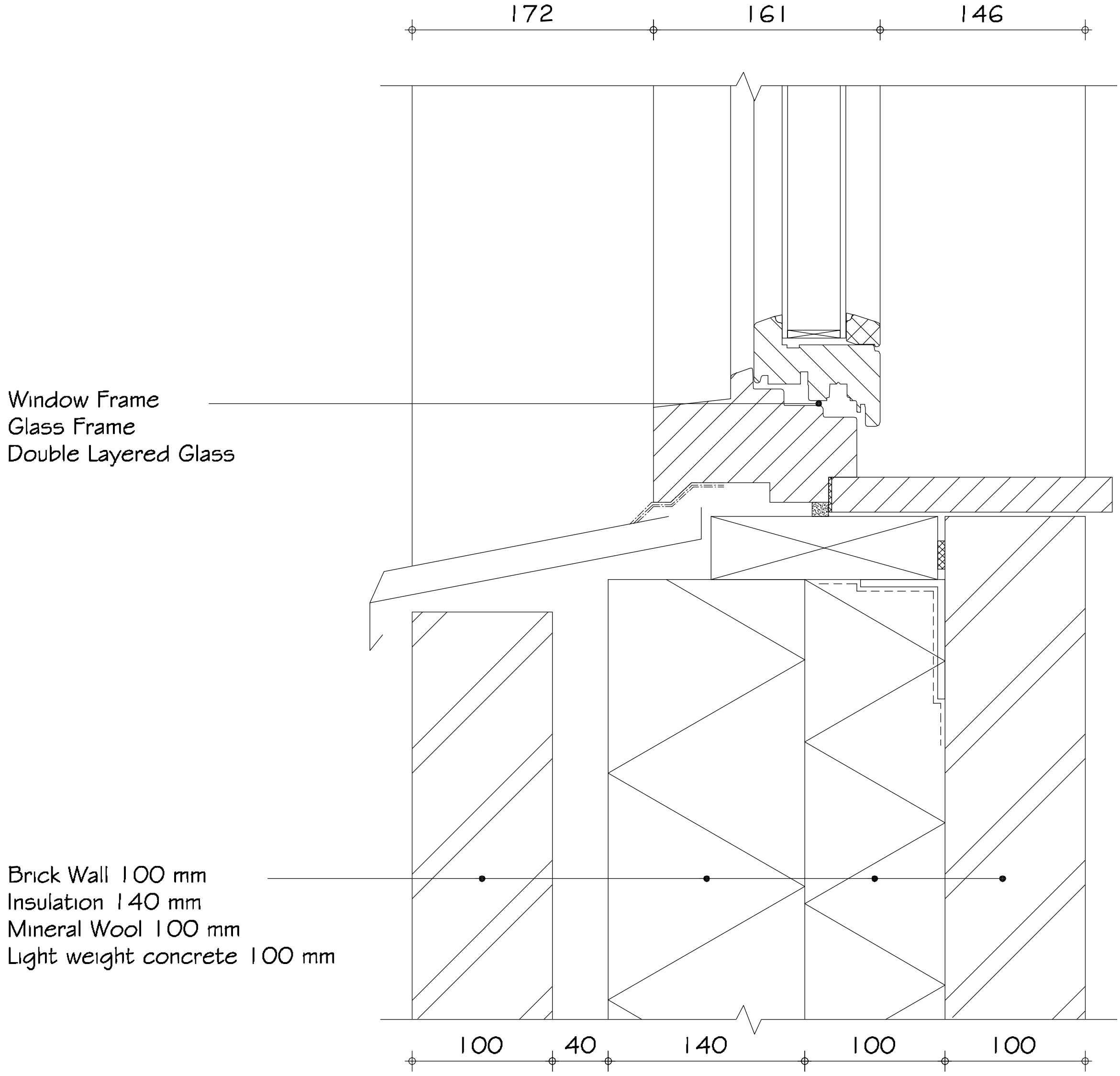
1:5

Report: 31XX

DRAWING NUMBER: F200

REVISION: 00

Appendix D: Wall/Window Detail Today's Case



3 WINDOW JAMB ENERGY EFFICIENT DETAIL TYPICAL

A4 @ Scale 1:5

DRAWING NOTES

DRAWING TITLE

REV	DATE	DESCRIPTION	DRAWN	CHECK
00	28-1	Thesis design	HH	NJ

PROJECT
Influence of Building Structure and Building Content on Residential Fires

Hilco Hiemstra

DRAWING TITLE
Case-Study

Window Detail

SCALE (A4)
1:5

Report 31XX

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Appendix E: Determination of Fire-Curves Building Content

Every living room is differently furnished. To determine a HRR-curve, data is used. In this appendix, the used fire-curves for each item is described.

