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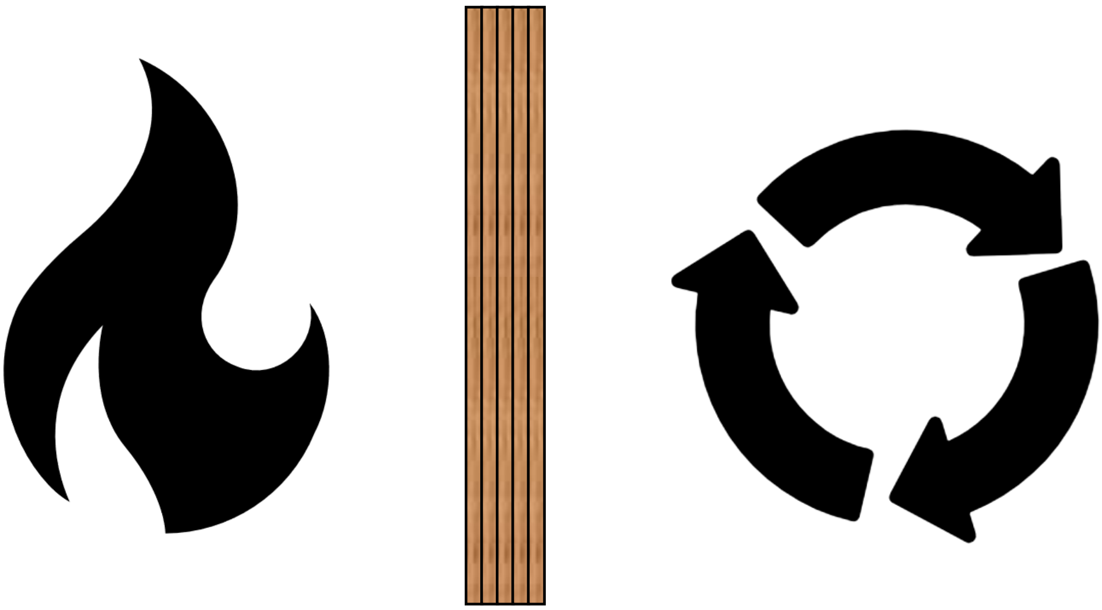
Balancing the impact between material use and fire risk



Siri Qvist

A CIRCULAR APPROACH FOR THE FIRE SAFETY DESIGN IN MASS TIMBER BUILDINGS

Balancing the impact between material use and fire risk

Master Thesis Report

Master of Science in Civil Engineering

By

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Date: 28-01-2022

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PREFACE

This thesis presents my research conducted at the Faculty of Civil Engineering in partial fulfilment of the requirements for the degree of MSc in Civil Engineering from the Delft University of Technology.

My interest in sustainable building design has been guiding in the choices I made during my masters. I got inspired on the topic of my thesis after a multidisciplinary course in which, together with a team of fellow students, I designed a sustainable high-rise building. In the course I was responsible for, among other things, the fire safety design. The high-rise building had a timber structure, with the aim to be a circular solution. However, this choice influenced the fire risk after which I decided to implement a sprinkler in the design. Though, I was not really satisfied with this solution as this way material use was increased, just to be able to build with timber.

I found this contradiction between sustainable building design and fire safety design so interesting that I decided to devote my thesis on the topic, focusing on mass timber buildings. The topic was however hard, as I had to define my own concepts and use these as guideline during my research. This led to multiple moments in which I got lost in all information.

Luckily, my supervisors from the TU Delft and Arup were there to guide me during the process. I want to thank my supervisors from the Delft University of Technology, Geert Ravenshorst, Henk Jonkers and Hoessein Alkisaei for their guidance and feedback during the process.

I would also like to thank the Fire team at Arup, and in particular my devoted supervisors Yvonne Wattez and Pascal Steenbakkers, who have helped me a lot during this research by guiding me and sharing their expertise. They entrusted me with the freedom to conduct the study how I saw fit, steering me into the right direction when needed.

Lastly, I want to thank my family and friends for all their mental support during this long journey as well as helping me with difficulties during the research process, keeping me motivated and helping me putting things into perspective. Without their help, I would not have reached this result.

Siri Qvist
February 2022

EXECUTIVE SUMMARY

INTRODUCTION

PROBLEM DESCRIPTION

The building industry consumes a lot of material, which causes depletion of material stocks, toxic emissions, and waste. Circular building design can help to reduce this impact, by moving from a linear to a circular design approach.

To reach a circular build environment, all disciplines should be involved, including fire safety design. However, it is observed that there is a contradiction between the objectives of circular and fire safety design, either affecting the aim of protection of material sources, or protection against fire risk.

Timber is a material that has high potential in contributing to a circular building industry, as it is renewable, recyclable and can store CO_2. However, timber is combustible, which increases the risk of fire. Therefore, mass timber building design has traditionally been restricted by building regulations. To enhance mass timber building design research on timber buildings has increased, to allow understanding of the risks. However, yet general guidelines or understanding on the fire behaviour and risk in timber buildings is lacking. This is a problem for the fire safety design and the potentials of timber contributing to a circular building industry.

KNOWLEDGE GAP

Knowledge and methods are lacking to determine the influence of fire safety design on the balance between material use and fire risk in mass timber buildings.

OBJECTIVE

Therefore, the objective of this research is: ***Enhance the understanding of the influence of the fire safety design on the balance between material use and fire risk in mass timber buildings, by creating a design approach that presents the relation between circular- and fire safety-design and utilize this approach to create a design tool for preliminary design phase that quantifies the balance between material use and fire risk for the fire safety design in mass timber buildings.***

MAIN RESEARCH QUESTION

To reach the objective, the following research question is defined:

How can a circular design approach be used as a means to steer fire safety design in mass timber buildings towards a solution that provides economic and environmental safety?

To answer the main research question, the research is split into two parts. First a design approach is created, which defines the aspects that should be considered in circular fire safety design, relating to material use and fire risk. Secondly a design tool is created which quantifies the relation between material use and fire risk in mass timber buildings expressed as economic and environmental impact.

Circular fire safety design approach

In the first part of the research, a design approach is created that presents a relation between circular building design and fire safety design. In the approach a circular design life cycle is integrated with a fire resiliency life cycle. The relation presents the balance between the influence of circular material use for the fire safety measures (green arrows) and the relating fire risk (yellow arrows). The material use consists of the fire safety material needed during the circular life cycle of a building and the end-of-life residual circularity value in normal, non-fire conditions. The fire risk is presented as the probability that a fire occurs during the use-phase of a building, and the relating impact that is expected. The impact of a fire can be defined by for example toxicity of emissions, material damage and more. The rehabilitation represents the material needed to rehabilitate after a fire.

The two outputs are expressed in impact relating to quantity of material, which can be linked to economic and environmental costs. This way an approach is created that presents important aspects to consider for circular fire safety design, representing a balance between material use and fire risk. This approach can be used for circular fire safety design in all types of buildings in case a risk-based approach is required.

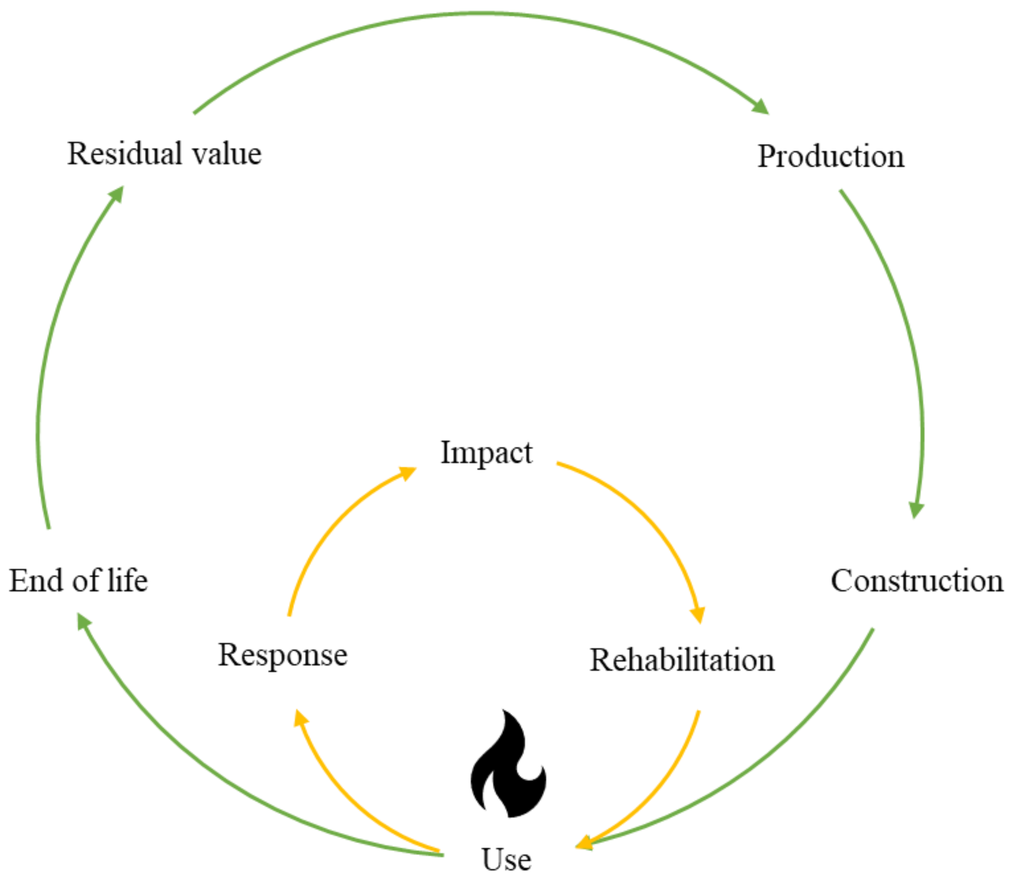

Figure 1: Circular fire resiliency life cycle

Circular fire safety in mass timber design tool

In the second part of the research, the circular fire safety design approach is used as a guideline to create a method that quantifies the balance between material use for fire safety measures and the relation to fire risk in mass timber buildings. The quantification therefore consists of two parts: quantification for material use, and quantification for relating fire risk. The quantifications are expressed as economic and environmental impact.

In the quantification method, the building design consists of identical mass timber compartments, in which walls and floors are constructed by CLT, placed on top of each other. The focus is residential buildings up to 25 building storeys. The method considers different building characteristics and fire safety design measures related to CLT, encapsulation and sprinkler systems.

The quantification of the material use for fire safety measures is done based on a circular Life Cycle Assessment by methods presented by Platform CB'23 (2020).

The quantification of the fire risk is based on methods presented by NEN 6079, though altered for fire risk in mass timber buildings. Methods used for the calculation of the fire dynamics are based on Brandon (2018) and fire resistance calculations based on Swedish Wood (2019). The quantification consists of a four-step decision tree that quantifies the probability of a certain fire scenario and the relating damage in terms of material loss. The total fire risk of the building is the sum of the risks of the considered fire scenarios.

By summing the material use and fire risk, one "circular fire safety impact" value is calculated. This allows comparison between different fire safety designs. The most optimal design from a material perspective is determined by the design with the lowest total impact.

Results

The calculation methods are integrated in a design tool created in Excel which allows changing the design parameters. The tool calculated the effect on material use and fire risk. The use of the tool consists of three main steps:

1. Implementation of design parameters
2. Analysis of the results
3. Variant study

This way, the tool gives insight in the influence of the fire safety measures on material use, fire risk and the combined "circular fire safety impact". By changing the fire safety design, the most optimal design variant can be determined. This is the variant with the lowest total impact value.

The tool is tested on a variant study of two building designs with different dimensions and height. The economic results of the variant study for a compartment with a Gross Floor Area (GFA) of 48 m2 are presented in Figure 2. The figure presents the total "circular fire safety impact" of the design variants for varying building heights.

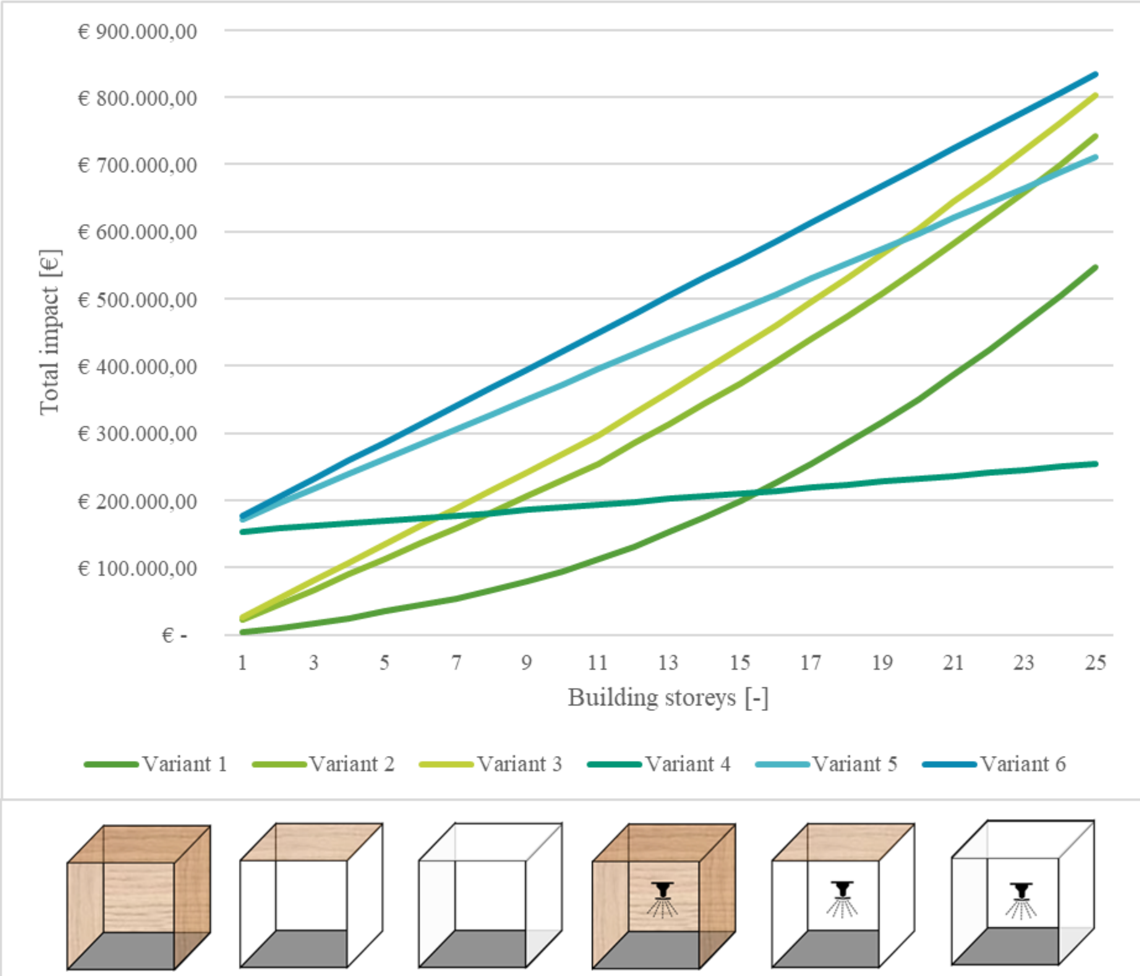

Figure 2: Economic impact results of variant study for compartment GFA 48m2

On the horizontal axis of Figure 2, the number of building storeys are presented. The vertical axis presents the economic impact. It is observed that the total impact of the design variants increases for increased building height. This is explained by a combination of increased material use and increased fire risk. However, it is observed that the rate at which the impact increases differ for the different design variants. This is explained by the balance between material use and fire risk, in which material impact and risk present a combined value.

For all designs, the material-use results in a linear impact growth for increased building height. The risk results in an exponential growth. The combined impact presented in Figure 2, this way shows the balance between material use and fire risk for the different design variants. The variants in which an exponential growth is observed (variant 1 significantly, and variant 2 and 3 slightly) the fire risk presents a relatively higher part of the total impact compared to the material use. The variants with a more linear increase show that the material use has a relatively higher impact compared to fire risk.

From a material perspective, the design variant with the lowest total impact presents the most optimal design. From the figure it is observed that the most optimal design is relating to the building height. Variant 1 (which represents a fully exposed mass timber compartment) results in the lowest impact up to 15 building storeys (41m). Above this height, variant 4 (which represents a fully exposed mass timber compartment with a sprinkler installation) becomes more optimal.

CONCLUSIONS

There is a contradiction between circular- and fire safety design. Circular design focusses on reducing the impact of material use, and fire safety design focusses on reducing the fire risk.

Until now, there was no specific method available that relates and quantifies these two aspects of design. This limits the possibility of fire safety design to contribute to a more circular building industry.

By creating a method that allows comparison between the economic and environmental impact of material use and fire risk, a well-founded choice of building materials is easier to make.

The design tool quantifies the impact on material use for fire safety measures relating to CLT, encapsulation and sprinkler availability and their effect on the fire risk in mass timber buildings. This way insight is provided between the balance of material use and fire risk. By the sum of the impact on material use and fire risk, the total “circular fire safety impact” value is calculated. This value represents the total economic and environmental impact of the design based on the choice of building materials. By changing the fire safety design, the most optimal design variant can be determined. This is the variant with the lowest total impact value.

This way, a circular design approach is used to steer fire safety design in mass timber buildings towards a design solution that does not only provide sufficient safety for people, but also provides maximum economic and environmental safety from a material point of view.

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1 INTRODUCTION

1.1 PROBLEM DESCRIPTION

The world is facing large challenges in terms of climate change, access to resources and population growth. To tackle these problems, the United Nations have defined 17 sustainable development goals (UNSDG) to reach a sustainable world in 2050 (UNSDG, 2017). The building industry plays an important role in reaching these goals, as it contributes to more than 40% of the final energy use, 35% of the emissions relating to global warming and is responsible for 50% of the total material use (Herczeg et al., 2014). Therefore, new sustainable design solutions are required which has led to innovations in the building industry.

1.1.1 CIRCULAR BUILDING DESIGN

Circular building design is considered an important means to reach the sustainability goals, by designing with and for reusability and this way reducing the negative impact of material consumption. In the Netherlands three main objectives are stated for circular building design: (1) Protection of material sources, (2) protection of environment, and (3) protection of element/material value. (Platform CB'23, 2019)

1.1.2 CIRCULAR FIRE SAFETY DESIGN

To reach a circular building industry, involvement and engagement of all stakeholders and design disciplines is required, of which fire safety design. A building fire can have a large negative impact on building and surrounding, affecting the safety of people, and damaging material, environment, and economy. (Fire Safe Europe, 2020) This way, a building fire negatively affects the objectives of circular building design, as (1) material is lost and this way end-of-life value damaged, (2) a fire results in toxic emissions, affecting the environment, and (3) additional material is needed to either rehabilitate or build a new building.

To reduce the negative impact of a fire, fire safety measures are implemented in the design. However, this affects the initial objective of circular design, to reduce the negative impact of material consumption. (Breunese & Maljaars, 2015; Hagen & Witloks, 2018)

This means that there is a contradiction between circular and fire safety design, either affecting the aim of protection of material sources, or protection against fire risk. However, currently methods are lacking to determine this balance, and this way allow fire safety design to accurately contribute to a circular build environment. Moreover, *data and methods are lacking for establishing the ecological and economic impact of fire safety, including emissions from accidental fires and environmental costs of replacing damaged installations."* (McNamee et al. 2019, p.5).

1.1.3 MASS TIMBER BUILDING DESIGN

Timber design is one of the sustainable building design solutions which has high potential to contribute to reaching a circular build environment. Timber is natural and renewable and the forests in which it is harvest functions as a carbon sink. Moreover, the production of timber elements requires less energy compared to other building materials and it has high potentials to be re-used or recycled into new engineered timber elements. (Gerard & Barber, 2013)

Due to the development of Cross Laminated Timber (CLT) in early 1990s, mass timber building construction has become possible in which floors and walls in buildings are constructed by CLT elements. This has made it possible to build large and high-rise buildings with a mass timber structure. However, timber is a combustible material and mass timber constructions result in additional risks relating to fire safety (Pettersson, 2019; McNamee and Meacham, 2020). Around the world, building codes have therefore traditionally restricted mass timber building construction by limiting height and area. (Gerard & Barber, 2013) This limits the potentials of mass timber buildings contributing to a sustainable build environment. Therefore, since the last decade research on timber buildings has increased, to allow understanding of the risks, and this way increase the possibilities regarding mass timber construction.

Since then, the knowledge regarding the fire behaviour and risks in timber buildings has increased. (Pettersson, 2020) However, yet general guidelines or understanding on the fire behaviour and risk in timber buildings is lacking. This is a problem for the fire safety design, which can lead to risks relating to safety, property loss and more.

1.2 KNOWLEDGE GAP

To reach a circular build environment, holistic design is required of which fire safety design plays an important role, as a building fire may affect people, economy, and environment. However, there is a contradiction between the objectives of circular and fire safety design, leading to a balance between material use and fire risk.

Moreover, knowledge, data and methods are lacking to quantify this balance and limits fire safety design to contribute to a circular build environment. Therefore, a circular fire safety design approach is required, that goes beyond general fire safety guidelines, and presents the risks and impact of the fire safety design, for people, economy, and environment.

Timber design is one of the sustainable solutions which can help to reach the circularity goals. However, timber is a combustible material and mass timber constructions result in additional risks relating to fire safety (McNamee and Meacham, 2020). Since the increased interest in mass timber construction, there has been a lot of research on the fire risks and fire behaviour in these types of buildings (Pettersson, 2020). However, the knowledge gained from this research has yet not led to a general guideline or understanding for design.

Therefore, to enable mass timber to contribute to a circular and safe build environment the theoretical knowledge on fire risks and behaviour in mass timber buildings should be translated to a design method that allows comparison of different fire safety designs on the relation between material use and fire risk. By this, a deliberate fire safety strategy can be proposed that does not only ensure safety for people, but also enhances the goals to reach a circular build environment.

2 RESEARCH APPROACH

2.1 OBJECTIVES

Based on the presented knowledge gap, the following research objective is defined:

Enhance the understanding of the influence of the fire safety design on the balance between material use and fire risk in mass timber buildings,

By:

Creating a design approach that presents the relation between circular- and fire safety-design,

And utilize this approach to:

Create a design tool for preliminary design phase that quantifies the balance between material use and fire risk for the fire safety design in mass timber buildings.

The design approach will provide insight in the aspects that should be considered for circular fire safety design and can be used as a guideline for the design tool. The tool will enhance deliberate decision making by quantifying the balance between material use and fire risk for the fire safety design in mass timber buildings. This way allowing comparison of different fire safety designs, which will boost the construction of fire safe mass timber buildings without compromising the circularity potentials of the material. Moreover, by early insight of the risks of the fire safety design and the influence on circularity of timber buildings, fire safety becomes a pro-active part of the design, resulting in a more holistic design approach, which is needed to reach a circular, fire safe build environment.

2.2 RESEARCH QUESTIONS

The objective is reached by answering the main research questions:

How can a circular design approach be used as a means to steer fire safety design in mass timber buildings towards a solution that provides economic and environmental safety?

2.2.1 SUB-QUESTIONS

The main research question is answered by answering the sub-research questions. These can be divided into two parts. The first question relates to the relation between the goals of the circular economy and fire safety design.

Q1: How can the relation between circular building design and fire safety design be defined and translated to an approach for circular fire safety design?

The next sub-question relates to the impact of fire safety design on the balance between material use and fire risk in mass timber buildings. The question is defined as follows:

Q2: How can a circular design approach be used to quantify the relation between material use and fire risk for the fire safety design in mass timber buildings?

The questions consist of one sub-sub question:

Q2.1: Which aspects must be considered for fire safety design in mass timber buildings?

2.3 REPORT STRUCTURE

The report is divided in three main parts: (1) Circular fire safety design approach, (2) Circular fire safety design tool for mass timber buildings, and (3) conclusions

Part 1: Circular fire safety design approach

In this part of the report, the circular fire safety design approach is presented. This starts with a short summary of the theory of the circular building design and fire safety design. This theory is integrated such that a circular design approach is defined. With this, the first research objective is reached which is defined as:

Create a design approach that presents the relation between circular- and fire safety-design.