Modern Furniture

In the report “Heat release rates of modern residential furnishings during combustion in a room calorimeter” (Bwalya et al., 2015), fire tests have been done for different items. In the report, four tests are done with chairs and two with sofas. The tests were done in a room calorimeter (3.8 m wide x 4.2 m deep by 2.38 m high) with a window opening (1.5 m x 1.5 m).

Chair and Sofa

Table E 1 lists the chairs and sofas that were tested. The seat cushions were made of PUF slabs with a layer of polyester fibre batting between the cover and the PUF, whereas the cushioning material in the backrests and armrests consisted of polyester fibre batting only. All the frames were made of wood. Test 40 and 41 were conducted with a two-seat and three-seat version of the chair SI-26 to evaluate the effect of size.

Table E 1 Tests With Upholstered Seating Furniture (Bwalya et al., 2015)

Test ID	Size Description	Fabric	Total Mass [kg]
9-SI-25	Chair	100% Polyester	30.8
10-SI-24	Chair	100% Polyester microfibers	33.6
15-SI-27	Chair	51% Acrylic, 49% polyester	12.2
26-SI-26	Chair	40% Acrylic, 60% polyester	32.9
40-SI-31	Two-seat sofa	40% Acrylic, 60% polyester	44.3
41-SI-32	Three-seat sofa	40% Acrylic, 60% polyester	55.6

The following HRR have been measured for the items.

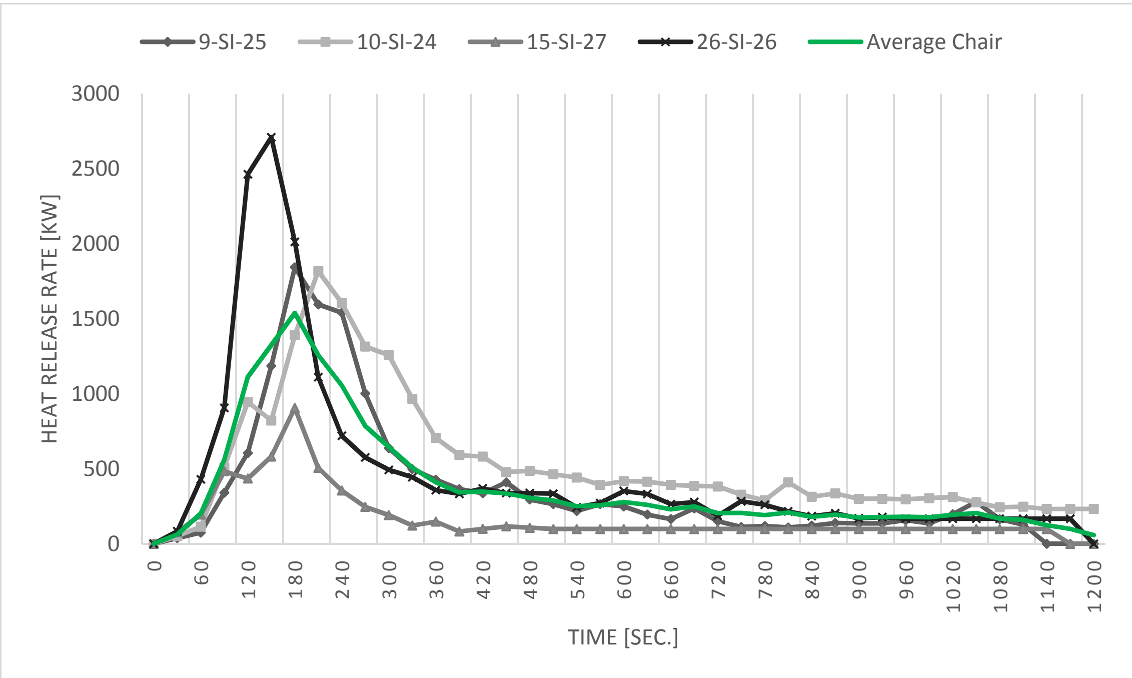

Figure E 1 Heat Release Rate vs. Time curves Chairs (Bwalya et al., 2015)