Part 2: Circular fire safety design tool for mass timber buildings

In this part of the report, a design tool is created that quantifies the balance between material use and fire risk for the fire safety design in mass timber buildings. In chapter 4, the theory of fire safety design in mass timber buildings is presented. Chapter 5 presents the boundary conditions of the tool. In chapter 6, the quantification methods for material use are presented. Subsequently, in chapter 7, the quantification methods for fire risk are presented. Chapter 8 presents the fire resistance calculations. Finally, in chapter 9 the design tool is presented. With this, the second objective of the research is reached which is defined as:

Create a design tool for preliminary design phase that quantifies the balance between material use and fire risk for the fire safety design in mass timber buildings.

Part 3: Results

In the last part of the research the research results are discussed in chapter 10. The report ends with the conclusions in chapter 11, in which the research questions are answered. With this, the main objective of the research is reached which is defined as:

Enhance the understanding of the influence of the fire safety design on the balance between material use and fire risk in mass timber buildings.

PART 1

CIRCULAR FIRE SAFETY DESIGN APPROACH

In this part of the report, the circular fire safety design approach is presented. This starts with a short summary of the theory of circular building design and fire safety design. This theory is integrated such that a circular design approach is defined. With this, the first research objective is reached which is defined as:

Create a design approach that presents the relation between circular- and fire safety design.

3 CIRCULAR FIRE SAFETY DESIGN APPROACH

In this chapter, the circular fire safety design approach is presented. This approach is the integration of the relation between the objectives and methods of circular design and fire safety design. The first sections present the most important theory regarding circular building design and fire safety design. After this the circular fire safety design approach is presented. With the information presented in this chapter, the first sub-research question is answered:

Q1: How can the relation between circular building design and fire safety design be defined and translated to a design approach for circular fire safety design?

3.1 Circular building design

In this section, a short summary of the main definitions, objectives and methods of circular building design are presented.

3.1.1 Objectives

Circular design is an important means to reach the sustainability goals of the United Nations, tackling the negative impact of material consumption relating to material source depletion, toxic emissions, and waste (Ellen McArthur Foundation, 2012; UNSDG, 2015).

The main idea behind circular design is to change the current linear "take-make-use-waste" approach to a circular approach by using waste as an input and this way minimize raw (finite) material consumption (see Figure 3). With this, the main essence of circular design is rethinking the end-of-life phase of building elements by reusing, repairing, refurbishing, remanufacturing, repurpose, recycling or recovering of materials (Ellen McArthur Foundation 2012; Platform CB'23, 2019).

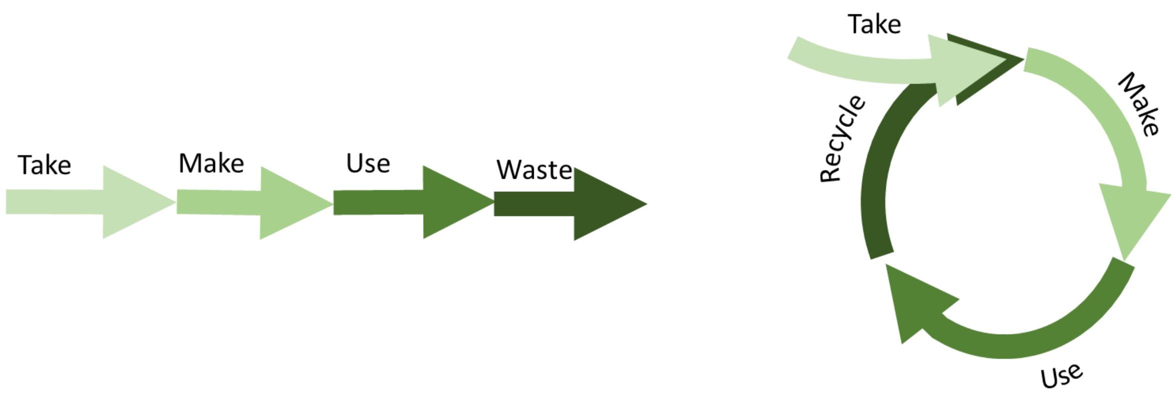


Figure 3: From a linear to circular approach (Own figure)

3.1.1.1 Goals

The opportunities of circular design in reducing material use, waste and protect the environment was recognized by the European Union (EU), leading to the goal of a fully circular economy in 2050 which all members of the EU must fulfil. Consequently, in 2016 the Netherlands stated two clear goals regarding the Circular Economy: (1) In 2030 the raw material use must be reduced by 50% (2) In 2050 there must be a fully circular economy. (Rijksoverheid, 2016).

This is a large challenge, especially for the building sector, as approximately 50% of all raw material is used for construction purposes (Rijkswaterstaat, 2015), and contributes to a large part of all the generated waste (Rijksoverheid, 2016).

3.1.1.2 DEFINITION

To achieve these goals, a clear "common conceptual framework", "clear agreements" and a "uniform measurement method" are required. (Platform CB'23, 2019) To create this, a platform has been established in the Netherlands by the Dutch government and building industry consisting of experts and specialists. The platform is called Platform CB'23, and defines a circular building as:

"Circular building means developing, using, and re-using buildings, areas and infrastructure without unnecessarily depleting natural resources, polluting the environment, and damaging ecosystems. It is building in a manner that is economically and ecologically responsible and contributes to the well-being of people and animals. Here and there, now and later." (Platform CB'23, 2019, p. 12)

The platform defines three key objectives of circular buildings: (1) Protection of material stocks, (2) Protection of the environment and, (3) Protection of the value. In circular design, these should all be considered during the design phase. Moreover, currently methods are established that allow the quantification of the three objectives, and this way integrated quantification of on circularity impact which allows comparison of different design choices. (Platform CB'23, 2019)

3.1.2 CIRCULAR DESIGN PRINCIPLES

The three key objectives described by Platform CB'23 (2019) require a shift in our current linear design approach to a circular approach (see Figure 4). This requires life cycle thinking and focussing on residual value at end-of-life phase. NEN-EN 15804+A4 (2019) defines five main life cycle phases for buildings: the production phase, construction phase, the use phase, the end-of-life phase, and the residual value phase (reuse, recovery, recycling) see Figure 4. In a linear economy, the life cycle ends at the end-of-life phase. In a circular approach, the end-of-life phase is considered in such a way that value is maximized.

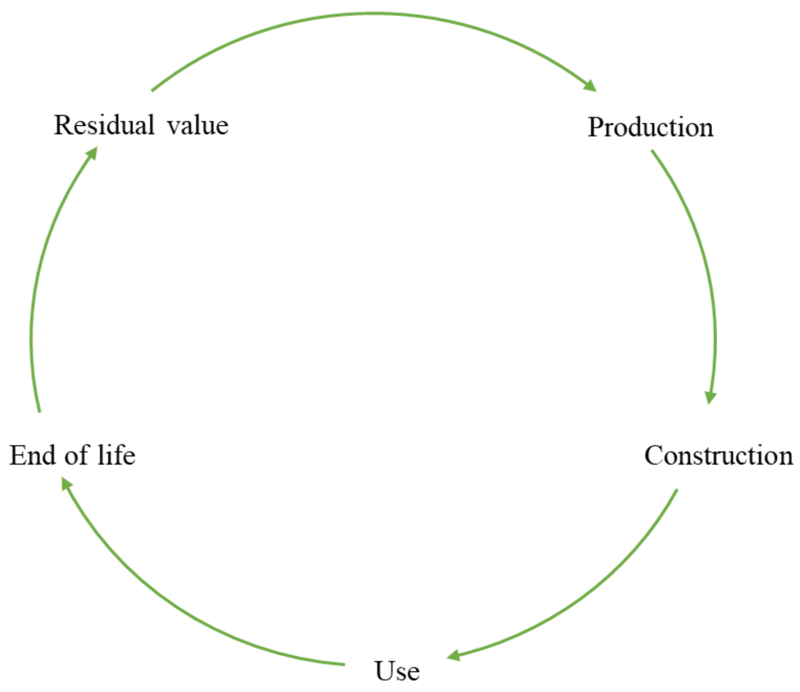


Figure 4: Circular life cycle phases (Ow figure)

3.1.2.1 10R Model

An acknowledges approach for circular design is making use of the “10R model”, which originates from “de Ladder van Lansink” representing three main design approaches: (1) Design smarter elements to minimize required material, (2) Design to increase the service life of the elements, and (3) Design for end-of-life value. (Figure 7)

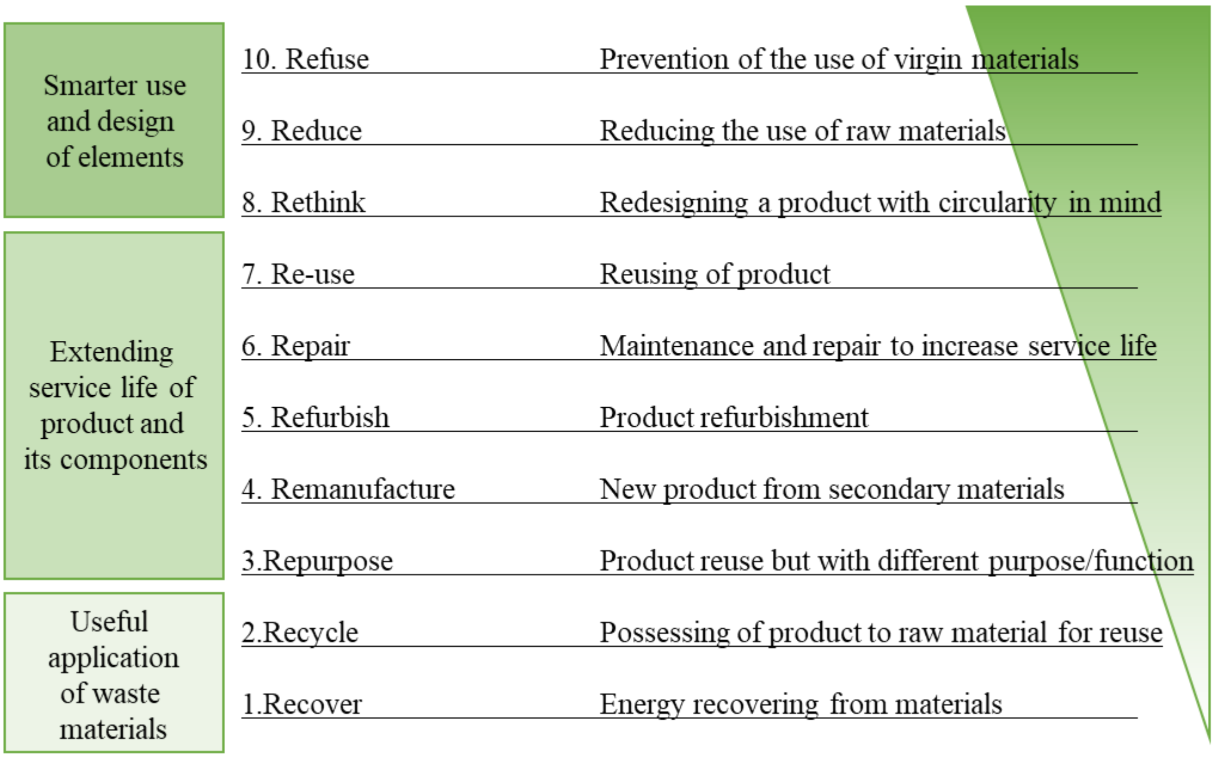


Figure 5: Ladder van Lansink, redesigned based on Platform CB’23, 2019 p.15

In this approach, material stocks are protected by refusing to use virgin/raw materials by for example only using renewable materials or materials from donor buildings, reducing the required virgin/raw material by designing smarter and by rethinking the design approach with circular principles in mind. Moreover, by extending the service life of building (elements) less material is required and by keeping the elements in the highest possible loop at end of life, the value is maximized. In general, circular design means that nothing should be waste and everything at least convertible to energy. (Platform CB’23, 2019)

3.1.2.2 Quantification methods

In the most recent document by Platform CB’23 (2020) a method is described to measure the circularity impact of a building (element). The document presents methods to calculate and quantify the circularity impact expressed as the three key objectives for circular building: Impact on (1) material stocks, (2) environment and (3) residual value.

By calculating the circularity impact of the three objectives, over each life cycle phase, the total circularity impact of a building over its entire life cycle can be calculated.

3.2 FIRE SAFETY DESIGN

In this section, a short summary of the theory behind fire safety design in buildings is presented. First the objectives are presented, followed by design methods relating to rule- and risk-based design approach.

3.2.1 OBJECTIVES

A building fire can have a large negative impact on building and surrounding, affecting the safety of people, and damaging material, environment, and economy. (Fire Safe Europe, 2020) The objective of fire safety design is to reduce the potential negative impact of a fire, by implementing fire safety measures. (Breunese & Maljaars, 2015; Hagen & Witloks, 2018)

The combination of fire safety measures used in a design is called the "total fire safety design". With the total fire safety design, the fire safety objectives of the building design must be reached. The objectives are typically defined as a set of rules by public authorities presented in building regulations focusing on two main objectives: (1) Protect the safety of occupants and fire fighter services and (2) protect against severe damage, often related to reducing damage for neighbouring building (Breunese & Maljaars, 2015). Typically, if these are ensured a building is considered fire safe.

Beside the rule-based objective (requirements), other additional design specific requirements may be stated, which can be expressed as e.g., the aim for functional continuity, economical value, architectural wishes and more. These requirements are called "functional" requirements, and are project and stakeholders dependent (Pettersson, 2020).

3.2.1.1 FIRE RESILIENCE

An important, rather new functional requirement which, according to experts in the field, including firefighters and fire engineers, is needed for a building to be circular is the aim for fire resiliency. Fire resiliency is the ability to rehabilitate after a fire and depends on the damage of the burning building and the material required to regain to original function (Figure 6).

The main aim of fire resiliency is to minimize the impact of a fire by making specific design decisions, either to withstand the fire or ensuring quick recovery of the function after a fire. By considering fire resiliency in a building design, circularity is considered not only based on reducing the environmental impact but also reducing the impact on social and economic level by ensuring recovery. In terms of sustainability and circular design, fire resiliency presents a requirement that considers the severity of a fire in terms of loss. (Meacham & McNamee, 2020)

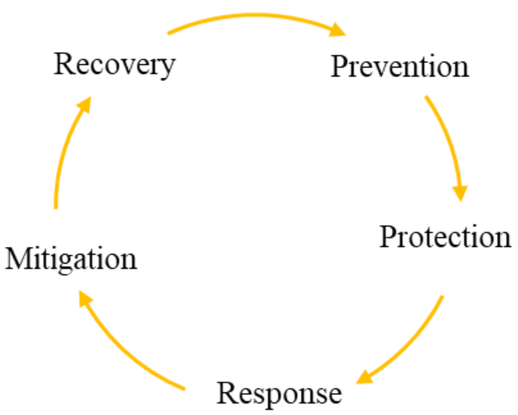


Figure 6: Fire resiliency life cycle (Redesigned based on McNamee et al. 2019, p)

3.2.2 Design methods

"Achieving protection objectives is the key element of fire prevention." (Hagen & Witloks, 2018 p.82). This is done by the implementation of fire safety design measures, together forming the total fire safety design. There are two different approaches to determine the total fire safety design: (1) By a rule-based approach or, (2) by a risk-based approach. Both are based on the implementation of fire safety measures, which reduce the probability or negative impact of a fire, by affecting the fire dynamics or providing sufficient resistance. (Hagen & Witloks, 2018).

3.2.2.1 Fire safety measures

Fire safety measures can be implemented to influence the severeness of a fire by affecting the potential behaviour of a compartment fire, or by ensuring sufficient fire resistance for a certain time. In general, fire safety measures can be categorized into 2 groups: (1) active fire safety measures and (2) passive fire safety measures. (Hagen & Witloks, 2018).

Active fire safety (or fire protection) systems are systems that require some form of action in order to work. Some examples of active systems are fire and smoke alarm systems, sprinkler installations and fire extinguishers. Apart from this, fire fighter services may also be considered, although consensus regarding their impact is needed. Detection systems report the fire, whereas sprinkler systems help control the growth phase and extinguishers and fire fighters to extinguish the fire altogether.

Passive fire protection are systems that compartmentalize a building by fire resistance rated walls and floors. This helps preventing spreading of the fire or smoke and ensuring structural stability for a certain time, and this way reducing the impact and/or ensuring safety. The total fire safety design is determined based on the expected characteristics of the compartment fire dynamics. Typically, active measures are used to positively affect the fire dynamics. Passive measures are determined either to withstand the duration of the fire, or for a certain amount of time.

3.2.2.2 Compartment fire dynamics

The fire dynamics in a compartment, can be divided into five parts: (1) Ignition, (2) Developing or growth phase, (3) fully developed phase, (4), decay phase and, (5) extinguishing (Figure 7)

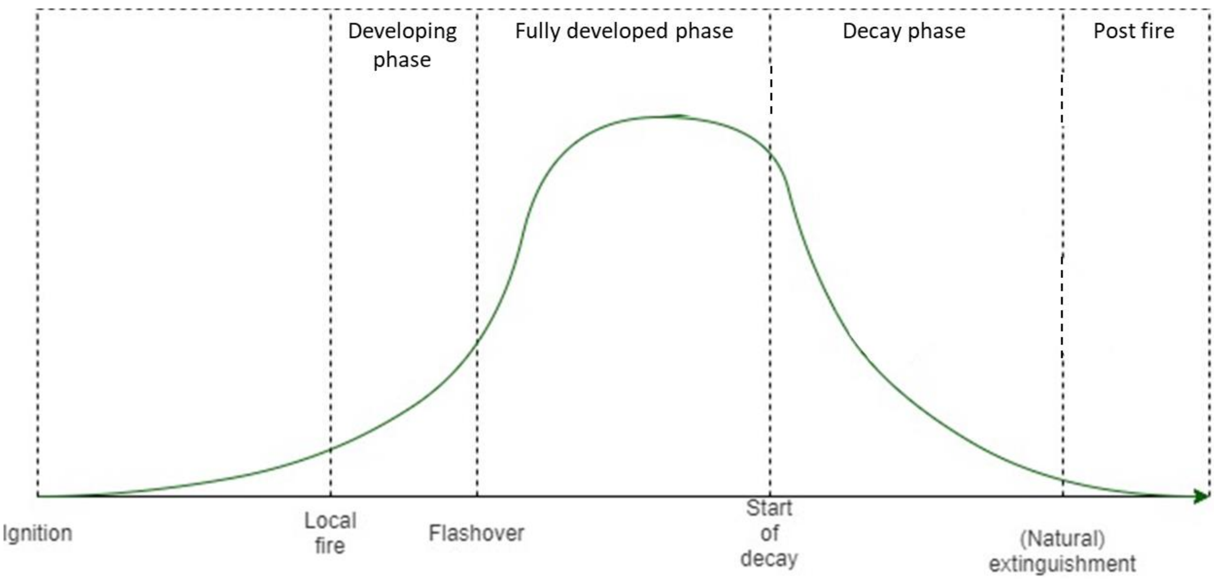


Figure 7: Temperature Fire dynamics in non-combustible compartment (Own figure)

Ignition of a fire can only occur if there is an ignition source, fuel, and sufficient oxygen. If one of these elements is lacking, ignition is not possible, and a fire will not occur. (Breunese & Maljaars, 2015) Typically, reducing the probability of ignition is done by avoiding flammable materials near potential ignition sources.

If ignition occurs, and fuel and oxygen are sufficient the fire starts to grow, which is called the growth phase. In the growth phase, the fire develops into a local fire. If during the growth phase the fire is controlled or extinguished, the impact will remain small. Potential methods to control or extinguish a fire during the growth phase can be done by applying manual fire extinguishers, fire blankets or automatic sprinklers.

If the fire is not controlled during the growth phase, and conditions are such that the fire can grow further, the local fire can develop into a fully developed fire. A fully developed fire is a fire in which all compartment content is involved and contributing to the fire. The moment at which this occurs is called flashover. When a fire reaches the fully developed phase, the fire is typically too severe to be manually controlled from inside, and fire fighter intervention typically handled defensively (from outside). Defensive intervention is however only possible up to 28m, as this is the reach of the fire fighter ladder. In this phase, the passive fire safety measures play the most important role, controlling the compartmentation by ensuring insulation, integrity, and structural capacity. (Hagen & Witloks, 2018).

When all the fuel in the compartment is consumed, the fire starts to decay. In the decay phase, the flames are slowly replaced by smouldering. If in this stage the risk is significantly low, fire fighter intervention can reduce the decay phase and the moment of extinguishing.

3.2.2.3 RULE-BASED DESIGN

Rule-based fire safety design is fire safety design, which is created by following a set of rules typically presented in building regulations. In the Netherlands, fire safety regulations are presented in the Dutch Building Decree in the document NEN-EN 1991-1-2 (2019) This document presents prescriptive requirements intended to avoid fatalities and severe damage. The rules are based on a set of assumptions, following from experience due to fire related events in history, acquired rights and feasibility. (Hagen & Witloks, 2018) The general assumptions are based on a certain amount of time (expressed in minutes) that fire safety measures, building characteristics or facilities should last or operate during a fire. The maximum time for the requirements is related to the expected fire dynamics in “standard” building design and the duration of the fire. It is assumed that for these types of design the fire is naturally decaying or even extinguished after 60 minutes. (Hagen & Witloks, 2018) The considered fire dynamics are visualized in Figure 8.

To ensure these requirements are met, the Dutch Building Degree further defines prescriptive threshold values and determination/calculation methods. The aim of the prescriptive requirements is that by following the rules and guidelines, similar levels of fire safety can be achieved for different building designs.

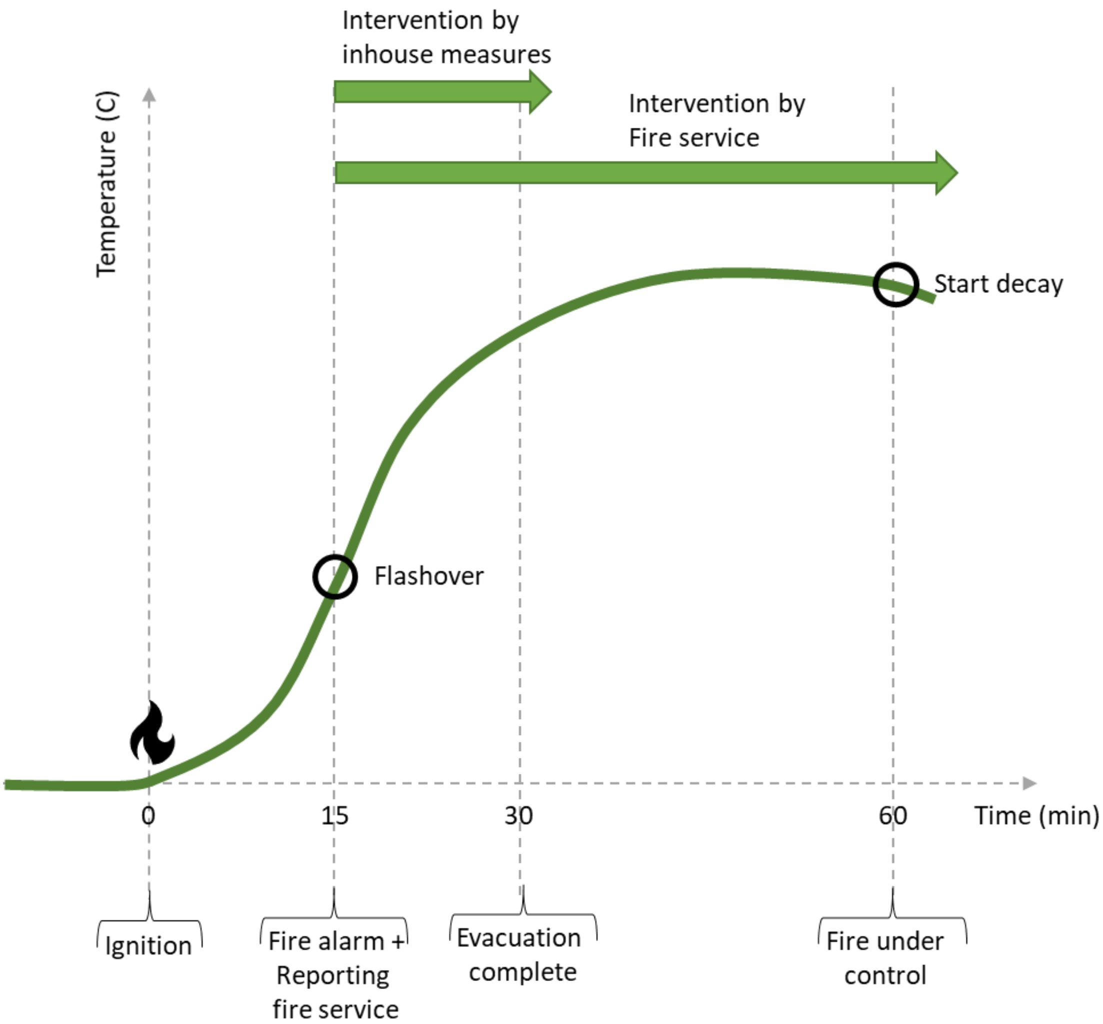


Figure 8: Standard fire dynamic and rules (Redesigned based on Hagen & Witloks, 2018)

The resistance to fire plays an important role in the fire safety design as it defines the time a building element can resist the fire from spreading (expressed by the integrity (E) and the insulation (I)) and/or the time the element keeps the required loadbearing capacity (R). The requirements stated for these, are based on building function and height. For these it is assumed that a fire will decay after at least 60 minutes (Hagen & Witloks, 2018). For standard construction materials, the maximum temperature determines the loadbearing capacity. Therefore, if the fire decays after 60 minutes, it is assumed that the fire does not have significant impact on the building. By this and considering additional risk factors related to building height and function, values are stated. (NEN-EN 1991-1-2+C3, 2019)

To be able to determine the fire resistance of building elements a so-called nominal standard fire curve (ISO 834) has been developed. This curve shows the time-temperature development in a compartment based on an exponential growth rate representing a flashover fire phase after which a constant continuous increase of the temperature is considered (Hagen & Witloks, 2018). The temperature distribution is derived from compartment tests by Efectis, representing a compartment fire in a non-combustible compartment. The curve is used to enable quantification and comparing the performance under fire for different building elements by exposing the elements to the standard temperature distribution and rating the elements based on the amount of time the required capacity is maintained. (Hagen & Witloks, 2018)

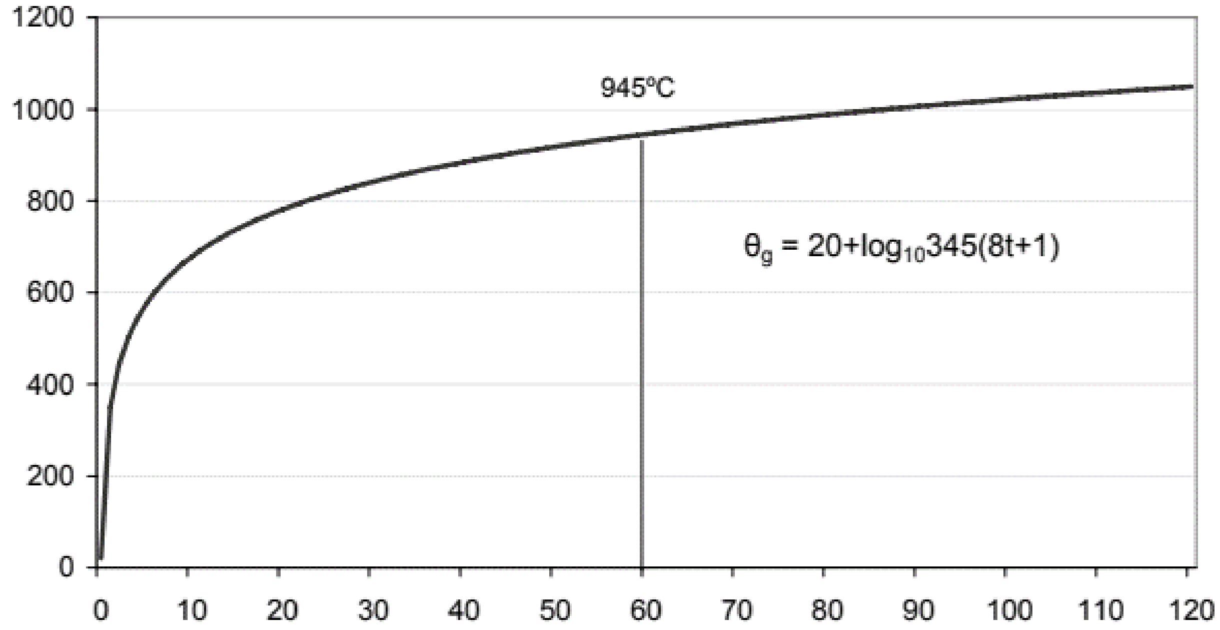


Figure 9: Standard fire curve (Own figure)

However, no fire is alike, and the rule-based regulations are only based on a generic representation of an expected compartment fire. These do however not consider the effect of building specific design characteristics. Therefore, it is always important to determine whether the standard fire curve presents a sufficient representation of a fire in the specific building. Moreover, NEN-EN 1991-1-2 (2019) states that the fire safety design for buildings with higher consequence classes, consequence class 2 and 3 (CC2 and CC3), a risk-based assessment should always be done to determine whether the nominal fires provide a sufficient representation of the building fire, or whether performance-based fire design is required.

3.2.2.4 Risk-based design

The prescriptive building regulation allows clarity on safety requirements but is only suitable when used for rather standard building design. As soon as the design becomes more complex (higher, larger etc.) or the structural material behaves differently in fires then conventional materials, the prescriptive regulation may not be sufficient. In this case, a risk-based (or performance-based) approached may be more suitable, in which the fire safety of a building is assessed based on the design specific risks.

In risk-based design, rather than complying with strict rules, performance requirements must be met. This way, fire safety design can be based on common sense and knowledge, by an equivalent approach in which the combined effect of several fire safety measures can be considered. This enhances not only fire safety for innovative building design, but also alternative fire safety design solutions. (Hagen & Witloks, 2018)

Risk is a combination of two things. It is the probability that a hazard will cause harm and the impact of that harm. In the case of fire risk assessment, the hazard is the fire, and the risk is the probability and impact of a particular fire scenario. A fire risk assessment therefore consists of two parts: (1) an assessment of the chance of a specific fire scenario and (2) the prediction of the negative impact of the specific fire scenario. (Hagen & Witloks, 2018). A six-step risk approach was established by Hagen & Witloks (2018), visualized in Figure 10.

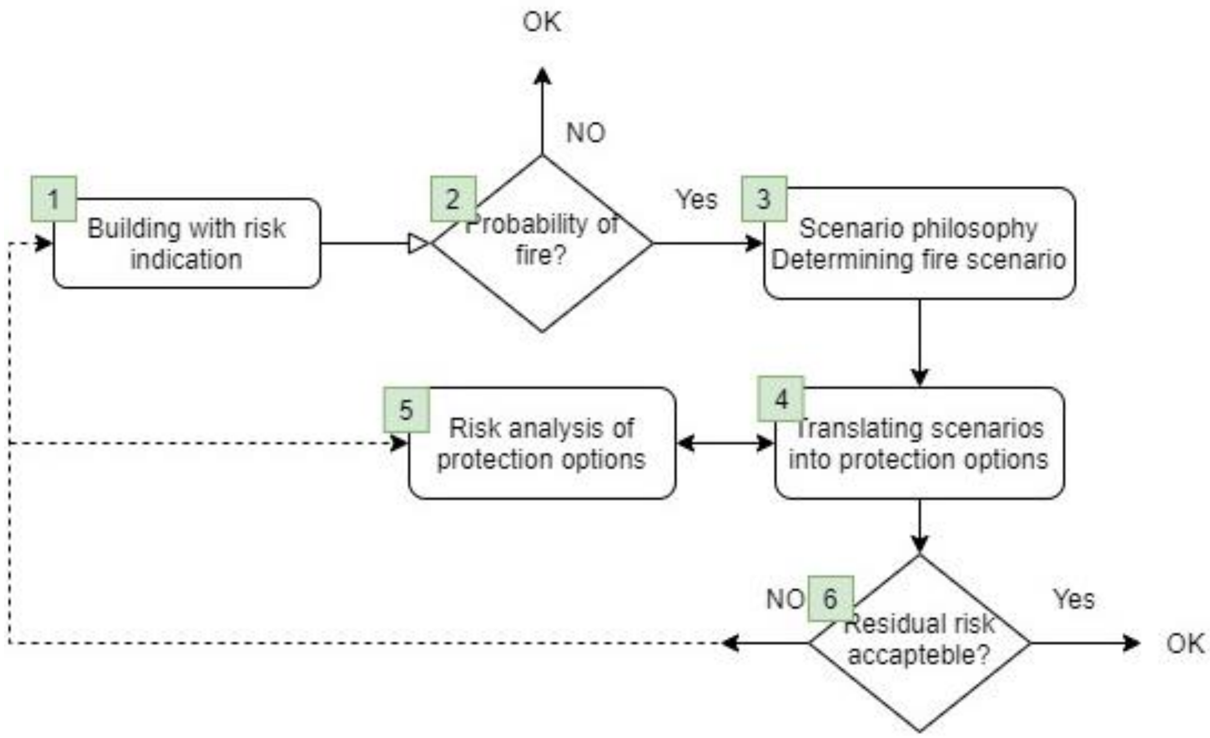


Figure 10: Six-step fire risk approach (Redesigned based on Hagen & Witloks, 2018, p.86)

The approach starts with providing information about the design of the building and the risks that should be considered, which depends on the type of building, the design characteristics, and materials used as well as the building requirements and objectives. The outcome of the step is an overview of the building characteristics and related concerns.

In the second step, the probability of a fire occurring is determined. If the probability is zero, fire safety measures may be unnecessary. In case there is a probability, a fire safety design should be determined which follows from steps 4-6.

With the information from step 1 and 2, the required design fire scenario should be determined in step 3. This is based on predicting the natural "real" fire dynamics in a compartment. Predicting the fire dynamics is either done by complying with the normative design fires as stated by the building regulations (if sufficient), or by performance-based design in which the influence of design specific parameters is considered by engineering prediction methods. Performance based design methods are equation-based methods, allowing the modelling of compartment fires more accurately. There are several engineering models available which can be used to predict the natural fire in a compartment. This is elaborately discussed in Appendix 2.1. The outcome of this step is an overview of the expected fire dynamics, and how this can be translated to sufficient requirements, which is a similar approach as presented in Figure 8.

Based on the fire scenario, protection methods can be proposed, followed by relating risk analysis of the protection in step 4 and 5. This is an iterative approach until the residual risk of the fire safety design stated in step 6 is acceptable. Determining the influence of a fire safety measure on the fire risk can be done by different methods, supported by testing, literature, modelling etc.

The approach presented in Figure 10 shows the steps required in a risk assessment, however, does not yet present proper methods regarding the quantification of the risk. In appendix E of NEN-EN 1991-1-2 (2019) a simplified method is defined that integrates the risk of fire safety design choices by risk -factors related to risk of ignition and risk of design choices. These risk factors are then multiplied to the considered fuel load, which can then be integrated to the parametric design fire approach, affecting the duration and characteristics of the expected fire.

In the document NEN 6079 (2016), a more elaborate approach for the quantification of fire risk is presented. In the document, the focus is on how to calculate the probability of different fire scenarios. The impact of the fire scenarios is related to the expected damage in terms of value loss. The risk of each fire scenario is calculated based on the expected frequency (probability) times the impact (damage) for the specific scenario. The total risk of the design is the sum of all fire scenario risks.

The first step in the fire risk assessment is to define certain fire scenarios. The document defines 5 scenarios, relating to the five phases of compartment fire dynamics ((1) ignition, (2) growth, (3) fully developed phase and, (4) decay) and the moment of extinguishing. This probability that each scenario occurs is determined based on a fault-tree as presented in Figure 11. Whether the fire is extinguished (whether a certain fire scenario is expected) depends on several design related aspects and the availability of fire safety measures.

The method is based on a worst-case scenario (scenario 4) in which the fire spreads beyond the considered compartment. However, the effect of the spreading is not considered. This is in line with the performance-based methods presented in NEN-EN 1991-1-2 (2019) on which also only the risk is based on the impact on one compartment. Yet methods are lacking to determine the influence of a fire on the whole building.

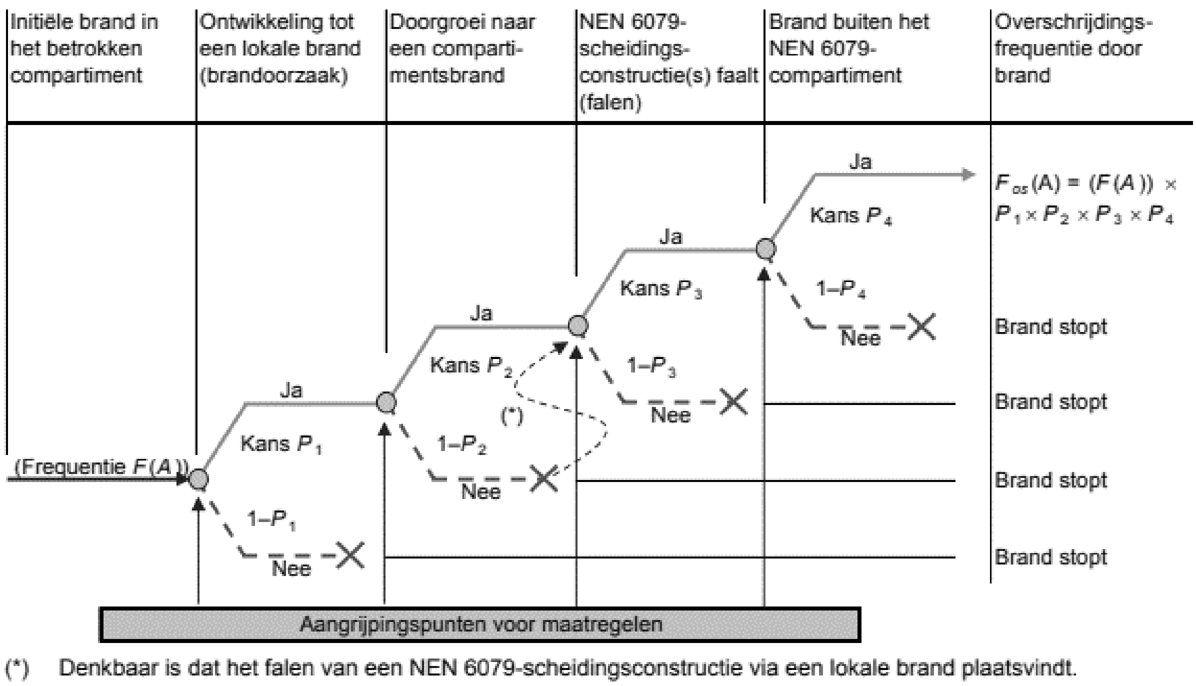


Figure 11: Fire scenarios gained from NEN 6079 p. 19

3.3 Description of the design approach

In this section, the main idea behind the proposed design approach is presented. This approach is based on an integration of the relation between circular- and fire safety design by comparing the objectives and methods and translating this to circular approach and quantification method.

3.3.1 Circular fire resiliency life cycle

The main objective of circular building design is to reduce the negative impact of material consumption. In the Netherlands three main objectives for circular building design are stated: (1) Protection of material sources, (2) protection of environment and (3) protection of material value. A building fire can have a large negative impact on building and surrounding, affecting the safety of people, and damaging material, environment, and economy. (Fire Safe Europe, 2020) This way, a building fire negatively affects the objectives of circular building design, as (1) material is lost and this way end-of-life value damaged, (2) a fire results in toxic emissions, affecting the environment, (3) additional material is needed to either rehabilitate or build a new building. To reduce the negative impact of a fire, fire safety measures are implemented in the design. However, this affects the initial objective of circular design, to reduce the negative impact of material consumption. (Breunese & Maljaars, 2015; Hagen & Witloks, 2018)

This means that there is a contradiction between the aim of reducing material consumption and the protection against fire risk. An increased amount of fire safety measures reduces the impact of a fire but increases the impact of material use.

This balance between material use for fire safety measures and fire risk can be integrated into one design approach. This is done by integrating a typical life cycle for circular building design, with a fire resiliency life cycle, forming a new "circular fire resiliency life cycle" as presented in Figure 12.

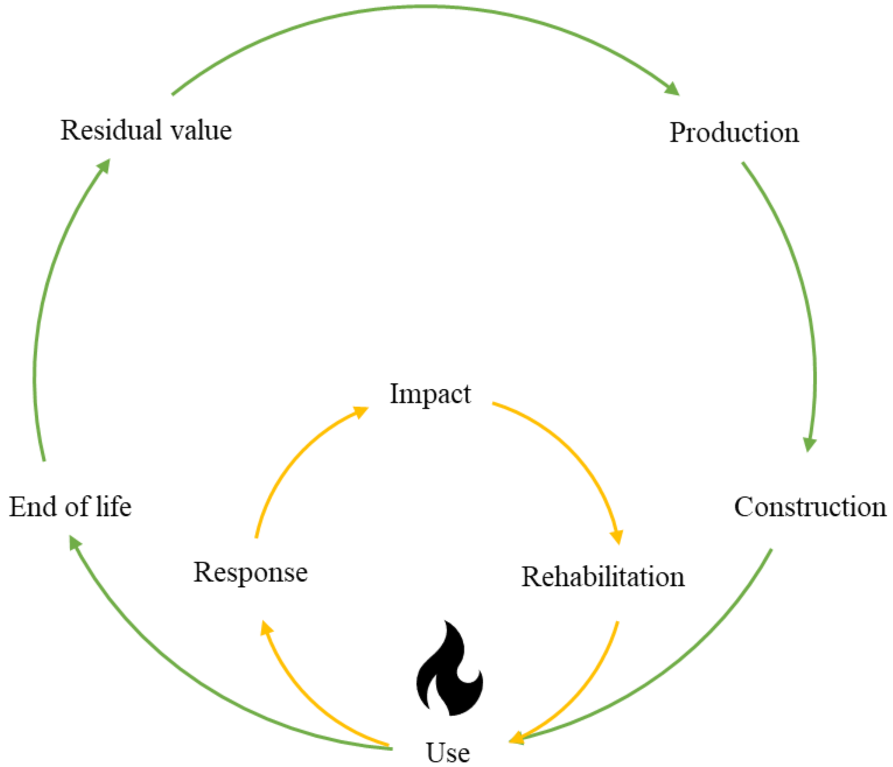


Figure 12: Circular fire resiliency life cycle (Own figure)

The green arrows in the figure present a typical circular life cycle of a building (element) and the yellow arrows indicate the fire resiliency life cycle in case a fire occurs during the use-phase of a building.

In this approach, the impact of fire safety measures on the material input and output in normal circular life cycle conditions is determined by following the green arrows. Quantification of the circularity impact of fire safety measures can be done by following LCA related methods presented by Platform CB'23 (2020). In this approach, circularity is quantified by determining economic or environmental impact of the use and end of life residual value of fire safety measures.

In the fire resiliency life cycle, presented as the yellow arrows, the fire risk during the building use-phase of a design is determined. The resiliency life cycle consists of four parts: (1) The probability of a fire during the use phase, (2) the expected response of the fire defined by different fire scenarios, (3) the impact of the fire, which may relate to, among others, toxic emissions and building and material damage, and (4) the required material (costs) to rehabilitate after a fire. For this, it is important to understand the influence of the fire safety design measure on the fire risk, which can be approached as presented in section 3.2.2.4.

3.3.2 QUANTIFICATION OF THE IMPACT

The design approach presents the relation between material use and fire risk in terms of a circular approach. To be able to understand the impact of a fire safety measures on the material consumption and fire risk a quantification method is required. This is done by integration of the aspects presented in the circular fire resiliency life cycle into one value that presents the balance between material use and fire risk. The value is defined as "the circular fire safety impact value" and is the sum of material use for fire safety measures and their effect on fire risk, which can be expressed as economic or environmental impact.

The material use presents the circularity impact of the fire safety measures, determined by the quantity of material input (defined as costs) and the end-of-life value (defined as benefits). The fire risk presents the probability and impact of a fire due to the fire safety design, in which the considered impact depends on the objectives of the calculation and can be defined as value loss, toxic emissions, rehabilitation and more. With this approach, quantification of the total circular fire safety impact value is defined by the following formula:

$$Circular\ fire\ safety\ impact\ = Material\ use\ + Fire\ Risk \qquad \textit{Eq. 1}$$

The impact can be expressed as economic and/or environmental (shadow) cost of a design. With this formula, the total impact can be quantified to one value, which allows comparison of the total impact of a fire safety design based on material consumption and fire risk. The total stepwise, iterative approach is summarized in a flow chart, which is presented in Figure 13 on the next page.

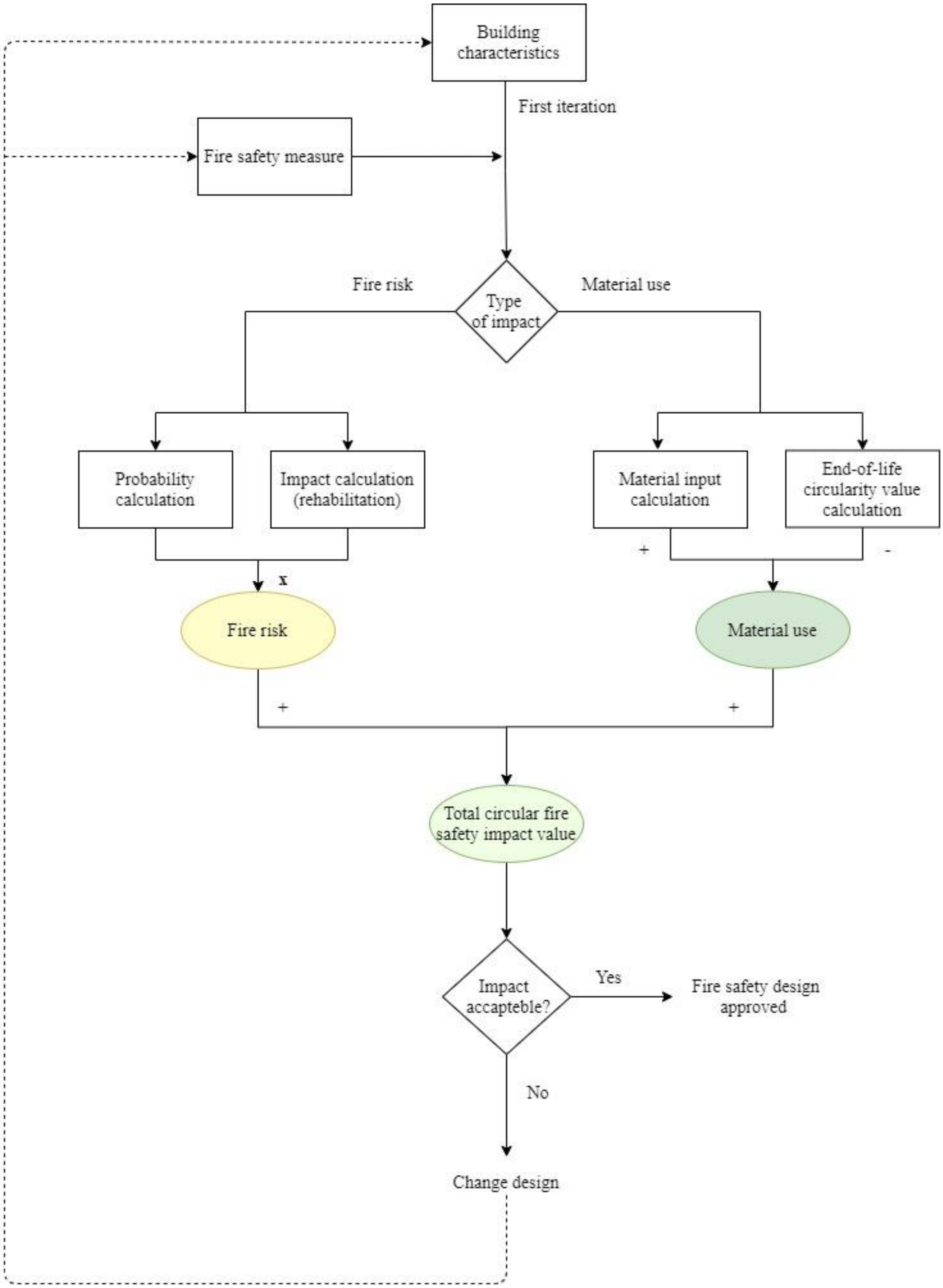


Figure 13: Flowchart for quantification of circular fire safety impact value (Own figure)

Figure 13 clearly shows the two main outputs, relating to material use of fire safety measures and fire risk. The approach allows iteratively determining the impact of fire safety design measures on the material impact by changing of design parameters.