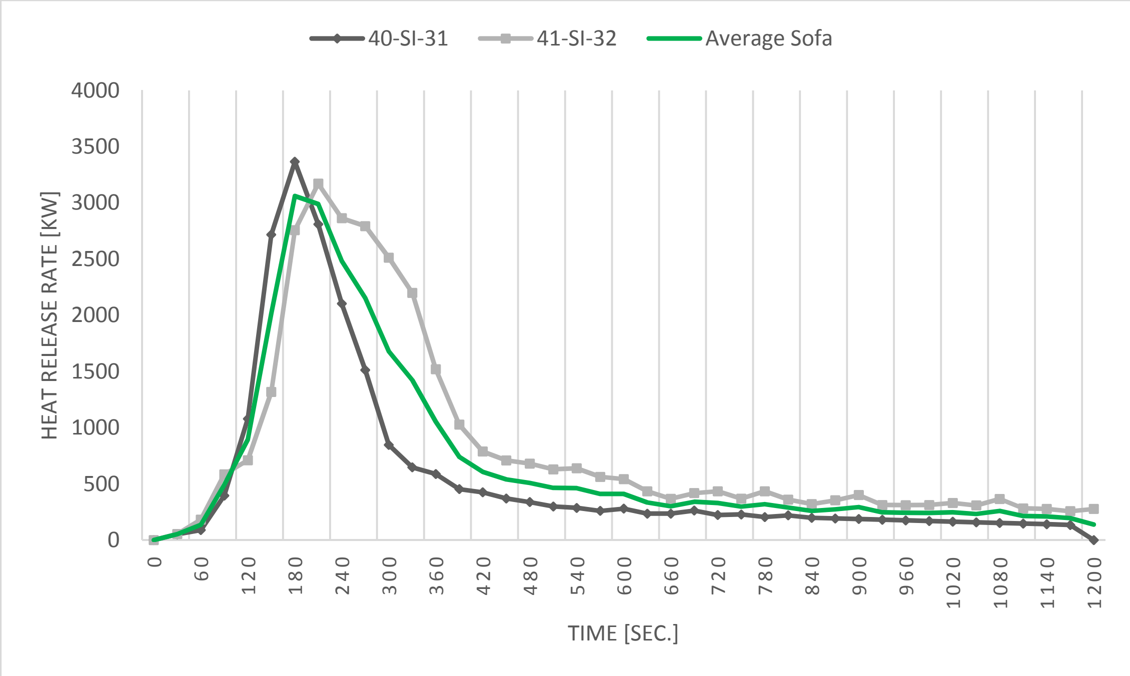

Figure E 2 Heat Release Rate vs. Time curves Sofas (Bwalya et al., 2015)

From Figure E 2 it can be seen that the Peak HRR of a two-seat sofa is higher than a three-seat sofa, likely because of the armrests being further apart in the three-seat sofa; in addition to the larger surface area, the flames had to travel.

As Dr. John DeHaan wrote: "*Today's furniture can be completely involved in 3 to 5 minutes and be reduced to a charred frame in 10 minutes while producing very high temperatures and enormous Heat Release Rates (2 to 3 megawatts being common for a sofa or recliner)*." (Dehaan, 2016). This is in relation to the test data done by Bwalye et al. For the input-data in the fire model, an average value will be used for the chair and the sofa. This will give the following HRR-curves for the chair and the sofas

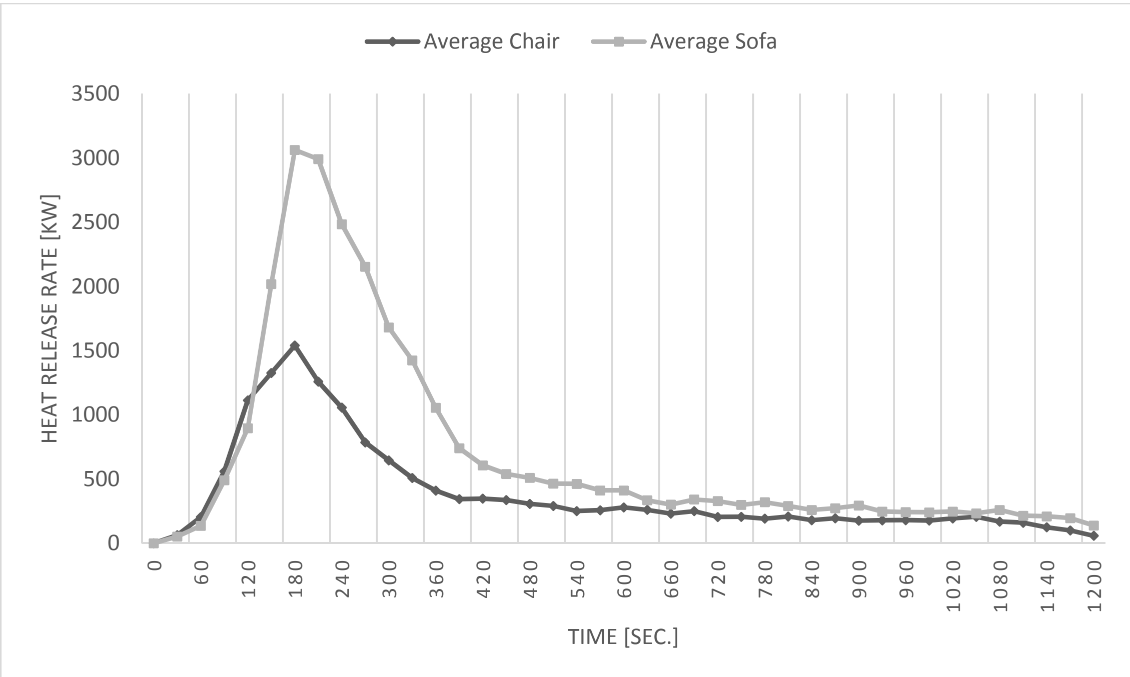

Figure E 3 Input Heat Release Rate vs. Time curves Chair and Sofa

To get average dimensions, ten chairs and sofas (5, 3-sits and 5, 2-sits) are taken from IKEA, from this ten the average value is taken to be the dimensions in the fire model. The table below shows the ten chairs and sofas, and the average value what will be used. The seat height will be used for the fire height.