3.3.2.1 Material use

The material use presents the circularity impact of the fire safety measures and is calculated by material input, expressed as costs, and end-of-life residual value, expressed as benefit. The costs of the design are the economic/environmental costs for material input during the expected lifecycle of a specific building in normal, non-fire conditions.

The benefits are the residual value at normal end-of-life scenario of the fire safety elements in terms of potential re-use or recycling. This value depends on the quantity of output of material, the expected technical and functional service life of the elements and the detachability. The value is expressed as the positive economic and environmental benefit of end-of-life value. The total material use of the fire safety measures is determined by extracting the material benefits from the costs.

3.3.2.2 Fire risk

Fire risk is the probability of a fire scenario times the impact of the fire scenario. The probability of a fire occurring is based on many aspects relating to fire characteristics due to design measures and fire fighter intervention. The impact is the lost value after a fire and this way assumed to be the material cost needed to rehabilitate.

3.4 CONCLUSIONS

In this section, the research question of the first part of the research is answered.

How can the relation between circular building design and fire safety design be defined and translated to a design approach for circular fire safety design?

The main objective of circular building design is to reduce the negative impact of material consumption. In the Netherlands three main objectives are stated for circular building design: (1) Protection of material sources, (2) protection of environment, and (3) protection of element/material value.

A building fire can have a large negative impact on building and surrounding, affecting the safety of people, and damaging material, environment, and economy. This way, a building fire negatively affects the objectives of circular building design, as (1) material is lost and this way end-of-life value damaged, (2) a fire results in toxic emissions, affecting the environment, (3) additional material is needed to either rehabilitate or build a new building.

To reduce the negative impact of a fire, fire safety measures are implemented in the design. However, this affects the initial objective of circular design, to reduce the negative impact of material consumption. This means that there is a balance between either affecting the aim of protection of material sources, or protection of fire risk. Where an increased amount of fire safety measures reduces the impact of a fire but increases the impact of material use.

This balance between fire safety design and circular design can be translated to a design approach where the influence of the fire safety design is considered in a circular and resiliency life cycle approach. The approach consists of two main parts: (1) Material use of the fire safety measures, and (2) the fire risk, representing the probability and impact of a fire for a certain fire safety design.

By the sum of material use and fire risk, one “circular fire safety impact” value is defined. This value presents the total economic or environmental impact of the design for the building materials. By changing the fire safety design, tot the most favourable design can be determined. The most favourable design is the design with the lowest economic or environmental total value.

PART 2

CIRCULAR FIRE SAFETY DESIGN TOOL FOR MASS TIMBER BUILDINGS

In this part of the report, the circular fire safety design tool for mass timber buildings is presented. First, the theory of fire safety design in mass timber buildings is presented. After this, the theory is translated to quantification methods to calculate the balance between material use and fire risk for the fire safety design in mass timber buildings. Lastly, the final design tool is presented. With this, the second objective of the research is reached which is defined as:

Create a design tool for preliminary design phase that quantifies the balance between material use and fire risk for the fire safety design in mass timber buildings.

4 Fire safety design in mass timber buildings

In this chapter, the theory behind the fire safety design in mass timber buildings is presented. The main aim of this chapter is to present the aspects that should be considered for the fire safety design in mass timber buildings, so that this can be related to the circular fire safety design approach. This way boundary conditions and methods can be formed to quantify the relation between material use and fire risks for the fire safety design in mass timber buildings, which is presented in chapter 5.

First, the fire risk in mass timber buildings is presented, focusing on the burning behaviour and its effect on fire dynamics and structural resistance. Secondly, methods for fire safety design in mass timber buildings is presented considering both rule and risk-based approaches. Lastly conclusions are presented, which will present the boundary conditions for the quantification methods. With this, the second sub-question is answered which follows:

Which aspects must be considered for fire safety design in mass timber buildings?

4.1 FIRE RISK

In this section, the theory regarding fire risks in mass timber buildings is presented by focussing on burning behaviour and its effect on compartment fire characteristics and the structural fire resistance. The theory is strengthened by an elaborate review regarding large scale compartment fire tests which is presented in appendix 1.

4.1.1 INTRODUCTION

Mass timber building design is a sustainable design solution which has high potential to contribute to reaching a circular build environment. Timber is natural and renewable and the forests in which it is harvest functions as a carbon sink. Moreover, it has high potentials to be re-used or recycled into new engineered timber elements. This has led to an increased interest in timber building design over the last years. (Gerard & Barber, 2013)

In the early 1990's, Cross Laminated Timber was developed. CLT is an engineered timber element build up from several timber lamellas, stacked such that the direction of the timber grain alternates per lamella and this way crosses (Figure 14). The lamellas are glued together by CLT adhesive. The composition of CLT makes that timber elements can be made which provide load-bearing capacity in two directions, rather than in one direction.

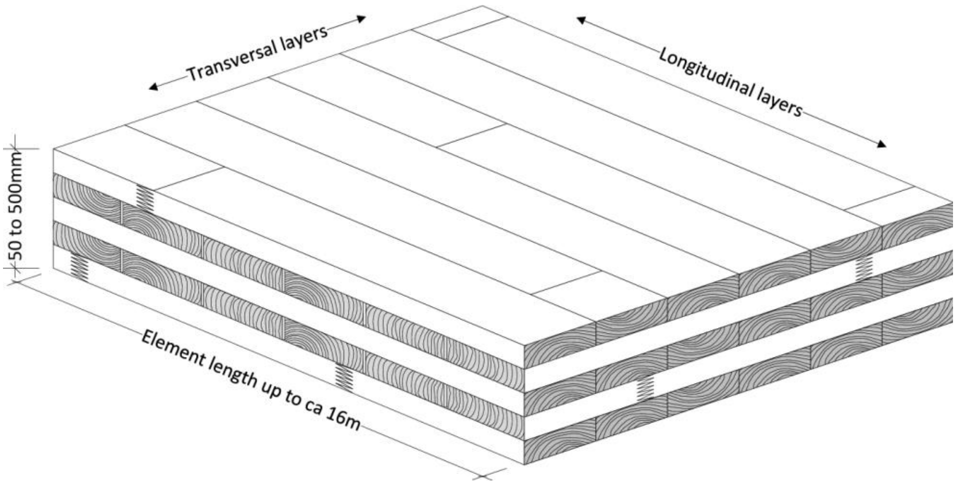


Figure 14: Cross Laminated Timber (Figure by Schmidt et al..2018)

Due to the development of CLT, mass timber building construction has become possible in which floors and walls in buildings are constructed by CLT elements. This has made it possible to build large and high-rise buildings with a timber structure. However, timber is a combustible material and mass timber constructions result in additional risks relating to fire safety (Pettersson, 2019; McNamee and Meacham, 2020).

The fire risks have since 2013 extensively been investigated. By large scale compartment test (discussed in appendix 1) the influence of different design measures on the fire dynamics are extensively investigated and the relating fire resistance of the elements.

From this research follows that the increased fire risks of mass timber buildings relate to the burning behaviour of the material. In the document by Pettersson (2020), seven main fire hazards were recognized: (1) Fuel load provided by timber construction, (2) duration of the fire, (3) internal fire spread, (4) external fire spread, (5) structural stability, (6) construction phase and, (7) fire fighter safety. In this research, the focus regarding fire risk is on the effect of the burning behaviour on the compartment fire dynamics and the structural fire resistance.

4.1.2 BURNING BEHAVIOUR

The burning behaviour of timber is characterized by four phenomena's: (1) pyrolysis, (2) ignition, (3) combustion, and (4) extinction. In general, for solid timber elements the processes and characteristics of the burning behaviour of timber are well understood. (Barlett et al., 2019) The burning behaviour of timber is presented in Figure 15.

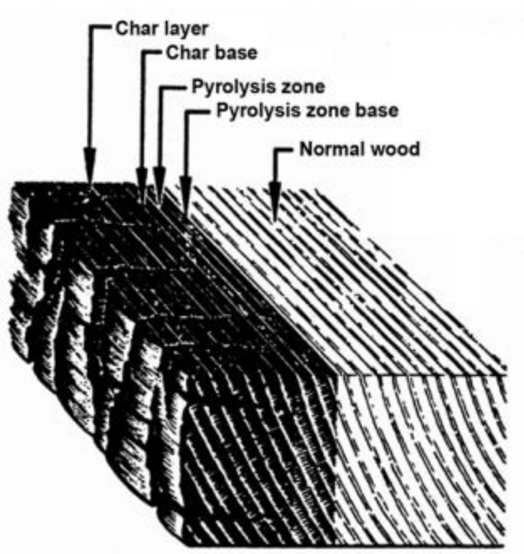


Figure 15: Burning behaviour of timber (Figure by White et al., 2010 Figure 18-3)

Pyrolysis is the thermal decomposition of timber, which results in physical and chemical changes of the material. Slow pyrolysis may occur above 100 degrees, however main pyrolysis is observed to occur above 225 to 275 degrees, for which pyrolysis gases are generated that can ignite. (Barlett et al., 2019)

Ignition of the timber occurs either by a spark or flame which comes in contact to the pyrolysis gasses, or by heating of the timber alone. When the pyrolysis gasses are ignited there will be combustion, which occurs when the pyrolysis gasses are mixed with the oxygen in the air. From this process, heat is generated which results in a self-sustaining fire. (Barlett et al., 2019)

When temperatures exceed 300 degrees there will be rapid pyrolysis which results in an increase of flammable gasses. Therefore, generally when the surface reaches above these temperatures, the timber will be burning (pilot ignition temperature). Moreover, at 300 degrees a layer of char is formed. The char limits further heat transfer from the fire and this way acts as a sort of insulation for the unburned timber. This process of charring therefore allows timber elements to achieve a level of inherent fire resistance, as the material beyond the char can still have its original temperature and thus unaffected chemical and physical properties. (Barlett et al., 2019)

Due to possible cracks in the char layer, radiative and conductive heat transfer is still possible beyond the char layer, which results in pyrolysis of the unburned timber below the char layer and this way provides additional fuel to the fire. Due to this, the char layer grows with sustained exposure to fire, creating even more insulation, slowing down the burning rate and reducing the unheated cross section of the member. (Barlett et al., 2019)

When there is insufficient heat, either generated by the timber due to the insulation from the char layer or lack of heat from a fire, the timber cannot self-sustain the fire and will self-extinguish. (Barlett et al., 2019)

Timber elements can be protected against fire by applying fire protection. One typical solution is to encapsulate a timber element by gypsum boards or other types of fire-insulating boards. Encapsulation by gypsum board extends the moment at which timber starts pyrolyzing. However, if the protection falls off, the pyrolysis rate is increased. (Barlett et al. 2019)

4.1.2.1 BURNING BEHAVIOUR OF CLT

The burning behaviour of CLT is different compared to solid timber, which is due to the composition of CLT, mainly related to the CLT adhesive. CLT adhesive type can be divided into two groups (1) fire resistant adhesive and (2) non-fire-resistant adhesive. Whether an adhesive is defined as fire resistant or not, depends on whether the adhesive is prone to temperature exposure, meaning that the temperature affects the adhesive strength. Fire resistant adhesive, (typically Melamine-Urea Formaldehyde, MUF), is an adhesive which is only limited affected by temperature exposure and a non-fire-resistant adhesive, (typically Polyurethane, PU), is an adhesive that is prone to temperature exposure. If a CLT element is constructed by fire resistant adhesive, a similar burning behaviour is expected as for solid timber. However, in a CLT element in which the timber adhesive is not fire resistant, the adhesive can fail, resulting in falling of the timber lamella. This is called delamination (see Figure 16).

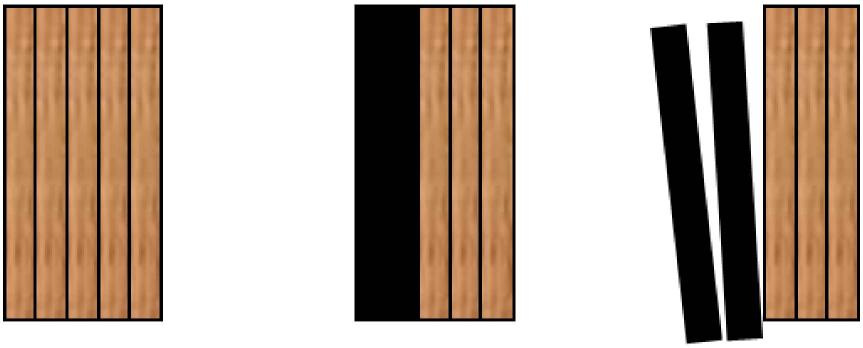


Figure 16:: Left: unburned timber.; Middle: Burned timber with fire resistant adhesive; Right: Delamination (Own figure)

The effect of delamination on the burning behaviour is that the insulation layer created by the char-forming, falls off, and results in fresh timber being exposed to high temperatures. This results in increased pyrolysis speed, until a new char layer is formed. If the heat exposure continues, delamination may continuously occur until the whole element is completely combusted.

From small and large-scale compartment fire tests follows that delamination reduces the chance of self-extinguishing of the element in case heat exposure is sufficient to continue the burning process of the element. (Crielaart, 2015; Janssen et al., 2017; Emberley et al., 2017; Gerard, 2018)

Barlett et al. (2019) recognized that the burning behaviour of timber is highly influenced by several aspects which can be related to material, system, and fire dynamic properties. From all the different aspects influencing the burning behaviour of timber, Barlett et al. (2019) concludes that the fire dynamic properties, especially the incident heat flux exposure and the effect of encapsulation failure are the most dominant factors determining burning behaviour of timber. In addition, it is observed that the burning behaviour of CLT deviates from the burning behaviour of solid timber due to the phenomenon of delamination.

4.1.3 FIRE DYNAMICS IN MASS TIMBER COMPARTMENTS

The fire dynamics in mass timber compartments are different compared to non-combustible compartments, due to the burning behaviour of the timber. The effect of timber on the fire dynamics has extensively been investigated by many large-scale compartment fire tests since 2013. In appendix 1, an overview of the large-scale compartment tests and their results are presented. Though the focus and aim of the tests vary widely, some general conclusions can be drawn regarding the behaviour of the fire dynamic phases of mass timber compartment fires. Figure 17 shows the different characteristics of the dynamic phases and scenarios, expressed in compartment temperature over time.

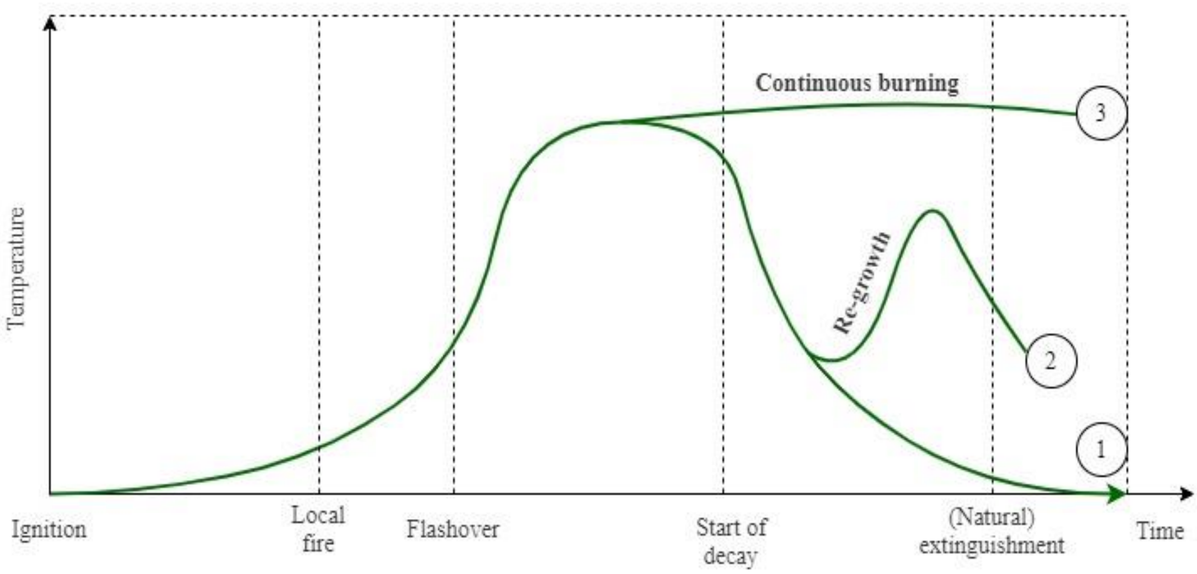


Figure 17: Fire dynamics in CLT exposed compartment (Redesigned based on Barber et al., 2020 p821)

4.1.3.1 IGNITION

Timber starts to release combustible pyrolysis gasses typically above 225-275 degrees Celsius. However, for timber to ignite and start burning, sufficient heat flux by a spark or flame is required or sufficiently high temperatures (Barlett et al., 2019). For this reason, structural timber elements will likely not quickly be involved in the compartment fire, until temperatures are sufficiently high.

4.1.3.2 GROWTH PHASE

When temperatures in the compartment gradually increase due to the increased involvement of the movable fuel load, the timber will start to participate in the fire and contribute fuel from the pyrolysis gasses and heat from the combustion process (expressed as heat release rate or HRR) (Pettersson, 2020)

From large-scale compartment tests follows that the involvement of exposed timber in the growth phase typically leads to decreased growth phase time, and therefore quicker flashover. The effect is increased by increasing of the exposed CLT percentage. (See appendix 1for the elaborate analysis).

Moreover, from test 4 by Zelinka et al. (2018), follows that if an automatic sprinkler is installed in a fully exposed compartment, the fire is controlled and extinguished before flashover is reached.

4.1.3.3 Fully developed phase

When flashover has occurred in a compartment fire, all compartment contents will be involved in the fire and release heat. At this moment, generally all the exposed timber will participate in the fire, as temperatures will be higher than 300 degrees (temperature at which char is formed). The fire in non-combustible compartments will typically decay when all movable fuel is consumed. However, timber can self-sustain a fire as it produces heat and fuel, which will typically increase the duration of the fully developed phase. The timber will continue to burn until the heat flux is insufficient to self-sustain the fire and the timber will start to decay, which results in a decrease of HRR and temperature. (Barber et al., 2020, Pettersson, 2020).

From large scale compartment tests follows that increased timber exposure increases the duration of the fully developed phase. Moreover, it is observed that intensity of the external flaming is increased by increased CLT exposure. (See appendix 1)

4.1.3.4 Decay phase

The decay phase of a compartment fire with exposed CLT surfaces can be very different compared to the decay phase of conventional building materials. As presented, the fully developed phase will generally be longer, meaning that the start of the decay is usually delayed compared to non-combustible compartments. Besides this, the decay phase itself can show many differences depending on characteristics of the compartment, material and more. Another possible scenario is that the fire will not decay. In Figure 17, the three possible scenarios of the decay phase are clearly presented, described as number 1, 2 and 3.

Scenario 1: Burnout with decay

Scenario 1 describes a burnout with a decay phase, leading to extinguishment before all structural timber is consumed, by the phenomenon self-extinguishment. Self-extinguishing of mass timber compartments has been investigated by small- and large-scale compartment tests. However, in these tests, the definition of self-extinguishing is not consistent and defined as either the moment that a flaming fire starts smouldering (Emberley, 2017) or if a smouldering fire self-extinguishes (Crielaard, 2015).

It is observed that self-extinguishing (either flaming or smouldering extinguishing) is related to the heat flux exposure and availability of oxygen. If there is insufficient oxygen or if a fire does not provide enough heat back to the combustible materials, or vice versa self-extinguishing is expected. Emberley et al. (2017) observed that a flaming fire generally transitions to a smouldering fire when the heat flux reduces below 45 kW/m2. Crielaard (2015) observed that for a smouldering fire to self-extinguish, a heat flux below 6 kW/m2 was needed.

Flaming extinguishing is observed in compartment experiments with exposed CLT and occurs when the combustion of materials cannot be maintained, resulting in a smouldering fire. However, due delamination, encapsulation base-layer failure or ventilation flow a smouldering fire can potentially lead to flames again, and contribute to a new fire (secondary flashover, see scenario 2; Crielaard, 2015).

Considering the results of large-scale compartment tests follows that several tests observe flaming-extinguishing, however only a very limited number of compartment tests were lasted long enough to observe smouldering extinguishing. In most of the tests, the fire was manually extinguished either after a certain time, when average compartment temperatures were below a certain threshold value (typically 300 degrees) or if regrowth or continued burning was observed (scenario 2&3). As witnessed from the tests by Brandon et al. (2021), if the gypsum protection is maintained during sufficient time and the structure cannot delaminate, (flaming) self-extinguishing of compartment fires with multiple exposed timber surfaces is possible.

Scenario 2: Secondary flashover
Scenario 2 in Figure 17 firstly shows a decay phase, but then during the decay phase a new rise in temperature (and HRR) occurs. This is called a secondary flashover. A secondary flashover occurs when cold, un-burned, unprotected timber suddenly gets exposed to high compartment temperatures. If this happens when the compartment temperatures are above the burning point of timber (300 degrees), the timber will start burning and by this contribute additional fuel and heat to the fire, leading to a secondary flashover and potentially a second fully developed fire. This causes serious problems when not accounted for in the design as structural and separational functions may not ensure sufficient capacity to resist a second fully developed fire. (Barber, 2020)

This phenomenon has been observed in various large scale compartment fire tests with exposed CLT. From these tests follows that secondary flashover occurs due to suddenly exposed unburned timber due to delamination of the burned outer lamella or due to failing of the protective encapsulation layer. Both are mainly dependent on the heat flux (temperatures) and duration of the fire exposure. (Barber et al., 2020; Pettersson, 2020) From the large-scale compartment tests follows that secondary flashover can be prevented by using fire resistant CLT adhesive, using fire resistant encapsulation that does not fail, or using enough encapsulation layers such that the timber remains protected during the feat exposure.

Scenario 3: Continuous burning
Decay scenario 3 in Figure 17, presents the scenario in which the fire will not decay but continuously burn until the building or compartment fails. This scenario could occur when the timber continues to contribute to the fire, after all movable fuel load is consumed, caused by the timber self-sustaining the fire due to sufficient heat radiation between the exposed surfaces. This will continue until the heat release is insufficient to sustain the fire (due to char forming) or all fuel from the structure is consumed and has failed. (Barber, 2020; Pettersson, 2020)

From large scale compartment tests follows that continuous burning is observed mainly relating to a combination of exposed CLT, delamination and encapsulation failure. For tests with exposed timber surfaces, it is observed that the duration of the fully developed fire is increased. When during this time the protection starts to fail or delamination occurs, more timber will be involved in the fire and prolong the duration of the fully developed phase. If during this more encapsulation fails or the elements delaminate further, a continuous contribution of fresh, unburned timber will contribute to the fire, leading to sustained burning.

However, as witnessed from the tests by Brandon et al. (2021), if the gypsum protection is maintained during sufficient time and the chance of delamination small (due to fire resistant adhesive), (flaming) self-extinguishing of compartment fires with multiple exposed timber surfaces is possible.

4.1.4 STRUCTURAL FIRE RESISTANCE

The strength of timber is strongly affected by heat. It is generally acknowledged that when timber reaches temperatures above 100 degrees, the strength of the timber has decreased to 75% in compression, 65% in stiffness parallel to the grain and 40% shears strength compared to ambient temperatures. Moreover, when temperatures exceed 300 degrees, a char layer is formed. At this temperature, all the strength in the timber is lost, therefore, the char does not contribute to the remaining strength of the timber. (NEN-EN 1995-1-2+C3, 2019).

Although the char limits the heat-transfer, temperatures in the timber behind the char may still be high enough to affect the strength, this is called the heat affected zone. Typically, the first 6 mm below the char are affected most as temperatures will be above 180 degrees Celsius. After this, the temperature in the timber is lower but generally above ambient temperature up to 35 mm below the char. (Barlett et al., 2019). Below 35 mm the timber will generally have ambient temperatures, which means that part of the wood still has the original mechanical and physical properties and therefore an inherent fire resistance, both structurally and as a separation function. This means that the fire resistance of a timber element is dependent on the damage, expressed as the depth of the char layer and an effected heat zone.

The depth of the char layer is dependent on the rate at which char occurs, also called the charring rate. The charring rate is affected by the similar aspects as the pyrolysis rate, with main influencing factors caused by heat flux exposure, delamination, and encapsulation failure.

4.1.4.1 INFLUENCE OF DELAMINATION

In the comparison study by Barlett et al. (2019), it is concluded delamination increases the pyrolysis speed, due to fresh timber being exposed to high compartment temperatures.

4.1.4.2 INFLUENCE OF ENCAPSULATION

The effectiveness of the protection has a direct influence on whether the timber behind the gypsum will be affected by the heat from the fire. This is dependent on the encapsulation type, and the number and thickness of the layers. Encapsulation by gypsum board extends the moment at which timber starts charring. However, if the protection falls off, the charring rate is increased. (Barlett et al. 2019)

4.1.4.3 INFLUENCE OF THE DECAY PHASE

A fully developed char layer has a temperature gradient across the thickness of approximately 650 to 350 degrees C. The rate at which char forms therefore reduces when temperatures drop below 650 degrees. However, the residual heat in the char will still transfer heat to the timber below the char. This means that when compartment fires go below 650 degrees, rather than protecting the timber from heat, the char layer transfers heat to the timber, which affects the strength of the timber. (Barlett et al. 2019)

4.1.4.4 INFLUENCE OF POST-FIRE

Besides the effect of the decay phase on the structural resistance, additional strength reduction is observed in tests after extinguishing of a fire. Wiesner et al. (2019) observed that after a fire of 90 min, 45% of strength was left. However, 2-3 hours after the fire was extinguished only 13% was left due to post fire heating.

4.2 FIRE SAFETY DESIGN METHODS

In the previous sections, the relation between the burning behaviour, fire dynamics and fire resistance of CLT has been presented. This section focusses on how to approach the fire safety design in mass timber buildings. This is done by presenting the methods described by the building regulations and some alternative fire engineering methods, focussing on fire dynamics and structural fire resistance.

4.2.1 RULE BASED APPROACH

In NEN-EN 1991-1-2+C3 (2019), the stated requirements regarding fire resistance of structural elements are dependent on building type and height, though independent of the building materials. NEN-EN 1995-1-2+C2 (2011) describes a method to calculate the structural fire resistance of a solid timber element by the reduced cross-section method. In the reduced cross section method, an estimation on the reduced cross section is done by predicting the char depth and assuming an additional zero strength layer of 7 mm, due to the heat affected zone below the char. The char depth is calculated by fixed char rate values depending on the timber type over a specific time for which the structural capacity is required. It is assumed that below the zero-strength layer the timber has ambient temperatures. In Figure 18, the reduces cross-section method is schematized.

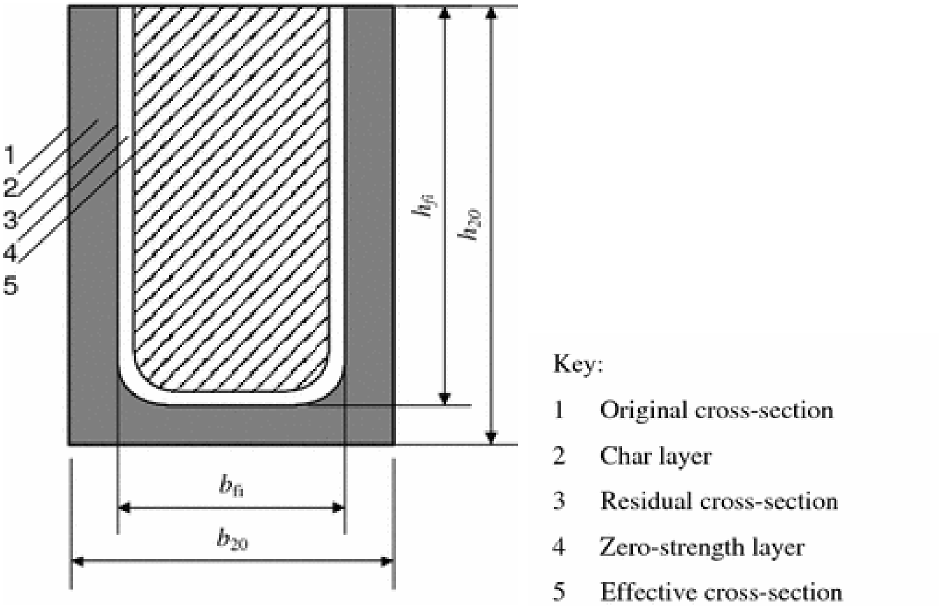


Figure 18: Reduces cross-section method (Figure by Schaffer, 1984)

NEN-EN 1995-1-2+C2 (2011) also presents a method to account for protection measures by encapsulation. In this method it is assumed that protection board postpones the charring for a specific time. Before a protection board fails, the temperatures in the timber can already be high enough to start the charring, which is accounted for this by assuming that after a specific amount of time, the timber will start charring, at a slower rate due to the still available insulting capacity of the board, until the board fails. At time of failure, it is assumed that the charring rate is doubled, due to the high room temperatures. After a char depth of 25mm, it is assumed that the char rate will be back to its original rate. In this approach it thus assumed that, if the fire is extinguished before the protection board fails, the timber will be unaffected.

These methods do not account for the effect of the burning behaviour of timber on the characteristics of the fire dynamics. Moreover, yet methods are lacking to consider the effect of delamination.

A solution is performing a risk-based approach. In case the safety risks are low (building with consequence class 1, CC1), and no additional requirements are stated for functional, economic, or sustainable impact after a fire, the prescriptive requirements may be sufficient. However, when the risks are higher, or higher requirements are stated, performance-based methods should be used to provide a more accurate prediction of the structural fire resistance by predicting the fire dynamics in mass timber compartments.

4.2.2 PERFORMANCE BASED METHODS

As explained in section 3.2.2.4, risk-based fire safety design considers the risks relating to different fire scenarios predicting the "real" fire dynamics in a compartment. Prediction of the fire dynamics can be done by literature review, experiments, or performance-based engineering models.

In the national annex of NEN-EN 1991-1-2+C3 (2019) several performance-based methods for conventional building design with non-combustible structures are presented. The parametric fire curve presented in annex A in NEN-EN 1991-1-2+C3 (2019) can be altered by some simplified methods to represent the burning behaviour in a timber exposed compartment. However, it is observed that this approach does not consider the burning behaviour in detail.

Therefore, approved engineering models have been developed in the last years, which consider the influence of the exposed timber on the fire dynamics more accurately. An elaborate overview and comparison of 5 different performance-based fire engineering methods is presented in Appendix 2, a summary of the comparison is presented in Table 1.

Table 1: Comparison of performance-based models

Reference	Model type	Char depth prediction	Temperature prediction	User possibility	Limitations
Hopkin et al. (2017)	One zone model	Not sufficient	Sufficient	Medium	No delamination No protection failure No surface radiation Homogenous temp
Brandon (2018)	Equation based	Conservative	Not very accurate	Good	No delamination No protection failure No surface radiation Homogenous temp
Barber (2018)	CFD model	Not validated	Not presented	Bad	No delamination No protection failure No surface radiation Homogenous temp
Wade (2019/20)	Two-zone model	Good but not always conservative	Very good	Difficult	No protection failure No surface radiation Homogenous temp
Barber (2016/2020)	Equation based	Good for well-ventilated fires, otherwise not always conservative	Not very accurate	Good	No delamination No Protection failure No surface radiation Homogenous temp

From the comparison follows that most of the models show limitations regarding the boundary conditions for prediction. Moreover, it is observed that the zone models provide more accurate temperature prediction than the equation-based models. However, simple use for design is harder than the equation-based models. The method by Wade provides most accurate predictions regarding both char depth and temperature. Also, this is the only method which accounts for the effect of delamination.

It is observed that in general, the prediction methods show sufficient predictions for flashover and fully developed phase. However, the main problem regarding the predictions is related to the decay phase. As in general the decay is way too steep compared to the results from the fire tests. Moreover, the models still have many limitations of which the models:

- Assume homogenic temperature distribution
- Assume same char depths throughout the structure
- Effect of delamination and gypsum base layer failure is only accounted for in the model by Wade (2019)
- The effect of charring behind the encapsulation on the fire dynamics is not considered
- Surface radiation not considered
- The models only consider char depth and not pyrolysis

4.2.3 Structural fire resistance calculations

Improved prediction of the structural fire resistance of an element consists of three parts: (1) Prediction of the fire dynamics, (2) Prediction of the thermal response of the element to the fire dynamics and (3) calculation of the structural resistance (response).

For CLT compartments, the prediction of fire dynamics can be done by the models presented above. Some of these models also allow prediction of the char depth, which is the thermal response of the CLT to heat exposure.

For non-combustible materials, the maximum temperature height is typically the factor that influences the structural capacity. However, timber keeps burning until either sufficient protected by a char layer, or if temperature exposure is below 300 degrees. This means that rather than the temperature height, the duration of the total fire, including decay phase affects the structural capacity and should be considered in the calculations.

Moreover, it was observed that delamination and encapsulation failure affect the burning behaviour (charring rate). The method to predict the influence of encapsulation on the char-rate as presented in NEN-EN 1995-1-2+C2 (2011) can also be used for CLT elements. The document by Swedish wood (2019) presents methods on how calculate the burning behaviour of delamination. Moreover, an improved heat affected zone beyond the charring is defined.

The structural fire resistance of CLT is dependent on the structural scheme. However, due to the aversively crossed timber lamellas, the load bearing capacity shifts. This means that only part of the lamellas can transfer the loads.

4.3 CONCLUSIONS

With the information presented in this chapter, sub-sub-question 2.1 can be answered. The question was stated as:

Which aspects must be considered for fire safety design in mass timber buildings?

4.3.1 FIRE RISK

Mass timber buildings result in additional fire risks, due to the burning behaviour of the material. The burning behaviour is defined by four phenomena: (1) pyrolysis, (2) ignition, (3) combustion, and (4) extinction. These aspects influence the fire dynamics in a compartment, the structural capacity and more.

4.3.1.1 FIRE DYNAMICS

Because of the burning behaviour of timber, the fire dynamics in timber building are different than conventional buildings, as timber contributes to the heat release rate and fuel load. The effect has been investigated in many large-scale compartment tests, which has resulted in the following conclusions:

- An increase of exposed CLT surfaces results in faster moment of flashover due to heat contribution
- An increase of exposed CLT increases the duration of the fully developed fire, due to fuel contribution and heat radiation between surfaces
- If delamination and encapsulation base layer failure are prevented (which may be done by using fire resistant adhesive or specific type of fire rated encapsulation), generally a fire will naturally decay, even if many surfaces are exposed. Though, the decay phase is generally longer
- However, if delamination or encapsulation base layer failure occur during decay whilst temperatures still hot, regrowth might occur due to freshly exposed timber
- If delamination or encapsulation base layer failure occurs during the fully developed phase, this may result in continuous burning due to a continuous additional exposure of unburned CLT

These affects are reduced by applying fire safety measures. The most commonly and investigated fire safety measures in mass timber compartments are sprinklers, encapsulation, and timber adhesives. These measures affect the fire dynamics in the following way:

- A sprinkler controls and may even extinguish a fire before flashover is reached, even if all surfaces are exposed
- Encapsulation reduces the contribution of CLT to the heat release rate and fuel load, the more surfaces are encapsulated the less the impact of the timber on the fire dynamics.
- If encapsulation base-layer can fail, this may result in regrowth or continued burning. This can be prevented by applying sufficient number of encapsulation layers or by applying encapsulation that does not fail.
- If delamination of exposed CLT can occur, this may result in regrowth or continuous burning. This can be prevented by using fire resistant adhesives.

4.3.1.2 STRUCTURAL FIRE RESISTANCE

The fire resistance of timber elements depends on the remaining cross section due to the damage after a fire, which is dependent on the char depth and the affected heat zone. From research by Barlett et. al. (2019) it was concluded that char rate in CLT is influenced by several aspects, which can be categorized as material, system, or fire related. Heat flux exposure, delamination, and encapsulation failure result in the most dominant influencing factors.

The effect of heat flux exposure makes that timber keeps burning as long as it is exposed to temperatures above 300 degrees, which means that during the decay phase, the cross section still reduces. In addition, the decay and even a period post-fire will affect the heat affected zone below the char layer. It is therefore concluded that the fire resistance and fire dynamics cannot be considered separately and are linked to each other.

4.3.2 DESIGN METHODS

The current rule-based regulations presented in NEN-EN 1991-1-2+C3 (2019) are based on the fire dynamics in conventional buildings with non-combustible surfaces and do therefore not consider the effect of the burning of the CLT on the fire dynamics. Therefore, a risk-based assessment should be done for every timber building. In case the safety risks are very low, and no additional requirements are stated for functional, economic, or sustainable impact after a fire, the prescriptive requirements may be sufficient. However, when the risks are higher, or higher requirements are stated, performance-based methods should be used to provide a more accurate prediction of the fire dynamics and the relating fire safety design.

4.3.2.1 FIRE DYNAMICS

The parametric fire curve presented in the Annex of NEN-EN 1991-1-2+C3 (2019) does not sufficiently account for the influence of the burning behaviour in CLT exposed compartments. There are some alternative engineering methods which account for this, however these still have many limitations. The main problem is observed to be the prediction of the decay phase, which is generally not accurate. From large scale compartment tests, it was observed that the characteristics of the decay phase mainly relate to the influence of delamination and gypsum base-layer failure. Therefore, by choosing CLT adhesives which result in structures which cannot delaminate, and ensuring enough gypsum layers, the decay phase is much better to predict. The parametric, iterative approach by Brandon (2018) provides good method to use in the next phase of this thesis, as integration in excel is possible.

4.3.2.2 STRUCTURAL FIRE RESISTANCE

The structural fire resistance can be calculated by the reduces cross-section method as presented by NEN-EN 1995-1-2+C2 (2011), by predicting the char depth and a heat affected zone. However, in this method, the char rates are defined as fixed nominal values depending on the type of timber. It is noted that the fixed charring rates, are determined based on standard fire tests under specific test conditions. With this, the influence of heat flux in real fires is neglected. Moreover, the current methods do not describe specific calculation for CLT, due to which delamination cannot be accounted for. Therefore, alternative methods have been proposed by alternative sources.

Therefore, rather than considering the standard fire curve and prescriptive rules, the influence of the fire dynamics in a CLT compartment must be understood and predicted by sufficient performance-based engineering models to safely state the structural fire resistance and the relating fire risk.

5 BOUNDARY CONDITIONS FOR DESIGN TOOL

In this chapter, the theory regarding fire safety design in mass timber buildings (presented in chapter 4) is integrated with the circular fire safety design approach (presented in chapter 3). This way, the objectives and boundary conditions for the design tool are generated. This chapter can be used as a guideline and overview for the coming chapters that present the quantification methods.

5.1 OBJECTIVE

The objective of the research is to enhance the understanding of the fire safety design on the balance between material use and fire risk in mass timber buildings. Therefore, a quantification method is needed that calculates this balance. This is done by utilizing the approach to quantify the circular fire safety impact presented chapter 3. The quantification of the circular fire safety impact consists of two parts: (1) Materia use of fire safety measures and (2) the fire risk:

$$Circular\ fire\ safety\ impact\ = Material\ use + Fire\ Risk \qquad \text{Eq. 2}$$

With this formula, the total material impact is quantified to one value, which allows comparison of fire safety design and its total economic and/or environmental impact on material consumption. This method is used and translated to an approach for fire safety design in mass timber buildings. This requires defining the considered fire safety measures and the relating fire risk, and translation to economic and environmental monetary values.

5.1.1 MATERIAL USE CALCULATIONS

The material use calculation present the economic or environmental impact of the total structural and fire safety material used in one building during the service life of a building. The method is based on a life cycle assessment, in which the costs for material input, and the end-of-life circularity benefits are quantified, expressed in economic and environmental monetary costs. This is calculated by the following equation:

$$C_{Design} = €_{Ec/Env,i} \times \sum M_{In,i} - V_{Out,i} \qquad \text{Eq. 3}$$

Where:

$€_{Ec/Env,i}$	Is the economic or environmental monetary cost of element i, expressed in cost per unit quantity
$M_{In,i}$	Is the quantity of material that is used during the buildings service life for element i, expressed in unit quantity
$V_{Out,i}$	Is the end-of-life circularity value of element i, expressed in unit quantity

5.1.2 Fire risk calculation

Fire risk can be defined in different ways, depending on the considered impact. In this research, fire risk is expressed as the monetary cost to rehabilitate after a fire, depending on the damage and probability of different fire scenarios. The total output of this calculation is the fire risk of the design, expressed in economic and environmental impact. This is calculated by the following equation:

$$R_{Design} = VB_{Ec/Env} \times \sum P_i \times D_i \quad \textit{Eq. 4}$$

Where:

$VB_{Ec/Env}$	Is the economic or environmental monetary value of the design representing the cost needed to rehabilitate after a fire, expressed in total €/GFA
P_i	Is the probability that a certain fire scenario i can be expected over the life cycle of the building, expressed in percentage
D_i	Is the impact (damage) for a certain fire scenario i, representing the loss of the building expressed in percentage of the building that is lost

5.2 Scope

The scope of the design tool consists of building and fire related characteristics, the considered calculation methods, and the considered input data. A short overview of the scope is presented in Table 2 and further elaborated in the following sections.

Table 2: Overview of design tool scope

Design aspect	Description
Building type	The focus is on residential buildings
Building design	The method considers rectangular buildings, up to GFA of 500m2, and with a maximum number of 25 storeys
Structural elements	The method considers mass timber, in which walls and floors are completely constructed from CLT elements
Fire safety measures	The fire safety measures considered are untreated CLT, automatic sprinkler and encapsulation
Material use calculation	The method is based on a life cycle analysis. The input data is based on EPD data and literature review
Fire risk calculation	The method is based on the method described by NEN 6079, altered based on literature to be used for CLT buildings The input data is based on literature review.
Economic cost data	The economic cost data is based on literature review and manufacture data
Environmental cost data	The environmental data is based on EPD data from manufacturers

5.2.1 Building characteristics

5.2.1.1 Building type

The large-scale compartment tests performed over the last years typically represent residential compartment buildings. Residential compartments are typically smaller compartments, have a fuel load around 560 MJ/m^2 and no significant ventilation (Brandon et al., 2021) The results of the tests are therefore most applicable to residential buildings and therefore the focus in the design tool.

5.2.1.2 Building design

It is observed that the quantification methods for the fire dynamics present limits for the use for maximum compartment area of 500 m^2. A building height of maximum 25-storeys is considered as it is assumed that this results in a building height of 70 m, which presents a building of consequence class 2 as defined by the Dutch Building Decree.

5.2.1.3 Structural elements

The walls and floors consist of structural CLT. This consists of a number and thickness of lamellas. The number of lamellas is either 3, 5 or 7. The thickness of the lamellas is user defined, though all presenting similar thickness.

5.2.2 Fire safety measures

From the theory presented in chapter 4, follows that there are three fire safety elements in mass timber design that provide an important part of the fire safety strategy. These three elements are (1) CLT, (2) encapsulation and (3) sprinkler installation.

5.2.2.1 CLT

From the theory presented in chapter 4 follows that the type of adhesive in CLT has a large influence on the burning behaviour, fire dynamics and structural capacity. For this reason, the type of adhesive is considered in the structural calculations and fire risk assessment, though not specifically in the material data.

5.2.2.2 Encapsulation

The encapsulation consists of a number and thickness of layers. It is assumed that the encapsulation is constructed directly on the CLT, without cavity or insulation as this represents most of the studied large-scale compartment fire tests.

From the theory presented in chapter 4 follows that the type of encapsulation largely influences the fire dynamics and burning behaviour. The fire-resistant fibre reinforce encapsulation from Promat is considered. The risks relating to failing of encapsulation is integrated in the risk-assessment, though not in the material specifics.

5.2.2.3 Sprinkler system

Sprinkler installations consist of multiple elements of which, the sprinkler heads, pipes, pumps, water storage, and more. In the design tool, the sprinkler consists of the sprinkler installation per GFA, consisting of sprinkler pipes and a “central unit” representing water storage and pumps, which represents one unit per 10.000 GFA (Dukers & Latten, 2000).

5.2.3 Calculation methods

The calculations are divided into three parts (1) material use calculations, (2) fire risk calculations and (3) fire resistance calculations which are used in the risk calculations.

5.2.3.1 Materia use calculations

The material use calculations are based on methods presented by Platform CB’23 (2019), with a simplified method for the end-of-life benefit calculation.

5.2.3.2 Fire risk calculations

The fire risk calculations are based on NEN 6079 (2016), though altered to quantify the risk in mass timber compartments. This is based on literature review.

5.2.3.3 Fire resistance calculations

The fire dynamic calculations are based on Brandon (2018). The structural fire resistance calculations are based on Swedish Wood (2019) and NEN-EN 1995-1-2+C2 (2011).

5.2.4 Data

Two types of data are used for the quantification.: (1) Material data and (2) values for calculations. An overview of all considered input data is presented in appendix 4.

5.2.4.1 Material data

The data used in this research is based on literature, product and EPD data. An elaborate overview of the theory regarding the material data used in the calculations is presented in appendix 3.

5.2.4.2 Values for calculations

Values are used for several calculations, of which the fire dynamic calculations, fire resistance calculations and fire risk calculations. The values used for the fire dynamic calculations are similar as the values used by Brandon (2018). The values for the structural calculations are gained from Swedish Wood (2019). The values used for the fire risk calculations are either defined in the research based on literature or gained from NEN-EN 1991-1-2+C3 (2019).

5.2.5 FUNCTIONAL UNIT

The aim is to compare the impact of different total fire safety design strategies for a timber building. To allow comparison of different fire safety designs, a functional unit is defined. A functional unit (FU) is *"a quantified description of the function of a product that serves as the reference basis for all calculations regarding impact assessment".* (Arzoumanidis et al., 2019)

The defined functional unit is the total material use and fire risk in one building, presented as the combination of structural CLT and fire safety measures, considering sprinklers and encapsulation. It is assumed that the building consists of several identical compartments placed on top of each other. The floor of each compartment is protected with a non-combustible layer, which is only considered in the fire dynamic calculations and not part of the material calculations.

An example of the functional unit is visualized in Figure 19. The characteristics of the elements were described in previous sections.

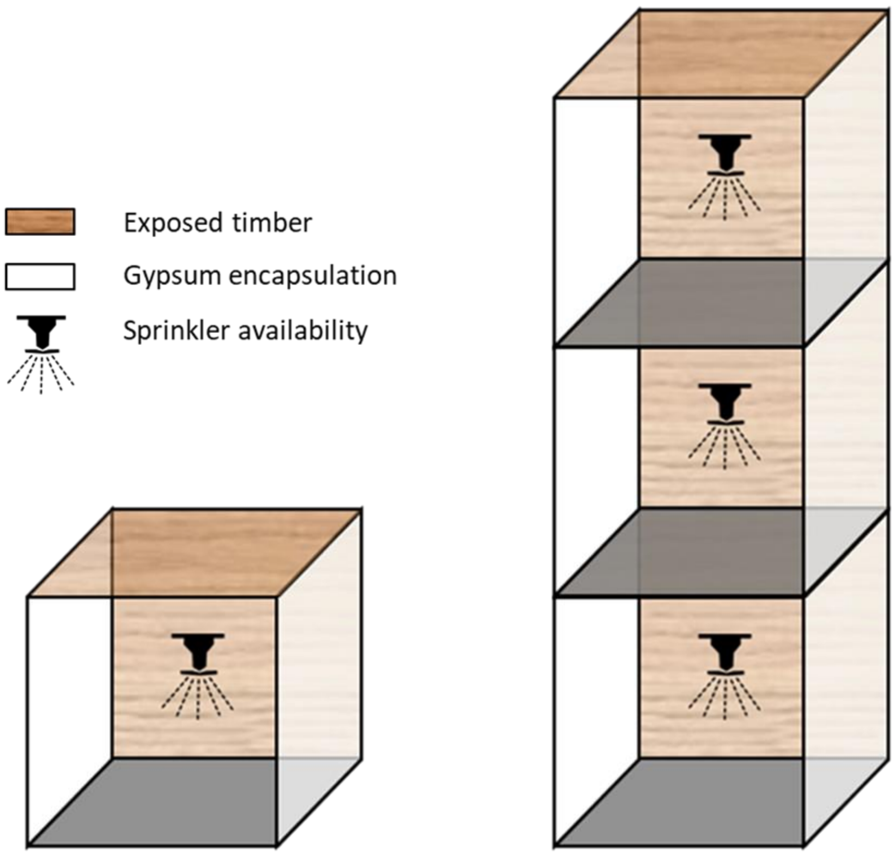


Figure 19: Functional unit

6 MATERIAL USE CALCULATIONS

In this chapter, the calculation methods are presented that are used to quantify the material use for structural and fire safety measures during the service life of a building. The method is based on a life cycle assessment, in which the costs for material input, and the end-of-life circularity benefits are quantified, expressed in economic and environmental monetary costs. This is calculated by the following equation:

$$C_{Design} = €_{Ec/Env,i} \times \sum M_{In,i} - V_{Out,i} \qquad \text{Eq. 5}$$

Where:

$€_{Ec/Env,i}$	Is the economic or environmental monetary cost of element i, expressed in cost per unit quantity
$M_{In,i}$	Is the quantity of material that is used during the buildings service life for element i, expressed in unit quantity
$V_{Out,i}$	Is the end-of-life circularity value of element i, expressed in unit quantity

Figure 20 presents the circular life cycle, used to determine the material use of the fire safety measures.