Table E 2 Dimensions Chair (IKEA, 2016b)

	Ektorp	Kivik	Landskrona	Stockholm	Muren	Mellby	Stocksund	Ekerö	Söderhamn	Ekenäset	**Average**
Width [cm]	104	90	89	79	85	78	92	70	105	62	**85**
Depth [cm]	88	98	89	83	94	85	95	73	99	73	**88**
Height [cm]	88	83	78	109	97	80	89	75	83	75	**85**
Seat Height [cm]	45	45	44	42	45	45	49	43	40	42	**44**

Table E 3 Dimensions Sofa (IKEA, 2016b)

	Ektorp (3 sit)	Kivik (3 sit)	Norsborg (3 sit)	Nockeby (3 sit)	Stocksund (3 sit)	Ektorp (2 sit)	Kivik (2 sit)	Norsborg (2 sit)	Nockeby (2 sit)	Stocksund (2 sit)	**Average**
Width [cm]	218	228	213	251	199	179	190	153	203	154	**197**
Depth [cm]	88	95	88	97	95	88	95	88	97	95	**93**
Height [cm]	88	83	85	66	89	88	83	85	66	89	**81**
Seat Height [cm]	45	45	43	44	49	45	45	43	44	49	**45**

Sofa- and Side table

Wooden tables were not tested in the research of Bwaly, but Han SHou Suo did a test with a wooden desk. (SHou Suo, 2007). The wooden desk had a width of 1.4 m, 0.6 m deep and a height of 0.8 m. The test was done in a room calorimeter and has a HRR-curve as shown in Figure E 4.

Hughes Associates, Inc, have done a test with a coffee table from IKEA. (Mealy and Guttuk, 2013). The coffee table used in this test was an IKEA Lack style table. The overall dimensions were 0.9 m wide by 0.5 m deep with a total height of 0.46 m. The top of the table was constructed of particleboard, ABS plastic, and acrylic paint. The HRR was measured with free burning characteristics. The HRR-curve is also shown in Figure E 4.

Because of the free burning characteristics in the test of Mealy and Guttuk, there was no influence of irradiation from the wall and hot smoke layer (as in the test of SHou Suo). When the irradiation was taken into account, the growth phase would be faster and the HRR slightly higher.

With this in mind, a fire-curve for a wooden table is generated by the T-Square equation.

$$\dot{Q} = \alpha * t^2$$

Equation E 1

Where $\dot{Q}$ is the Peak HRR, α the Fire Growth Rate and t the time. By using a fire growth rate of 0.012 kW/s^2, what is normally used for solid wooden furniture (Hurley et al., 2016), the growth phase is determined. The peak HRR is assumed to be 700 kW.
In the decay phase, it can be assumed that the HRR exhibits a linear decrease with time. In this case, every 30 seconds a decrease of 50 kW is taken. This will give the following HRR-curves for a wooden table (see Average Wooden Table, the green line in Figure E 4).