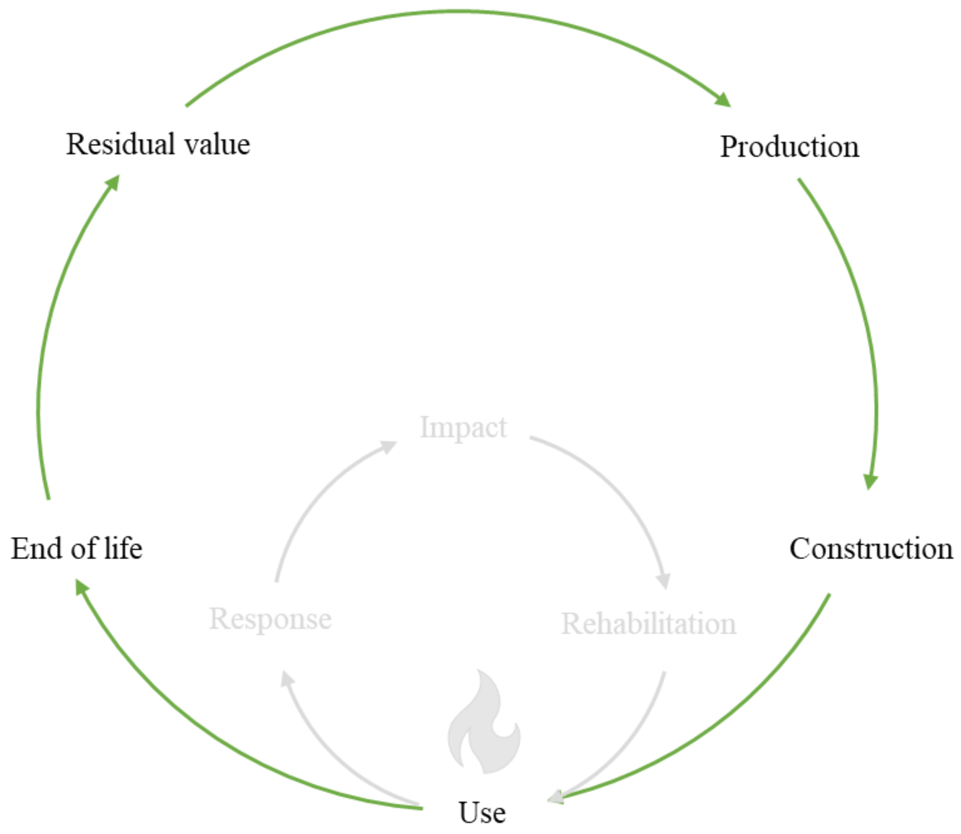


Figure 20: Circular life cycle (Own figure)

6.1 Monetary quantification

In this section, the monetary quantification of the elements is presented. The method calculates material use of the fire safety design measures for both economic and environmental impact, both based on the costs per material/element quantity, for a total functional unit. The values needed for the calculations are elaborately presented in appendix 3.

6.1.1 Economic element cost

The economic cost of the elements is the cost for the quantity of material used in a building. For CLT and encapsulation, this is determined based on €/kg of used material, which is chosen based on manufacture data. For sprinklers this is based on material installation cost per m^2, and one central unit for the building.

6.1.2 Environmental element cost

The environmental impact of an element is expressed as the shadow costs per year, representing the amount of monetary value needed to compensate for the negative impact that an element has on the environment. The environmental shadow cost is calculated based on a Life Cycle Analysis (LCA) and the expected service life. The LCA is based on the methods presented by CB'23, considering NEN 15978 (2011).

The environmental impact of a certain unit is calculated by multiplying Life Cycle Inventory (LCI) data with a weight factor. LCI data is data that is defined by manufacturers which represent the impact of different life cycle processes on a selection of environmental impact categories. LCI data is typically summarized in an Environmental Product Declaration (EPD) document. With this, the total shadow cost of a unit element is calculated as:

$$€_{Sh,Impac,i} = \sum LCI_i \times f_{Sh,i} \qquad \textit{Eq. 6}$$

Where:

LCI_i Is the environmental impact data for a certain impact category i
$f_{Sh,i}$ Is the weight shadow cost factor for a certain impact category i

To calculate the shadow costs, environmental impact categories are defined. In the Netherlands, typically 11 categories are required. However, as insight in EPD values from Dutch environmental databases are lacking, EPD datasheets from manufacturers are used in the calculations. In these sheets, typically 7 environmental impact categories are defined, which is visible in Table 3.

Table 3: Environmental impact categories

Impact category	Abbreviation	Unit	Weight factor
Global warming potential	GWP	Kg-CO_2-Eq.	€0,05
Ozone layer depletion	ODP	Kg-CFC_{11}-Eq.	€30,00
Acidification potential	AP	Kg-SO_2-Eq.	€4,00
Eutrophication potential	EP	Kg-PO_4-Eq.	€9,00
Photochemical ozone creation depletion	POCP	Kg-C_2-H_4	€2,00
Abiotic depletion potential non-fossil resources	ADPE	Kg-Sb-Eq.	€0,16
Abiotic depletion potential fossil resources	ADPF	MJ*	€7,70E-5

*In NEN-EN 15978, the unit is presented as Kg-Sb-Eq., however in EPD datasheets the impact is expressed in MJ rather than Kg-Sb-Eq. The recalculation factor of $4,81E^{-4}$ is used, which represents 1 Kg-Sb-Eq./MJ. (Stichting Bouwkwaliteit, 2019 p.30)

6.2 Material input calculation

In this section, the calculation methods used to determine the total quantity of material input during the building service life of the design elements is presented. The quantity of material input consists of the amount of material used during production and use phase. The total material input per element is calculated by the following formula, expressed as quantity of material per functional unit over the service life of the building:

$$M_{In,i} = m_i \times (f_{Production,i} + f_{Use,i}) \quad \text{Eq. 7}$$

Where:

m_i	Is the quantity of material/element per unit for element i
$f_{Production,i}$	Is the factor that defines the quantity of material for realizing the total amount of material for one compartment for element i
$f_{Use,i}$	Is the factor that defines the amount of material required during the use phase for element i

6.2.1 Quantity of material

Fire safety measures are typically on an element level, consisting of a combination of raw materials. Therefore, to calculate the quantity of the elements, it is important to understand the composition and quantity of materials of which an element exists of. This is typically described in product or EPD data.

The quantity of the elements should be expressed in such a way that it can be interpolated to calculate the amount of material on a compartment and building level. For the three considered elements, the quantity is calculated in different ways representing the total quantity in one building.

6.2.1.1 CLT

CLT is used for the walls and floors in the compartments, where the thickness of the element is determined by the number and thickness of the lamellas. The total structural timber for the building is this way calculated by the following formula, expressed as kg/building:

$$m_{CLT,building} = \rho_{CLT} * (A_{walls} * t_{walls} + GFA * t_{floor}) * n_{storeys} \quad \text{Eq. 8}$$

Where:

ρ_{CLT}	Is the density of CLT in kg/m3
A_{walls}	Is the wall area of one compartment minus the window openings, expressed in m^2
t_{walls}	Is the thickness of the wall panels, calculated from lamella thickness ($t_{lam,wall}$) and number of lamellas ($n_{lam,wall}$) expressed in m
GFA_{comp}	Is the gross floor area of one compartment expressed in m^2
t_{floor}	Is the thickness of the floor panels, calculated from lamella thickness ($t_{lam,floor}$) and number of lamellas ($n_{lam,floor}$) expressed in m
$n_{storeys}$	Is the number of building storeys

6.2.1.2 ENCAPSULATION

The amount of encapsulation is depending on the encapsulated area, the number of layers and the thickness of the layers. For the gypsum board encapsulation this leads to, the following calculation expressed as kg/building:

$$m_{Enc,building} = \rho_{Enc} * A_{Enc} * t_{Enc,lay} * n_{Enc,lay} * n_{Storeys} \quad \text{Eq. 9}$$

Where:

ρ_{Enc}	Is the density of the encapsulation in kg/m3
A_{Enc}	Is the encapsulated area of one compartment, expressed in m^2
$t_{Enc,lay}$	Is the thickness of the encapsulation panels, expressed in m
$n_{Enc,lay}$	Is the number of encapsulation layers
$n_{storeys}$	Is the number of building storeys

6.2.1.3 SPRINKLER

The sprinkler is assumed to consist of 2 parts, the sprinkler pipes, and the required standard central installation. However, only the material use for sprinkler pipes is considered, the standard installation is only considered as additional environmental and economic costs for a total unit. With this, the material quantity of sprinkler pipes is calculated in the following way, expressed as kg/building:

$$m_{spr,pipe,building} = \rho_{spr,pipe} * A_{spr,pipe} * n_{spr,pipe/m2} * GFA_{comp} * n_{storeys} \quad \text{Eq. 10}$$

Where:

$P_{Spr,pipe}$	Is the density of the sprinkler pipe material, expressed in kg/m3
$A_{Spr,pipe}$	Is the cross-sectional area of a sprinkler pipe, expressed in m^2
$n_{Spr,pipe/m2}$	Is the factor for the number of pipes per meter squared, which is assumed to be 0,25 presenting one sprinkler pipe every 4 meter
$GFA_{Compartment}$	Is the gross floor area of one compartment, expressed in m^2
$n_{storeys}$	Is the number of building storeys

For the economic calculations, rather than pipe material, the costs are based on calculation of the total GFA, as the costs are a better representation. Moreover, the standard sprinkler installation is considered to require one central unit per building, independent on the size of the building.

6.2.2 PRODUCTION PHASE

The amount of material required for the production/construction phase is assumed to be equal to the material required for one building. With this the production/construction factor for the quantity of material is 1.

$$f_{Production,i} = 1 \quad \text{Eq. 11}$$

6.2.3 USE PHASE

The amount of material needed in the use phase is dependent on the functional service life of the elements during the service life of the building. The total amount of material required during the use phase is calculated by the following formula, with the value rounded up:

$$f_{use,i} = (\frac{t_{sl,b}}{t_{fsl,i}} - 1) \quad \text{Eq. 12}$$

Where:

$t_{SL,b}$	Is the is the expected service life of the building, expressed in years
$t_{fsl,i}$	Is the expected functional service life of element I, expressed in years

6.2.3.1 FUNCTIONAL SERVICE LIFE

The service life of a building (element) consists of two definitions: (1) Technical service life and (2) Functional service life. The technical service life of a building or element is the amount of time the required service can be ensured. The functional service life is the time the service is actually used. (Platform CB'23, 2019) The technical and functional service life vary throughout different building layers, relating to different functions. The layers by Brand (1994) are a commonly used representation of the expected functional service life for different layers, which is visualized in Figure 21. The functional service life varies from very short (1 day for stuff) to very long (300 years for structure), depending on the considered building layer.

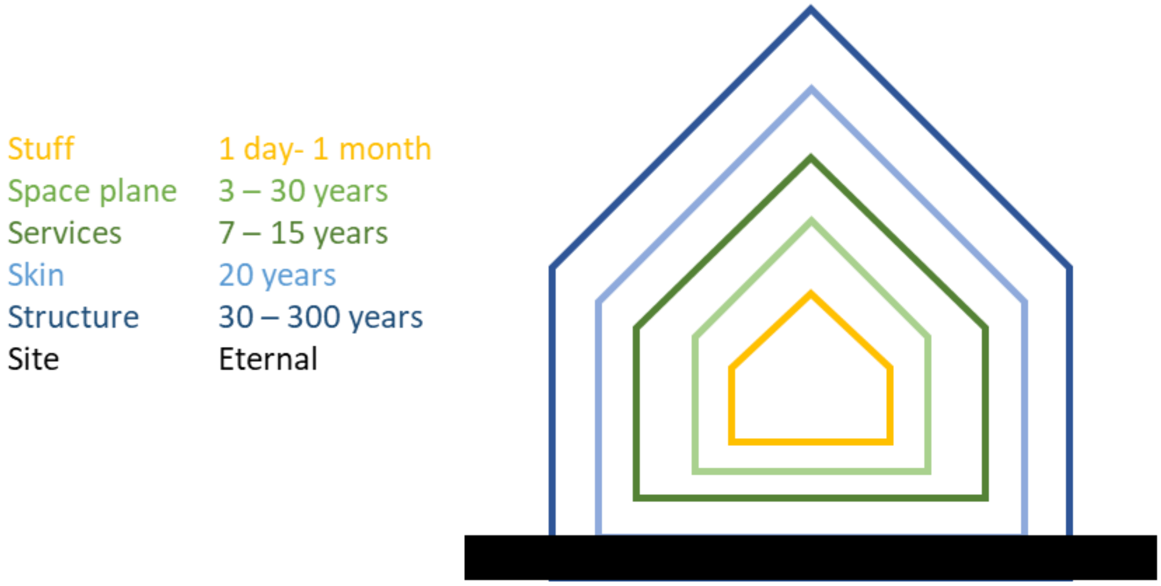


Figure 21: Functional service life based on layers from Brand (Redesigned based on Brand, 1994)

6.3 END-OF-LIFE VALUE CALCULATION

In this section, the calculation methods used to determine the end-of-life value of the fire safety elements is presented. To calculate this, material output flows, end-of-life scenario and re-use or/and recyclability value must be determined. With this, total benefit is calculated, expressed as quantity of material per functional unit for total building service life.

$$V_{Out,i} = M_{Out,i} \times MAX(V_{Reuse,i}; V_{Recycle,i})$$ *Eq. 13*

Where:

$M_{Out,i}$	Is the total quantity of material/element output for element i
$V_{Reuse,i}$	Is the reuse value of element i, expressed in percentage
$V_{Recycle,i}$	Is the recyclability value of element i, expressed in percentage

6.3.1 MATERIAL OUTPUT FLOWS

During the use phase, and at the end of the service life of the building, material from the building has reached the end of its functional service life and goes to waste management. This material may have residual value for next life cycle. Therefore, the quantity of output material should be calculated. It is assumed that this is similar as the material input calculated by Eq. 7 .

$$M_{Out,i} = M_{In,i}$$ *Eq. 14*

6.3.2 END OF LIFE SCENARIO

To calculate the end-of-life value, potential end-of-life scenarios must be determined, and the expected percentage of the element/material being suitable for this end-of-life scenario. Nationale Milieudatabase (2020) identifies four different types of end-of-life scenarios and states generalized fixed values for the percentage of a building element ending in a specific end of life scenario. The four end of life scenarios are:

- Landfill (waste)
- Recover (by burning)
- Recycle
- Re-use

From a circularity point of view, reuse, and recycling provide the potential highest value for next service life. This is therefore the focus in the research. The output of this step is the percentage of the quantity of an element expected to be suitable for the considered end-of-life scenarios expressed as:

$$\%_{Reuse,i}$$ *Eq. 15*

$$\%_{Recycle,i}$$ *Eq. 16*

6.3.3 Reusability value

The reuse potential is determined based on the remaining technical service life on an element and the detachability. With this, the total percentage of material available for reuse is calculated by Eq. 17, expressed as percentage of material quantity:

$$V_{reuse,i} = \%_{Reuse,i} * f_{Detachability,i} * v_{Reuse,i} \quad \text{Eq. 17}$$

Where:

$\%_{Reuse,i}$	Is the percentage of element i, for which reuse could be considered as a potential end-of-life scenario
$f_{Detachability,i}$	Is a factor representing the detachability of an element i
$v_{Reuse,i}$	Is the reuse value of an element i, expressed in percentage

6.3.3.1 Detachability factor

The detachability of an element is an important aspect of the reusability potential, as it represents the expected quantity that is usable for reuse of an element after being detached. The detachability index can be calculated in accordance with the methods presented by DGBC (2019). For simplification, only the type of connection is considered in the calculation, where the detachability factor is presented as follows:

Table 4: Detachaility factors

Type of connection	Examples	Factor
Dry connection	Velcro	1,0
Connection with additional elements	Screw, bolt, angle	0,8
Direct integral connection	Pin, nail	0,6
Soft chemical connection	Sealant, PUR	0,2
Solid chemical connection	Glue, weld,	0,1

6.3.3.2 Residual value

The residual value is dependent on the amount of technical service life left after functional use. The remaining value for reuse is this way calculated by calculating the factor based on these values, which results in the value for next lifecycle.

$$Value_{reuse,i} = \frac{t_{tsl,i} - t_{fsl,i}}{t_{fsl,i}} \quad \text{Eq. 18}$$

Where:

$t_{tsl,i}$	Is the expected technical service life of element i, expressed in years
$t_{fsl,i}$	Is the expected functional service life of element i, expressed in years

6.3.4 RECYCLABILITY VALUE

Recycling is: "*The recovery of materials and resources from discarded products (secondary materials), and to reuse them to make new products*." (Platform CB'23, 2019a, p.12). Recycling is possible on different building levels, typically on raw material, material, product or element level (Platform CB'23, 2019a). Currently, a generic method to quantify the reusability value is lacking. Therefore, a new, simplified method has been generated in this research. Eq. 19 presents the considered method, expressed in percentage of material quantity.

$$V_{recyclability,i} = \%_{Recyclel,i} * v_{Recycle,i} \qquad \textit{Eq. 19}$$

Where:

$\%_{Recyclel,i}$	Is the percentage of element i for which recycling could be considered as a potential end-of-life scenario
$v_{Recycle,i}$	Is the recycle value of element i, expressed in percentage

6.3.4.1 VALUE

The recyclability value is determined by considering whether the elements can be recycled to similar elements, or that the elements can be recycled to new, alternative elements. When this is determined, the amount of material that is usable in the recycled element is considered. With this, the recyclability value is calculated accordingly, expressed as percentage:

$$v_{recycle,i} = \%_{Recycle,1,i} * \%_{Recycle,2,i} \qquad \textit{Eq. 20}$$

Where:

$\%_{Recycle,1,i}$	Is the percentage of raw material within the primary element i, that can be used in the new secondary element
$\%_{Recycle,2,i}$	Is the percentage that the recycled raw material i, presents in the new-recycled secondary element

7 FIRE RISK CALCULATION

In this chapter, the methods and values that are used to calculate the fire risk of the fire safety design of a mass timber building are presented. Fire risk can be defined in different ways, depending on the considered impact. In this research, fire risk is expressed as the monetary cost to rehabilitate after a fire, depending on the damage and probability of different fire scenarios. The total output of this calculation is the fire risk of the design, expressed in economic and environmental impact. This is calculated by the following equation:

$$R_{Design} = VB_{Ec/Env} \times \sum P_i \times D_i \qquad \textit{Eq. 21}$$

Where:

$VB_{Ec/Env}$	Is the economic or environmental monetary value of the design representing the cost needed to rehabilitate after a fire, expressed in total €/GFA
P_i	Is the probability that a certain fire scenario i can be expected over the life cycle of the building, expressed in percentage
D_i	Is the impact (damage) for a certain fire scenario i, representing the loss of the building expressed in percentage of the building that is lost

Figure 22 presents the fire resiliency life cycle, in which response is the probability (P) of a certain fire scenario, impact is considered as the damage (D) and rehabilitation is the monetary cost needed for rehabilitation considered to be the value of the building (VB).

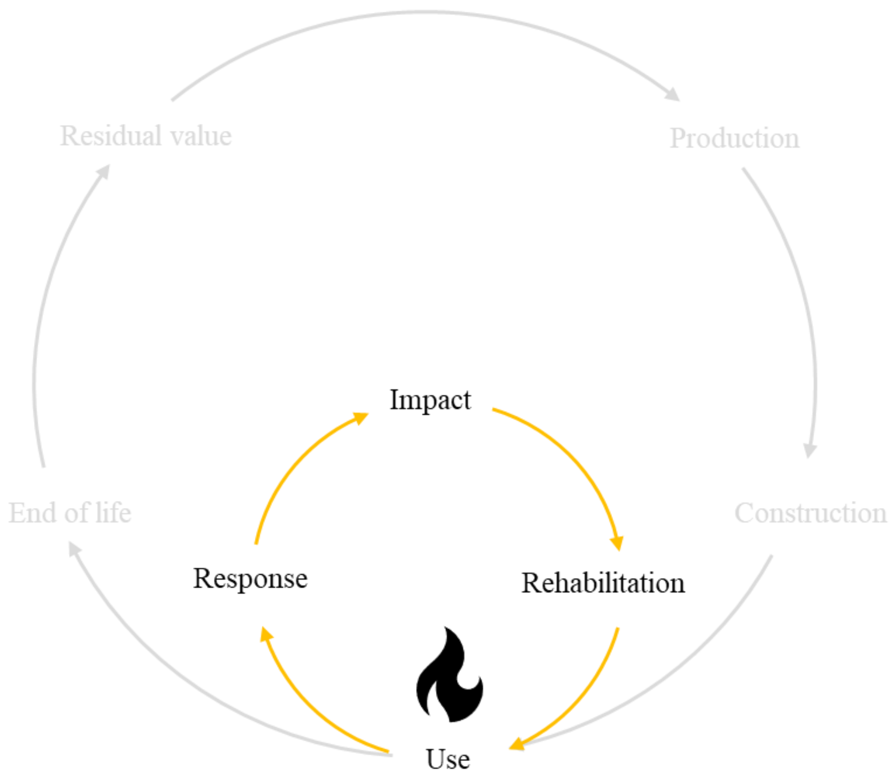


Figure 22: Fire resilience life cycle (Own figure)

7.1 MONETARY QUANTIFICATION

In this section, the monetary quantification of fire risk is presented. The risk calculation presents the probability and impact of a fire, in which the impact is the expressed as the percentage of the building that is lost by the fire. The risk is then quantified by the building value, which is expected to be the amount of cost (economic and/or environmental) that is required to rehabilitate after a fire, this way representing the expected amount of material needed for rehabilitation. The monetary value can be expressed in both economic as environmental value.

7.1.1 ECONOMIC REHABILITATION VALUE

The economic value of the building is the purchase price of a building per meter squared.

7.1.2 ENVIRONMENTAL REHABILITATION VALUE

The total environmental value of a building, can be determined by considering by assuming threshold values for the maximum shadow costs per meter squared per year of the service life of a new building, as presented in the norms. Previously, the threshold value was 1,0 €/m2*year. However, since July 1st the value must be below 0,8, and the goal is to reach a value below 0,5 for every new building from 2030 onwards. (Rijksdienst, nd.)

7.2 FIRE SCENARIOS

In this section, the definition of the fire scenarios for the risk-calculations on mass timber buildings is presented. The method is based on the method presented by NEN 6079 (2016), in which the different fire scenarios are related to the moment of extinguishing. The method is altered such that it represents the influence of (fire safety) design measures on the characteristics of the fire dynamics in mass timber buildings as presented in chapter 4.

The scenarios are based on the fire development and characteristics of the stages of a compartment fire relating to: (1) ignition, (2) growth, (3) fully developed phase, (4) decay, and (5) extinguishing. By considering the moment of extinguishing and relating this to the fire dynamic phases and structural capacity, different fire scenarios can be defined. For the calculation of the fire risk in this research, five different scenarios are defined:

- Scenario 0: There is no fire
- Scenario 1: If a local fire is extinguished before it grows into a fully developed fire
- Scenario 2: If a fully developed compartment fire is extinguished before structural failure
- Scenario 3: If a fully developed compartment fire results in structural failure without progressive collapse
- Scenario 4: If a fully developed compartment fire results in progressive collapse

The total scenario approach is presented in Figure 23. The aspects influencing the probability and moment of extinguishing for the different scenarios are shortly described in the following paragraphs.