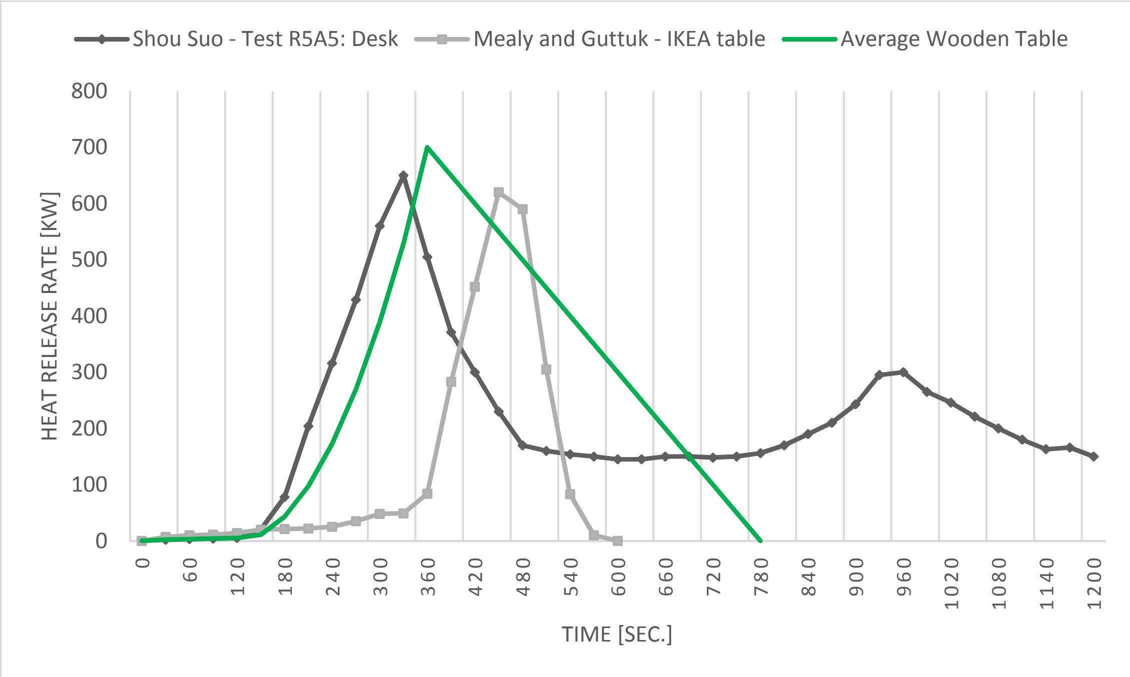

Figure E 4 HRR vs. Time curve Desk (SHou Suo, 2007), Coffee Table (Mealy and Guttuk, 2013) and used curve in the fire model

The area of the tested wooden tables were 0.84 m^2 and 0.45 m^2, the average value of this is 0.64 m^2 (0.8 m x 0.8 m). This area will be used for the wooden table in the fire model and a height of 0.5 m.

Traditional Furniture

There are many theories about traditional furniture compared to modern furniture. However, data as the HRR for traditional furniture is hard to find. Therefore, is in this report a more theoretical approach used to determine the HRR of each item.

UL, the standard in safety did a research about the Impact of Ventilation of Fire Behaviour in Legacy and Contemporary Residential Construction (Kerber, 2010). A part of this research conduct, Modern versus Legacy Room Furnishings Fire Comparisons. The main result of this experiment is that modern rooms and legacy rooms demonstrate very different fire behaviour. The natural materials in the legacy room burned slower and produced less energy than the fast burning synthetic furnished modern room.

Figure E 5 shows the temperature vs. time curve. From this figure, it can be seen that the modern furniture developed much faster than the legacy room. After approximate 280 seconds, a strong increase in temperature is presented. For the legacy room, this strong increase is at approximately 1 700 seconds (6 x more than the modern room). Also, the temperature in the tested rooms are slightly different. The legacy room shows lower temperatures; that means that less energy is released (not specified in numbers directly in the report).

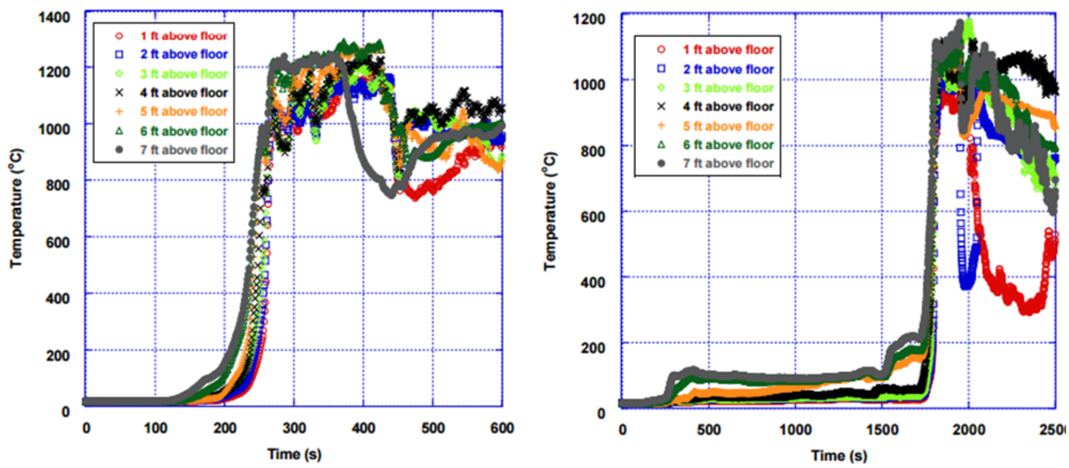

Figure E 5 Temp. vs. Time Modern Room Temp. vs. Time Legacy Room (Kerber, 2010)

From this research, it can be stated that the fire growth is much slower (approximately 6 x) and that the energy that is released in the room is lower.
This is similar to what Dr. John DeHaan wrote for traditional furniture: *"once ignited, they would burn slowly often reluctantly, producing small flames, preferring to smolder instead."*
Dr. John DeHaan also wrote*: "that the Heat Release Rates would be very low (300 – 400 kW being typical for a sofa), so spread to other fuels would require direct flame contact"* (Dehaan, 2016).

The value 400 kW (as written before the Peak HRR change not that much for a chair and a sofa) will be used as Peak HRR for the chair and the sofa to generate an HRR-curve for the traditional furniture. For the growth phase, the T-Square equation is taken with a slow growth rate (α: 0.003 kW/s^2). For the duration of the fire, the same energy that is released for the modern furniture is used. By using 80% of the released energy, the HRR for the traditional furniture is generated. Figure E 6 shows the HRR vs. Time for the traditional chair and the sofa.

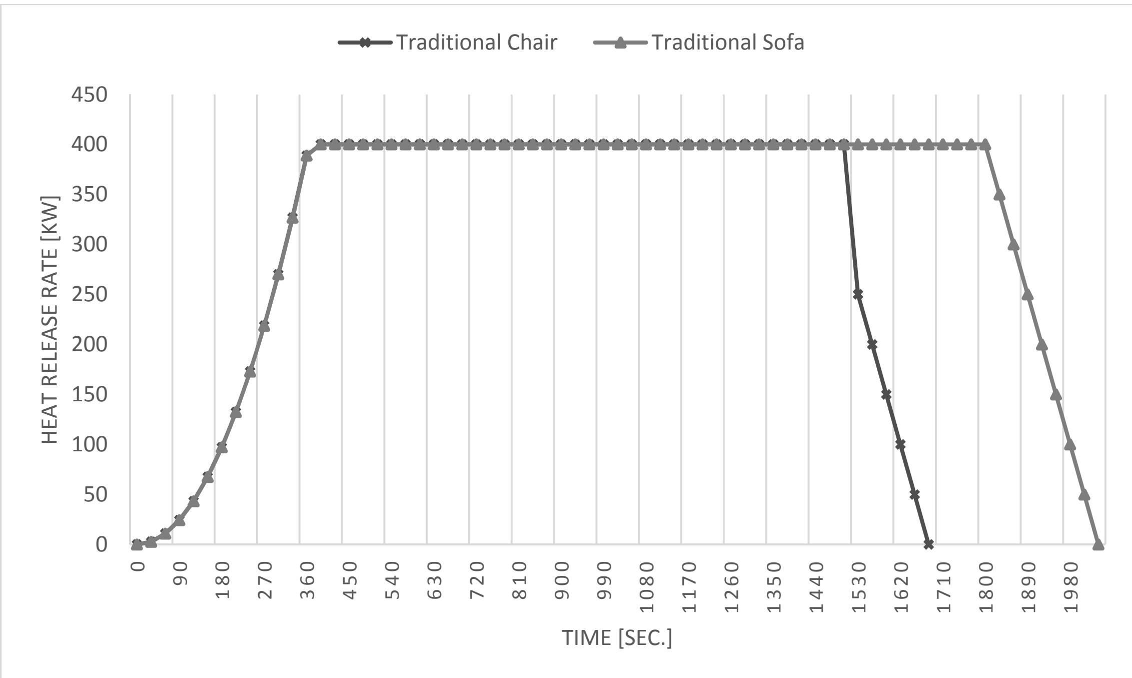

Figure E 6 Heat Release Rate vs. Time curve Traditional Chair and Sofa

The HRR for the tables is assumed to be similar to the modern case.

Appendix F: Random Configurations

Every living room is differently furnished. For the sensitivity analyse different set-ups are analysed. By the use of B-RISK five configurations are generated, the following configurations are generated.

Random Run 1

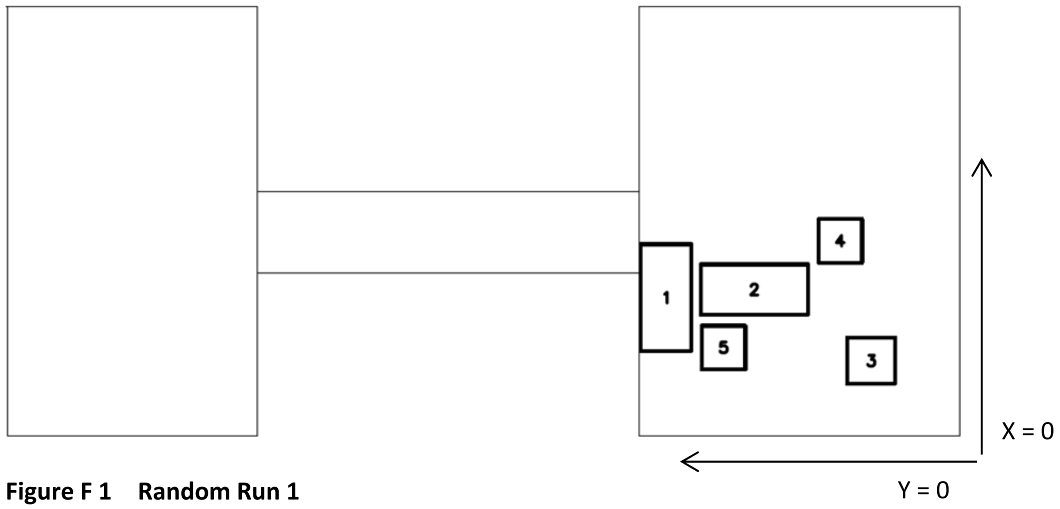

Figure F 1 Random Run 1

Table F 1 Coordinates Random Run 1

Item	Description	Coordinates		Unit
1	Sofa 1	X: 1.56	Y: 4.95	m
2	Sofa 2	X: 2.23	Y: 2.80	m
3	Armchair	X: 0.96	Y: 1.19	m
4	Coffee Table	X: 3.19	Y: 1.80	m
5	Side Table	X: 1.23	Y: 3.95	m