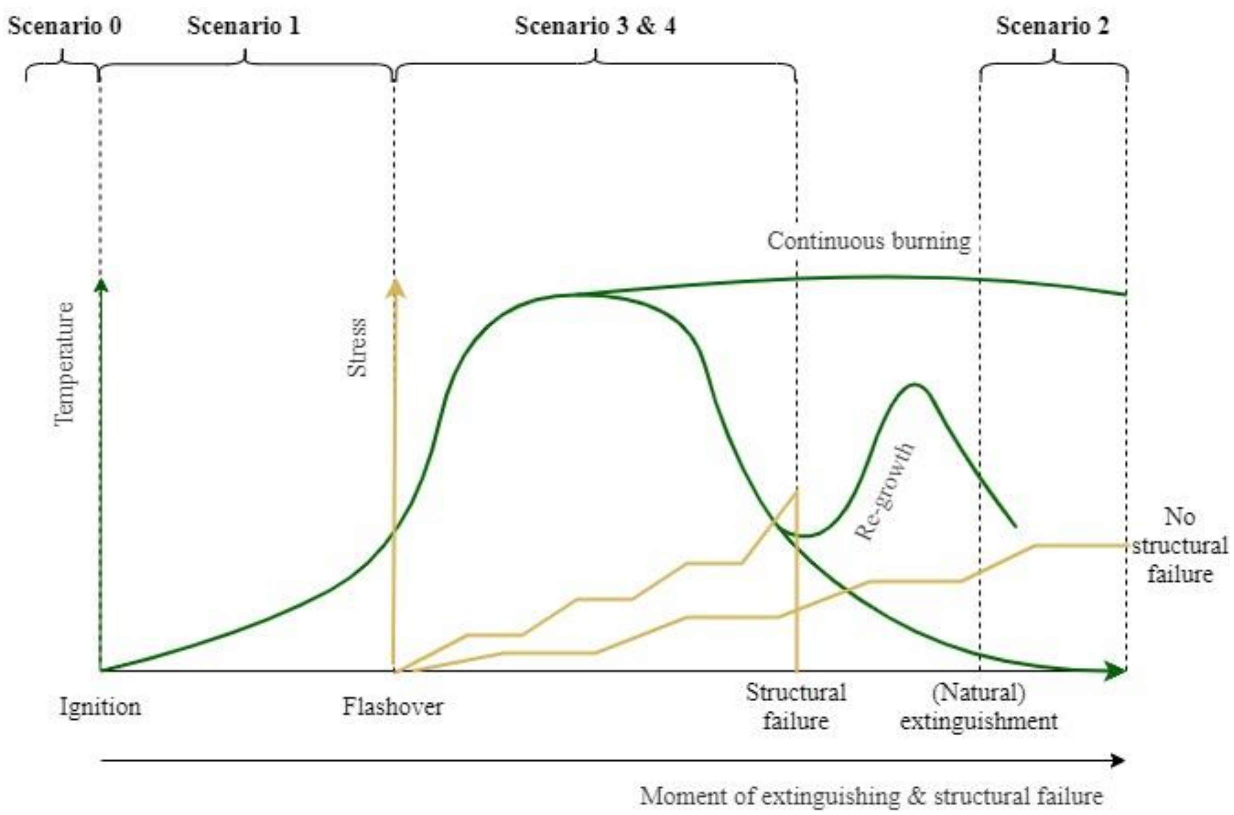


Figure 23: Fire scenarios (Own figure)

7.2.1 FIRE SCENARIO 0

Scenario 0 describes the scenario where no fire occurs in the building.

7.2.2 FIRE SCENARIO 1

Scenario 1 presents the specific scenario that in case there is ignition, the fire is extinguished before reaching fully developed phase (before flashover occurs). When comparing the results of large-scale compartment fire tests follows that extinguishing before flashover only occurs in test 4 and 5 by Zelinka et al. (2018). In these tests, all surfaces are fully exposed with CLT and an automatic sprinkler installation present. From the results of the compartment temperatures in these tests follows that when the sprinkler is activated, the fire is extinguished, before reaching fully developed phase.

7.2.3 FIRE SCENARIO 2

Scenario 2 describes the scenario that in case there is a fully developed fire, the structural elements can withstand the fire without failing. This concerns a case where an active sprinkler system is not available, and the structural elements must rely on the fire resistance caused by passive fire safety and either natural extinguishing due to passive measures or fire fighter intervention. For this, the influence of the fire safety and design measures on the fire dynamics is of importance as well as the structural characteristics of the CLT.

Based on the theory presented in chapter 4, it follows that there are several design aspects that influence the duration of the fire and the characteristics of decay. In this research, the probability of the moment of extinguishing is divided into two parts: (1) the probability of natural extinguishing and (2) the expected moment of extinguishing. From chapter 4 it is observed that the probability of natural extinguishing is highly influences by whether delamination and encapsulation base-layer failure is avoided. The moment of extinguishing is observed to be mainly dependent on CLT exposure and ventilation. This is further elaborated in section 7.3.3.

Whether the structure can withstand a burnout scenario depends on the fire resistance of the structural elements, the applied loads, and the element configuration. For CLT elements, this depends on the burning behaviour, of which heat flux exposure, delamination and encapsulation present the most dominant factors as observed from chapter 4. The methods to calculate the structural capacity are presented in chapter 8.

7.2.4 FIRE SCENARIO 3 AND 4

Scenarios 3 and 4 describe the scenarios that in case there is a fully developed fire, this results in structural failure, with or without progressive collapse of the total building. Whether progressive collapse occurs, depends on the structural scheme of the building, the location of the fire and the structural capacity of the remaining structural elements. Assumptions regarding the definition of progressive collapse and the structural scheme is further described in section 7.3.4and chapter 8.

7.3 PROBABILITY CALCULATION

In this section, the methods, and values used to quantify the probability of the fire scenarios are presented. The approach is based on the development and characteristics of a fire. following main steps: (1) the (probability) frequency that a fire should be expected each year, (2) the probability that in case of a local fire, the fire is extinguished before it developed into a fully developed fire, (3) the probability that in case of a fully developed fire, the structural function fails locally, and (4) the probability that in case of a fully developed fire, the structural function fails leading to progressive collapse. The method as proposed in NEN 6079 (2016) is used as a guideline for the probability assessment, adjusted according to relevance for fire safety strategies in mass timber buildings. The total approach is visualized in Figure 24.

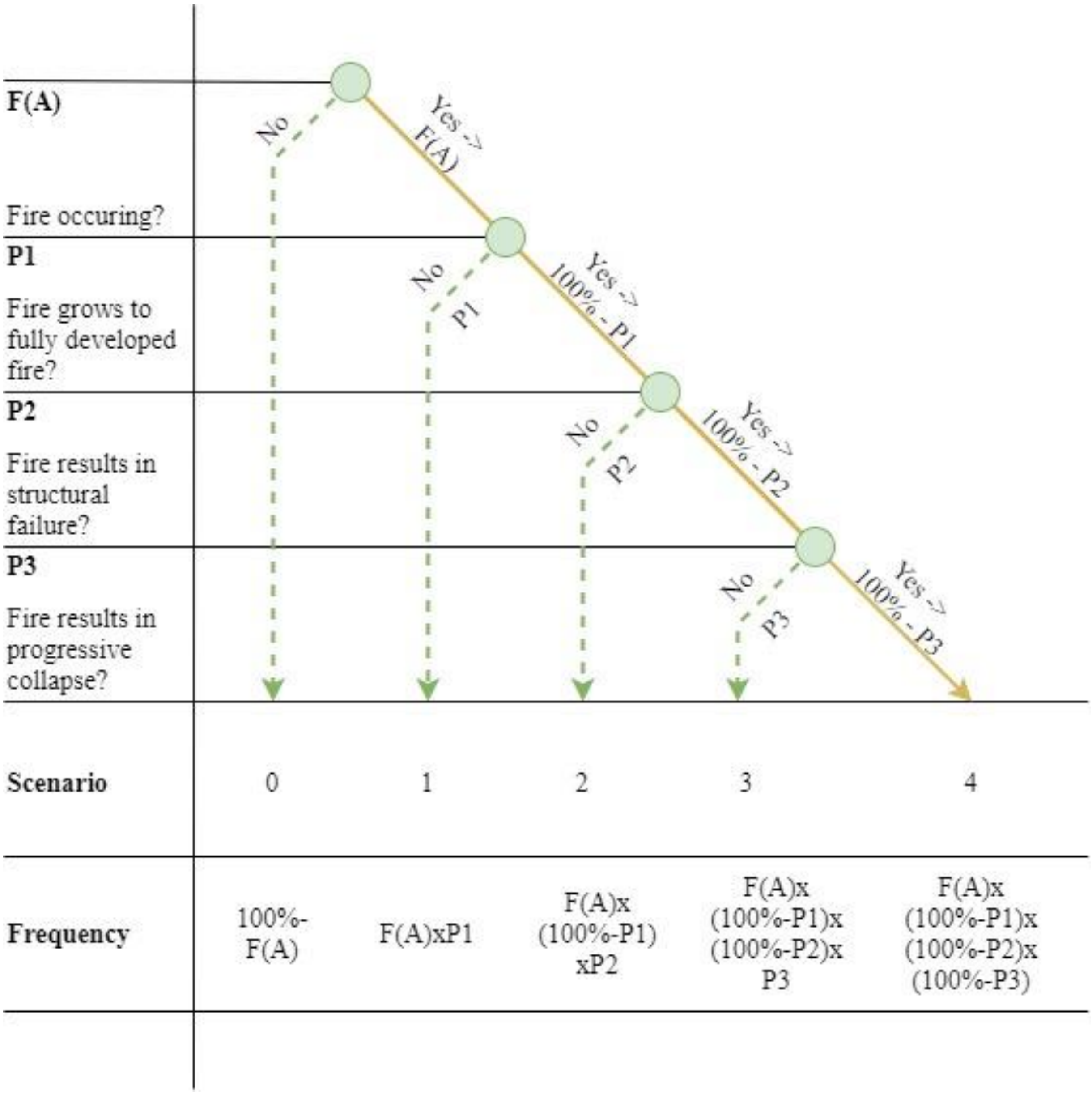


Figure 24: Flowchart for probability calculation (Own figure)

The figure presents four questions, which are used as a guideline for the calculations. Worst case scenario is that every question is answered with yes, resulting in total collapse of the building. Whether a question is answered with yes or no, is determined by calculation of the probabilities. In short, the frequency and probabilities describe the following aspects:

- F(A) is the frequency that a fire can be expected over the total service life of a building
- P1 is the probability that a fire is extinguished before it becomes a fully developed fire
- P2 is the probability that a fire naturally decays and is extinguished before structural failure
- P3 is the probability that in case there is structural failure, this does not lead to progressive collapse

In the next paragraphs, the methods and values used to determine the probabilities are described.

7.3.1 F(A): Frequency of fire

F(A) is the frequency that a building fire might occur. A general acknowledged value for the frequency of fire occurrence is $5*10^{-7}$, which describes the yearly frequency of a compartment fire per m2 gross floor area (GFA). This value is based on extensive research over several years. (Lecture slide CIE4281. Parwani, 2019, Slide 4). The value is in line with the value presented by National Annex in NEN 1991-1-2+C3 (2019) of $4*10^{-7}$. In this research, a value of $5*10^{-7}$ is used. The total frequency of building fires that can be expected over the service life of a building are calculated as follows:

$$F(A) = 5 \times 10^{-7} \times GFA_C \times n_{storeys} \times t_{SL,B} \qquad \textit{Eq. 22}$$

Where:

GFA_c Is the gross floor area of one compartment, expressed in m^2
$n_{storeys}$ Is the number of building storeys
$t_{SL,B}$ Is the expected service life of the building, expressed in years

7.3.2 P1: Probability of extinguishing before flashover

P1 presents the probability that a local fire is extinguished before it develops into a fully developed fire (before flashover). From the large-scale compartment tests follows that whether a residential fire develops into a fully developed fire is due to the availability of an automatic sprinkler system (Zelinka et al. 2018 test 4 & 5). Therefore, P1 should only be determined if a sprinkler is available. If a sprinkler is not available, P1 is 0. P1 is divided into a separate default-tree presented in Figure 25.Based on this, P1 is defined by two aspects, relating to the sprinkler system, defined as $P_{1,1}$ and $P_{1,2}$. The total probability P1 is then calculated by:

$$P_1 = P_{1,1} * P_{1,2} \qquad \textit{Eq. 23}$$

Where:

$P_{1,1}$ Is the probability of the sprinkler functioning accordingly
$P_{1,2}$ Is the probability of the fire being extinguished by sprinkler and firefighter combination

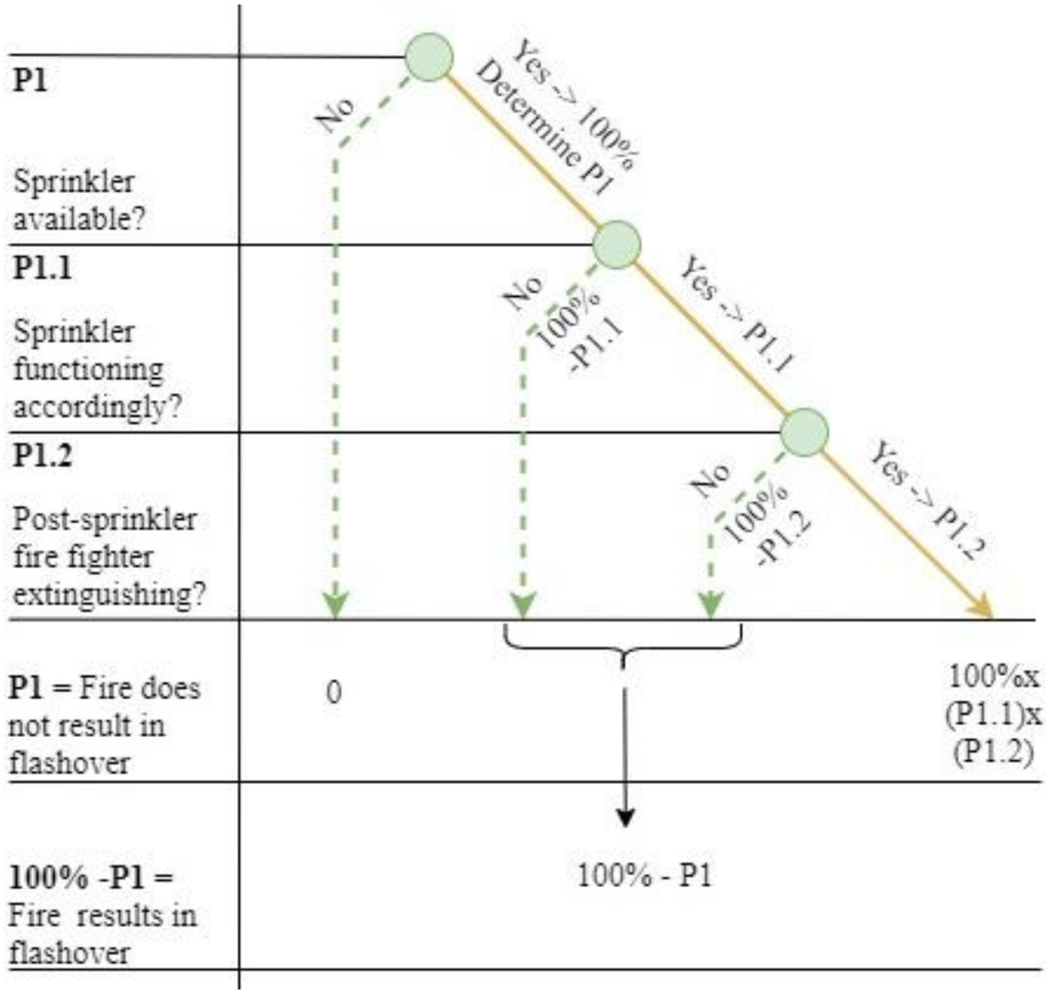


Figure 25: Fault tree for P1 (Own figure)

7.3.2.1 $P_{1.1}$: Probability of functioning

It is assumed that if a sprinkler does not function, the fire will not be extinguished before flashover. The probability of a sprinkler not functioning should therefore be determined. In this research, it is assumed that a normal sprinkler has a probability of 98% of functioning, as stated by the data presented by NEN-EN 1991-1-2-C3 Table 4. (2019). With this, $P_{1,1}$ is defined as:

$P_{1,1} = 98\%$

7.3.2.2 $P_{1.2}$: Probability of post-sprinkler fire fighter extinguishing

Although a sprinkler works, the fire may not be completely extinguished and only controlled. It is expected that the if the fire is not extinguished by the sprinkler and only controlled, the fire fighter can extinguish the fire by offensive attack, which is in line with test 4 and 5 by Zelinka et. al, (2018), in which the tests were offensively post-extinguished after sprinklers were activated. It is therefore considered that the probability of extinguishing is 100%. With this, $P_{1,2}$ is defined as:

$P_{1,2} = 100\%$

7.3.3 P2:

P2 presents the probability that in case there is a fully developed fire, the fire is extinguished before structural failure of the CLT elements. For this, the probability of the moment of natural extinguishing is compared to the expected moment of structural failure. The moment of expected structural failure is calculated by methods which are further presented in chapter 8. By comparing the expected moment of extinguishing $P_{2,ext}$ to the expected moment of failure, the total probability of extinguishing before collapse (P_2) is determined as follows:

$$P_2 = P_{2,ext} \qquad \textit{if:} \qquad t_{fail} > t_{ext,calc} \qquad \textit{Eq. 24}$$

$$P_2 = 0\% \qquad \textit{if:} \qquad t_{fail} \leq t_{ext,calc} \qquad \textit{Eq. 25}$$

Where:

t_{fail}	Is the expected moment of structural failure: MIN($t_{fail,floor}$; $t_{fail,wall}$), expressed in min
t_{ext}	Is the calculated moment of extinguishing further described in chapter 8, expressed in min
$P_{2,ext}$	Is the probability of moment of extinguishing, expressed in percentage

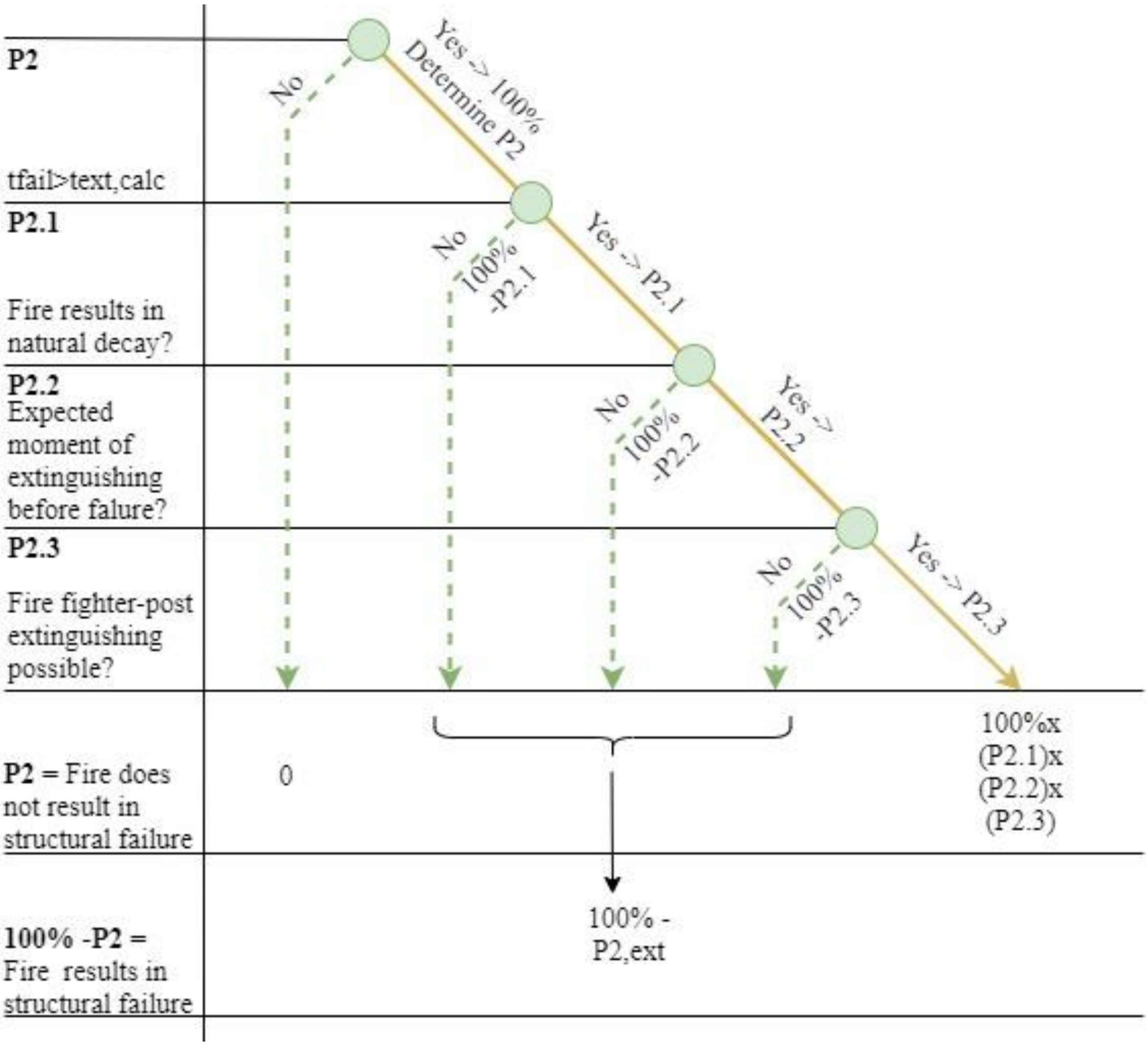


Figure 26: Fault tree for P2 (Own figure)

7.3.3.1 t_{fail}: Moment of structural failure

The moment of failure (t_{fail}) depends on several aspects of which: (1) material, (2) dimensions, (3) the configuration of the element, (4) connections etc. The moment of failure is determined by calculating the char depth over time and the residual loadbearing capacity. The calculation method is further elaborated in chapter 8, an example of a calculation is presented in Figure 27. The output is the minimum expected moment of failure of either wall or floor elements.

$$t_{fail} = MIN(t_{fail,floor}; t_{fail,wall}) \quad \text{Eq. 26}$$

Where:

$t_{fail,floor}$	Is the moment that the floor fails structurally due to fire exposure, expressed in min
$t_{fail,wall}$	Is the moment that the wall fails structurally due to fire exposure, expressed in min

7.3.3.2 $t_{ext,cal}$: Moment of calculated extinguishing

The moment of extinguishing is first calculated by performance-based methods presented by the document from Brandon (2018). This method is further elaborated in chapter 8. An example of the outcome of the calculation is presented in Figure 27. The outcome of this step is the calculated moment of extinguishing, expressed in minutes: ($t_{calc,ext}$).

From chapter 4 follows that the performance-based methods typically mis-predict the decay phase, leading to shorter moment of calculated extinguishing compared to the moment of extinguishing as observed in large-scale compartment fire tests. Therefore, it is assumed that if the moment of calculated extinguishing is larger than the moment of calculated structural failure, the probability of the fire resulting in extinguishing before failure is 0.

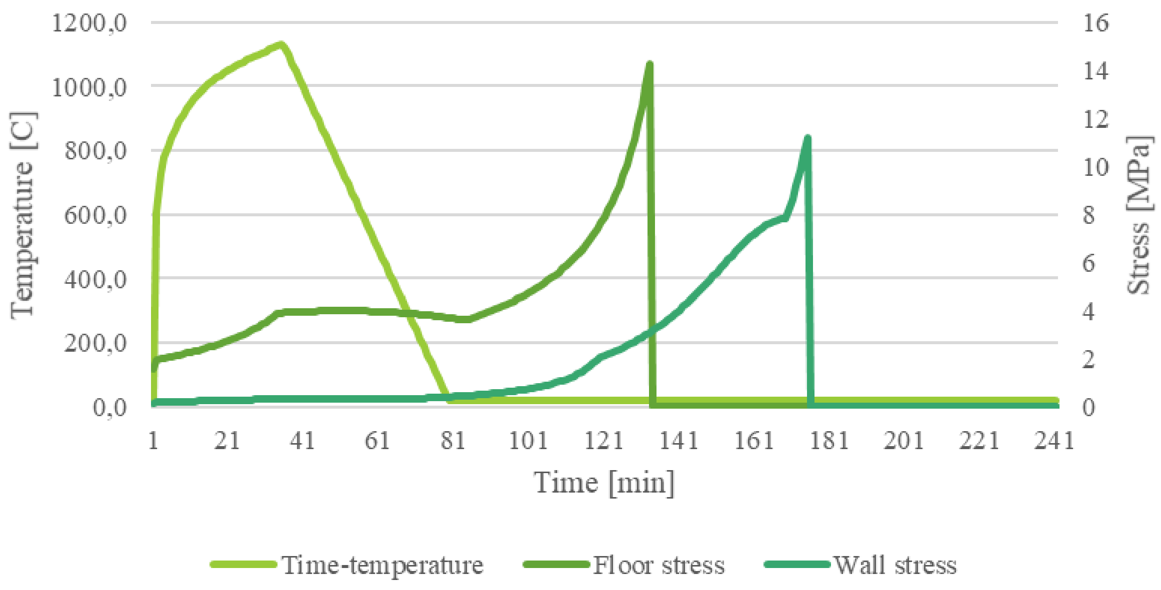


Figure 27: Example of calculation for structural failure (tfail) and moment of calculated extinguishing (tcalc,ext)

7.3.3.3 $P_{2,EXT}$: PROBABILITY OF MOMENT OF EXTINGUISHING

Due to the limitation regarding the methods to predict the fire dynamics by the methods presented by Brandon (2018), the probability of the moment of extinguishing is further supported by looking at the results from large scale compartment tests regarding the moment of extinguishing.