Random Run 2

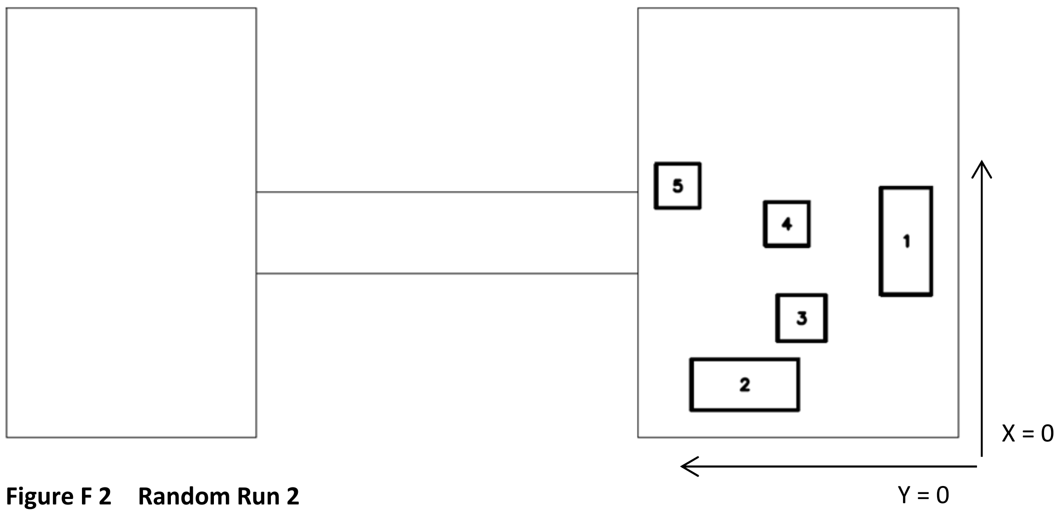

Figure F 2 Random Run 2

Table F 2 Coordinates Random Run 2

Item	Description	Coordinates		Unit
1	Sofa 1	X: 2.62	Y: 0.50	m
2	Sofa 2	X: 0.50	Y: 2.95	m
3	Armchair	X: 1.76	Y: 2.45	m
4	Coffee Table	X: 3.52	Y: 2.76	m
5	Side Table	X: 4.22	Y: 4.77	m

Random Run 3

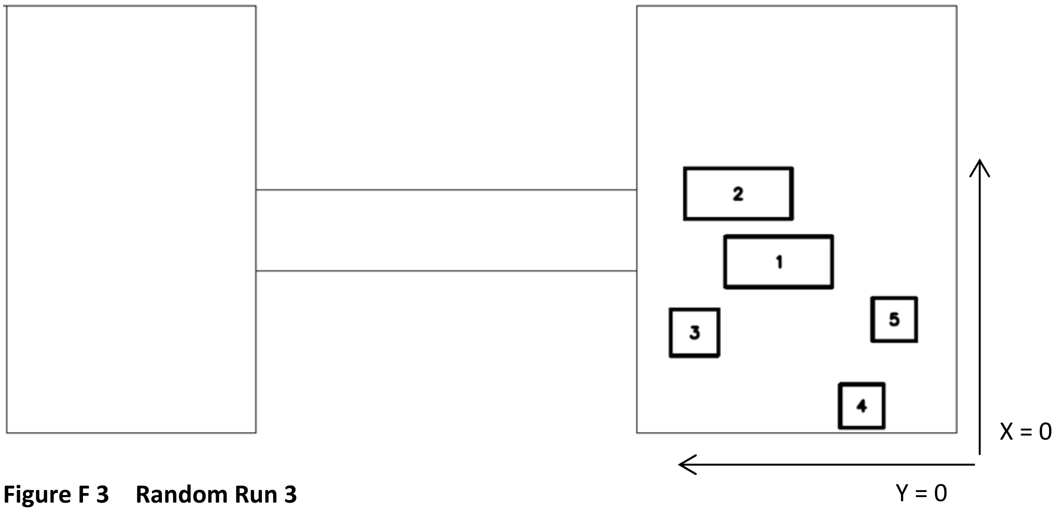

Figure F 3 Random Run 3

Table F 3 Coordinates Random Run 3

Item	Description	Coordinates		Unit
1	Sofa 1	X: 2.70	Y: 2.30	m
2	Sofa 2	X: 3.96	Y: 3.05	m
3	Armchair	X: 1.43	Y: 4.40	m
4	Coffee Table	X: 0.10	Y: 1.35	m
5	Side Table	X: 1.70	Y: 0.75	m

Random Run 4

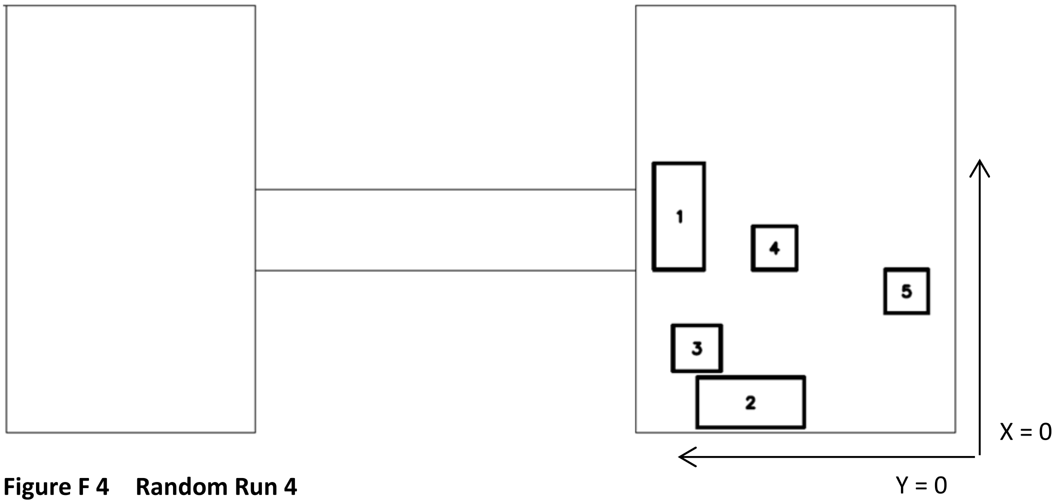

Figure F 4 Random Run 4

Table F 4 Coordinates Random Run 4

Item	Description	Coordinates		Unit
1	Sofa 1	X: 3.02	Y: 4.64	m
2	Sofa 2	X: 0.10	Y: 2.80	m
3	Armchair	X: 1.14	Y: 4.34	m
4	Coffee Table	X: 3.02	Y: 2.94	m
5	Side Table	X: 2.22	Y: 0.50	m

Random Run 5

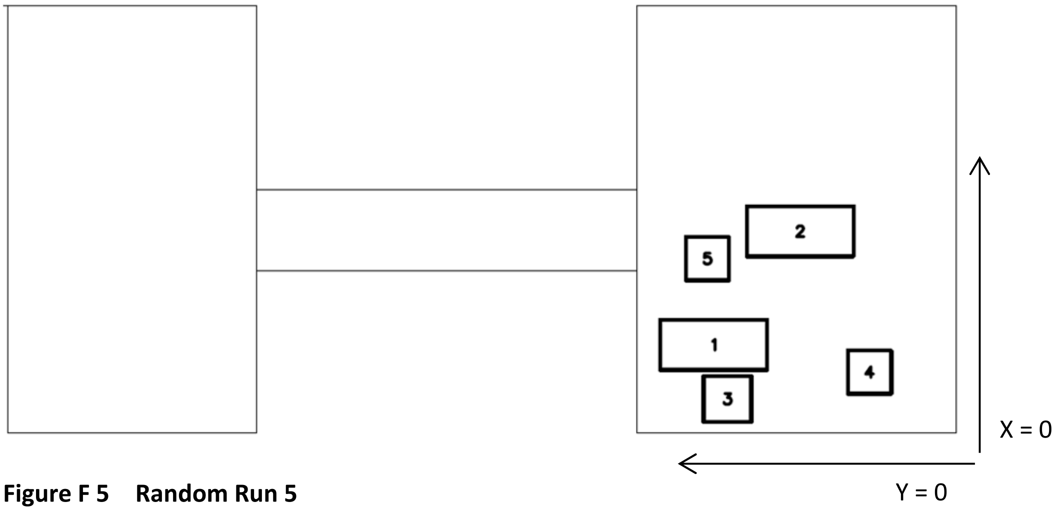

Figure F 5 Random Run 5

Table F 5 Coordinates Random Run 5

Item	Description	Coordinates		Unit
1	Sofa 1	X: 1.16	Y: 3.50	m
2	Sofa 2	X: 3.26	Y: 1.90	m
3	Armchair	X: 0.20	Y: 3.79	m
4	Coffee Table	X: 0.72	Y: 1.20	m
5	Side Table	X: 2.82	Y: 4.20	m