It is assumed that the moment of extinguishing may occur by the phenomenon self-extinguishing or by fire fighter intervention. However, the phenomenon of self-extinguishing in mass timber buildings is yet lacking proper definitions or conditions. This means that it is still difficult to predict whether self-extinguishing occurs and at which time. Therefore, rather than considering self-extinguishing, the probability of (moment of) natural decay is considered, defined as:

The moment that the average compartment temperatures drop below 300 degrees, without signs of regrowth or continuous burning, with an extinguishing time shorter than 240 min.

It is noted that this does not indicate the real behaviour of self-extinguishing, however, provides an indication of the moment that potential self-extinguishing could occur and suppression by fire fighters would be safe and necessary to reach full extinguishment. P2,ext is therefore divided into 3 parts: (1) the probability of natural decay, (2) the probability that in case there is natural decay, this occurs at a certain time, and (3) the probability that fire fighter services extinguish the fire after natural decay. With this, the probability of the moment of extinguishing $P2_{ext}$ is calculated by the following formula:

$$P_{2,Ext} = P_{2,1} * P_{2,2} * P_{2,3} \qquad \textit{Eq. 27}$$

Where:

$P_{2,1}$	Is the probability that the design leads to natural decay, expressed in percentage
$P_{2,2}$	Is the probability of the moment of natural decay, expressed in percentage
$P_{2,3}$	Is the probability that firefighter intervention results in the final extinguishing, expressed in percentage

P2.1 and P2.2 are determine based on the results from large scale compartment fire tests, in which the influence of different design characteristics on the results regarding natural decay (extinguishing) was analysed. From the large-scale compartment test results follows that the number of encapsulated surfaces present a big influence on the fully developed phase and decay phase, which affect the moment of extinguishing. Therefore, the compartment fire tests are divided into three design variants relating to the number of exposed surfaces, as presented in Figure 28.

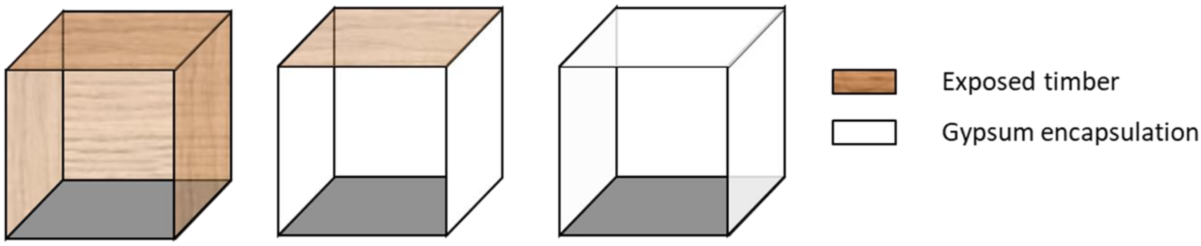


Figure 28: Design variants. Left: Variant 1 – multiple exposed surfaces. Middle: Variant 2: 1 exposed surface. Right Variant 3- Fully encapsulated

In Table 5 an overview of the categorized fire tests with important characteristics the results for the definition of the extinguishing characteristics are presented. The compartment tests that did not result in natural decay are highlighted in yellow. Note: type X encapsulation means encapsulation which will not fail.

Table 5: Overview of extinguishing characteristics

Test series	Tests number	Adhesive type	Encapsulation type	Moment at which avr 300C is reached	Extinguish time (min)
Variant 1: Multiple surfaces exposed					
McGregor (2013)	Test 5	PU	Type X		63 continuous
Hadden et al. (2018)	Alpha 1	PU	Normal		61 + regrowth
	Alpha 2	PU	Normal		60 + regrowth
	Beta 1	PU	Normal	35	60
	Beta 2	PU	Normal		60 + regrowth
	Gamma	PU	Normal		78 continuous
Su et al. (2018)	1-6	PU	Type X		160 continuous
Brandon et al. (2021)	Test 2	Fire resistant PU	Type X	130	240
	Test 3	Fire resistant PU	Type X		221 at regrowth
	Test 4	Fire resistant PU	Type X	90	240
	Test 5	Fire resistant PU	Type X	120	240
Variant 2: 1 surface exposed					
Medina Hevia (2014)	Test 3	PU	Type X	65	81
Janssen (2017)	Test 1	PU	Type X		92 + regrowth
	Test 2	MUF	Type X	100	210
	Test 3	Fire resistant PU	Type X	110	240
Su et al. (2018)	1-3	PU	Type X	-	240 + regrowth
	1-4	PU	Type X		159 + regrowth
	1-5	PU	Type X		202 + regrowth
Zelinka et al. (2018)	Test 2	PU	Type X	120	240
	Test 3	PU	Type X	180	240
Brandon et al. (2021)	Test 1	Fire resistant PU	Type X	100	240
Variant 3: Fully encapsulated					
McGregor (2013)	Test 2	PU	Type X	53	53
	Test 4	PU	Type X	>53 (400C)	53
Su and Muradori (2014)	-	PU	Type X	100	120
Zelinka et al. (2018)	Test 1	PU	Type X	105	240
Su et al. (2018)	1-1	PU	Type X	130	134
	1-2	PU	Type X	80	104

7.3.3.3.1 $P_{2,1}$: Probability of natural extinguishing

Based results presented by Table 5 it is observed that the probability of natural extinguishing is mainly influenced by the type of CLT and encapsulation, relating to the effect of delamination and gypsum base-layer failure. It is observed that in compartment fires where delamination or gypsum failure occurred, the probability of natural extinguishing was decreased significantly. Moreover, it is observed that the natural decay is observed for multiple exposed surfaces in case delamination is avoided (Test series by Brandon et al., 2021).

Determining the probability of extinguishing is therefore based on the type of CLT adhesive and including additional risk factors relating to the type of encapsulation. With this $P_{2,1}$ is calculated by:

$$P_{2,1} = P_{2,1,1} * R_{2,1,enc} \qquad \textit{Eq. 28}$$

Where:

$P_{2,1,1}$	Is the probability that the design leads to natural extinguishing
$R_{2,1,enc}$	Is the risk relating to the type of encapsulation used

For the three design scenarios as presented in Figure 28, $P_{2,1,1}$ is determined by looking at the influence of delamination due to the adhesive type based on the results from large scale compartment fire tests. It is noted that only a small number of tests was done with fire resistant adhesives, and not for all three design scenarios. It is considered that for these, the probability of extinguishing is at least equal to the tests where non-fire-resistant adhesive was used. In Table 6, an overview is provided which represents the number of tests with the specific characteristics of the three presented scenarios, for PU and fire-resistant adhesives, and the number of tests that resulted in extinguishing.

Table 6: Probability of extinguishing

Design variant	Number of tests	Non-fire resistant adhesive	Probability	Fire resistant adhesive	Probability
1	11	1/7	14%	3/4	75%
2	10	3/7	43%	3/3	100%
3	6	6/6	100%	-	100%

From Table 6 follows that typically fully encapsulated compartments results in extinguishing both with PU, as fire resistant adhesives. For compartments with one surface exposed, only 43% of the tests with PU adhesives resulted in extinguishing whereas 100% of the tests with fire resistant adhesive resulted in extinguishing. In tests with multiple exposed surfaces, only 14% of the tests with PU adhesive resulted in extinguishing whereas this was 75% for compartments with fire resistant adhesives. With this table, $P_{2,1,1}$ can be determined.

$R_{2,1,Enc}$ is the effect of the risk of natural extinguishing relating to failing of encapsulation and the potential result of exposing fresh timber to high temperatures. This mainly depends on the type of encapsulation used. If the encapsulation cannot fail, the risk factor is 1. If the encapsulation can fail, it is assumed that the risk increases, though expressed as a decreased factor, leading to decreased probability of extinguishing. For normal encapsulation therefore a risk-factor of 0,8 is defined.

7.3.3.3.2 $P_{2,2}$: Probability of moment of extinguishing

It is expected that the influence of delamination and encapsulation type are incorporated in the probability of natural extinguishing and are therefore not considered in the probability of the moment of extinguishing.

Now, the tests above which showed a decay with end temperature below 300C are compared and categorized into different design scenarios. As the probability of natural decay for the type of adhesive is already considered, the total probability of moment of extinguishing is only based on the number of tests that showed natural decay, which is summarized in Table 7. This was based on the number of tests that resulted in a specific time range. The reason the conditions go to 240 min is because the maximum range n time in the large-scale tests is 240 min. Before his time, all tests were mitigated manually.

Table 7: Number of tests presenting moment of extinguishing

Scenario	**Number of tests**	**<30 min**	**>30min <60 min**	>60 min **<90 min**	>90 min **<120 min**	>120 min **<180min**	>180 **<240 min**
1	4		1/4		1/4	2/4	
2	6		1/6		4/6		1/6
3	6		1/6	2/6	2/6	1/6	

With this, the probability of the moment of extinguishing ($P_{2,2,2}$) can be determined by the values in Table 8, by comparing the calculated moment of failure (t_{fail}) to the probability of the expected moment of extinguishing, based on the results from large scale compartment fire tests.

Table 8: Probability of moment of extinguishing

Design variant	**Number of tests**	**<30 min**	**<60 min**	**<90 min**	**<120 min**	**<180min**	**<240 min**
1	4	0%	0%	25%	50%	100%	100%
2	6	0%	17%	17%	83%	83%	100%
3	6	0%	17%	50%	83%	100%	100%

7.3.3.4 $P_{2,3}$: Probability of post-fire fire fighter extinguishing

In all the large-scale compartment test that were investigated, the fires were manually extinguished after certain threshold values were met (e.g., time passing, average temperature etc.). Therefore, it is important to consider whether fire fighter services may be expected to extinguish the fire. It is assumed this depends on the probability of the location of the fire and the expected accessibility. It is assumed that below 28-meter, defensive extinguishing is possible as this is below the reach of the fire fighter ladder. Based on the examined large scale compartment tests follows that for all cases, the fires were manually extinguished from outside for the compartments where the average temperatures reached below 300 degrees. Therefore, it is assumed that the probability of post-extinguishing is 100% in case fire fighters can access from outside. Above 28 meters, fire fighter extinguishing must be done offensively, from inside the building. It is considered that this presents a high risk and can only be expected for 50% of the time. Based on this, $P_{2,3}$ is calculated by:

$$P_{2,3} = P_{2,3,1} + P_{2,3,2} \quad \textit{for:} \quad h_{comp,i} \leq 28m \quad \textit{Eq. 29}$$

With these assumptions, $P_{2,3}$ is calculated as accordingly:

$$P_{2,3,1} = P_{2,3,1} \times 100\% \quad \textit{for:} \quad h_{comp,i} \leq 28m \quad \textit{Eq. 30}$$

$$P_{2,3,2} = \left(1 - P_{2,3,1}\right) \times 50\% \quad \textit{for:} \quad h_{comp,i} > 28m \quad \textit{Eq. 31}$$

Where:

$h_{comp,i}$	Is the floor height of a certain compartment i, expressed in m
$P_{2,3,1}$	Is the probability that the fire is located in a compartment with a floor height below 28m, calculated by the number of compartments with a floor height below 28m and dividing this by the total number of compartments in the building, expressed in %

7.3.4 P3: Probability of structural failure without collapse

P3 represents the probability that in case the structure fails before extinguishing, this does not lead to a progressive collapse of the total building. This depends on the location of the fire and the loadbearing capacity of the elements below the burning compartment. The considered progressive collapse is defined by whether or not the floor or walls of a compartment can carry the additional loads of the floors above. The process considered is visualized in Figure 29.

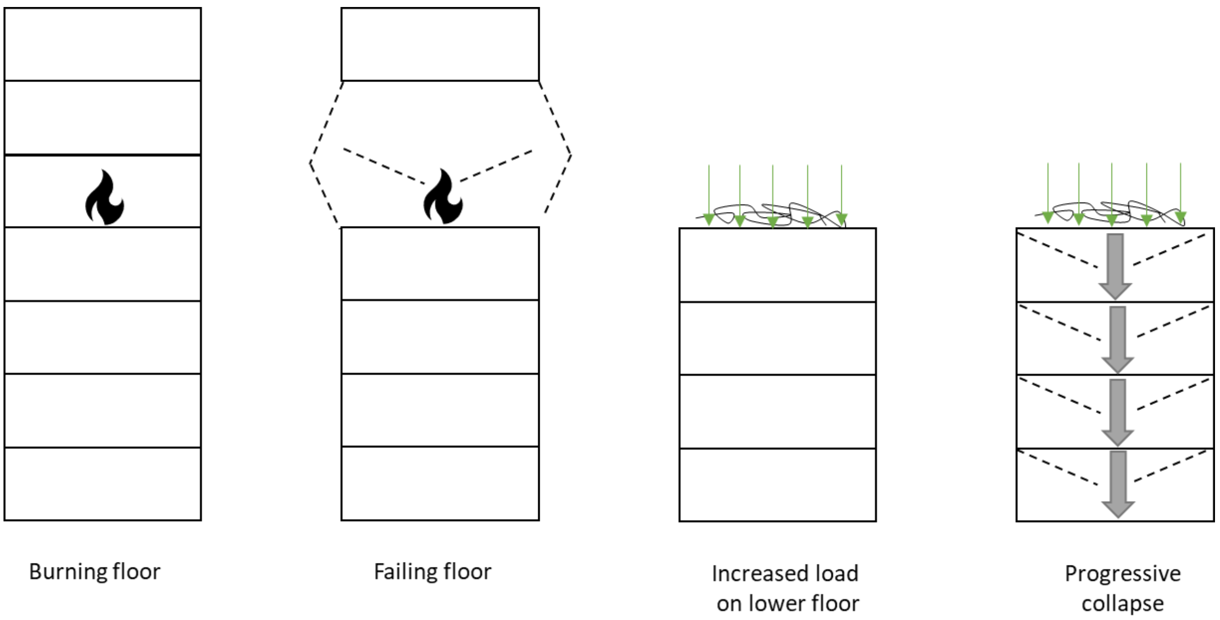


Figure 29: Concept of progressive collapse (Own figure)

The left figure presents the hypothetical location of a fire on the 5th floor of a 7storey building. In the next figure, the ceiling or walls fails, which results in a dis-balance compartment structure. By this, the loads of the total compartments above the burning compartment are now laying on top of the floor of the burning compartment, which is assumed to be evenly distributed. In case the floor and walls can withstand the additional loads, the compartments below the burning compartment are considered to fulfil their original function. If the loads cannot withstand the additional loads, it is considered that progressive collapse will occur. With this, it is assumed that in case floor or wall elements of the burning compartment fail, the compartments above the burning floor are lost.

To determine what the probability is that structural failure due to burning will not lead to progressive collapse, the location at which the fire must be located t still be able to carry all the loads from the floors above must be determined. The probability P_3 is then determined by calculating the probability that the fire is located above this height. With this, the total probability is calculated by the following formula:

$$P_3 = 100\% - \frac{n_{storey,collapse} + 1}{n_{storey,total}}$$ *Eq. 32*

Where:

$n_{Storey,collapse}$	Is the storey number at which the load bearing capacity of the floor or wall is insufficient to carry the additional load from the compartments on top
n_{Storey}	Is the total number of building storeys

7.4 DAMAGE CALCULATION

In this section, the methods and assumptions used to quantify the consequence of a specific fire scenario is elaborated. The consequence is related to the expected damage after a fire, expressed as the percentage of the total building that is lost due to a certain fire scenario.

7.4.1 SCENARIO 0: NO FIRE

Scenario 0 presents the scenario in which no fire is expected. The damage D_0 is thus 0.

7.4.2 SCENARIO 1: SPRINKLER ACTIVATION

Scenario 1 describes the scenario for which a local fire is extinguished before the fire developed to a fully developed fire (before it reaches flashover). From large scale compartment tests, it is observed that this is either reached by sprinkler activation or fire fighter intervention if the fire is sufficiently low to allow access. The relating damage is therefore smoke, and water related. It is assumed that this affects 5% of the value in one compartment. With this, the damage is calculated as:

$$D_1 = \frac{0{,}05}{n_{storeys}} \qquad \textit{Eq. 33}$$

Where:

$n_{Storeys}$	Is the total number of building storeys

7.4.3 SCENARIO 2: COMPARTMENT BURNOUT

Scenario 2 describes the event of extinguishing of a compartment fire, whilst keeping the required structural (separational) functions. It is considered that this scenario leads to total loss of value for one compartment.

$$D_2 = \frac{1}{n_{storeys}} \qquad \textit{Eq. 34}$$

Where:

$n_{Storeys}$	Is the total number of building storeys

7.4.4 SCENARIO 3: PARTIAL BUILDING LOSS

Scenario 3 describes the event of compartment elements not being sufficient to maintain the required capacity during a fire, which leads failure of the burning compartment and the compartments on top. If the compartment below the burning compartment can withstand the additional loads, only the top part of the building is considered to be lost. This depends on the probability of a fire being located in a certain storey, as explained in section 7.3.4. With this, the expected damage is calculated by:

$$D_3 = \frac{n_{storeys,building} - (n_{storey,collapse} + 1)}{n_{storey,total}} \qquad \textit{Eq. 35}$$

Where:

$n_{Storey,collapse}$	Is the storey number at which the load bearing capacity of the floor is insufficient to carry the additional load from the compartments on top
$n_{Storey,}$	Is the total number of building storeys

7.4.5 SCENARIO 4: TOTAL BUILDING LOSS

Scenario 4 describes the event of compartment elements not being sufficient to maintain the required capacity during a fire, which lead progressive collapse of the total building. It is considered that for this scenario, the damage is so server that the consequence is the total loss of the building.

$$D_4 = 1 \qquad \textit{Eq. 36}$$

8 STRUCTURAL FIRE RESISTANCE CALCULATION

In this chapter, the methods used to calculate the fire dynamics and fire resistance are elaborated. These calculations are required to determine the probability and impact of fire scenario 2. To calculate the fire resistance, a three-step method as presented by Buchanan et al. (2014) is used. This consists of three main models: (1) Fire dynamic model, (2) thermal model, and (3) structural model.

Besides the fixed design parameters, there are other aspects which may influence the fire dynamics and resistance during a fire. Buchanan et al. (2014), presented an overview of the different aspects that should be considered. This is summarized in Figure 30. To account for the influence of these unknowns, a sensitivity analysis can be done, and fire safety ensured by designing according to the worst-case scenario or based on a risk-assessment.

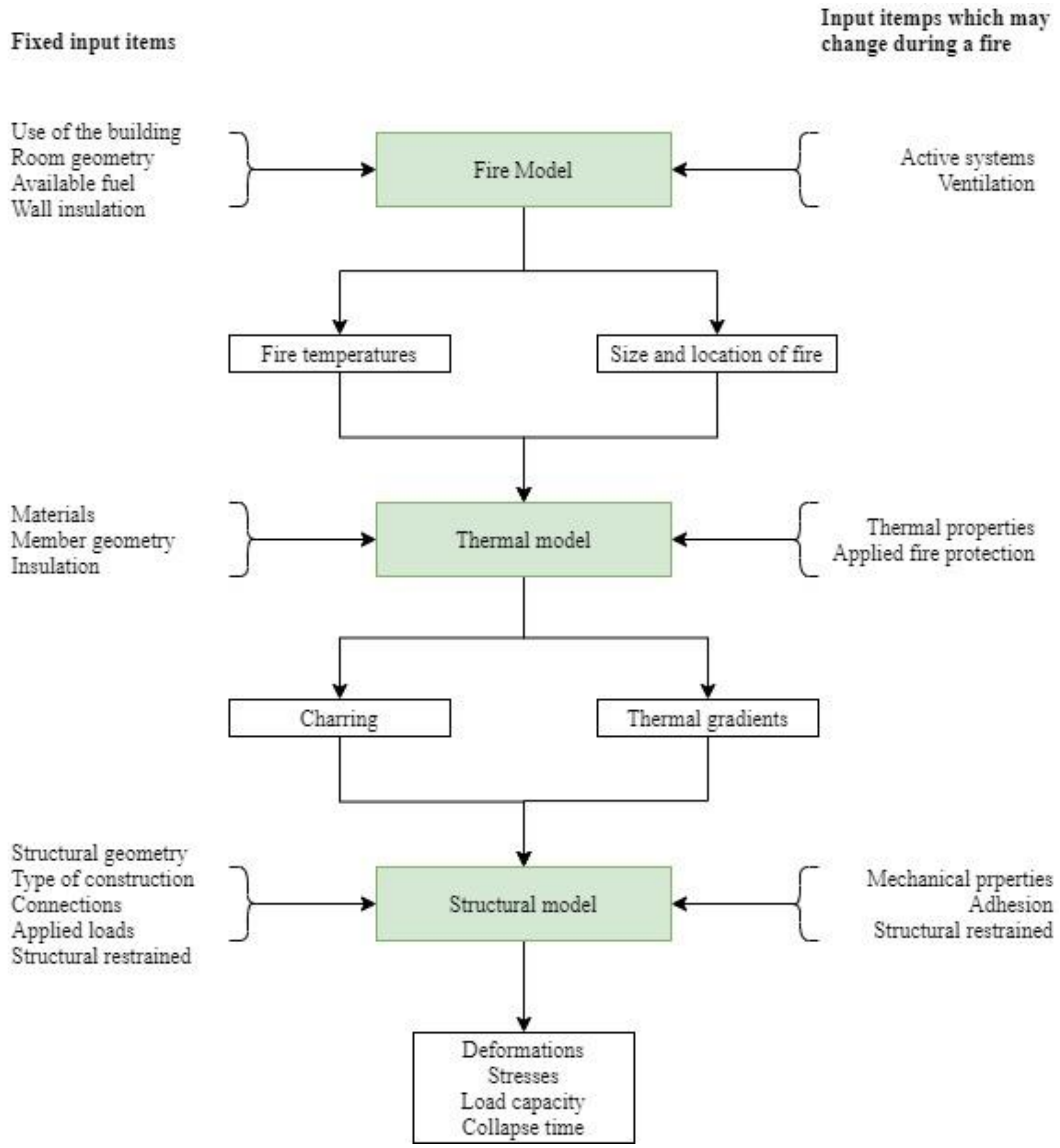


Figure 30: Structural fire resistance steps (Redesigned based on Buchanan et al. 2014 p.12)

8.1 Fire dynamic calculation

In this section, the performance-based design method used for the calculations of the fire dynamics is presented. Which is based on the method presented by Brandon (2018). The values used in design tool calculations are presented in appendix 4.

8.1.1 Description of method

Brandon (2018) describes a method to predict the fire dynamics and the relating char depth based on the general parametric design fire from the Eurocode. However, the method includes an iterative approach representing the additional fuel load from the exposed timber to the fire over time.

Brandon accounts for the contribution of CLT to the fuel load by looking at the test results from large scale compartment fire tests by Su et al. (2018) in which it is recognizes that during the fully developed phase approximately 70% of the contribution of timber combusts outside. The method therefore considered the following steps:

- Step 1: First iteration, calculation of the parameters for which the CLT does not contribute to the fuel, this results in the initial fire duration and final char depth for this iteration
- Step 2: Following iterations are needed to include the influence of the contribution of CLT to the fuel load. The iteration is stopped when the predicted char depths converge, at which the decay phase will start. In case the char depth does not converge, the fire is assumed to not decay
- Step 3: The maximum temperature found from the iteration at which char conversion is started can then be used to calculate the time-temperature curve

Based on this approach it is possible to account for the effect of different percentage of exposed timber. In Figure 31 an example is presented, presenting the difference between a fully exposed, a fully encapsulated and a 30% exposed CLT compartment.

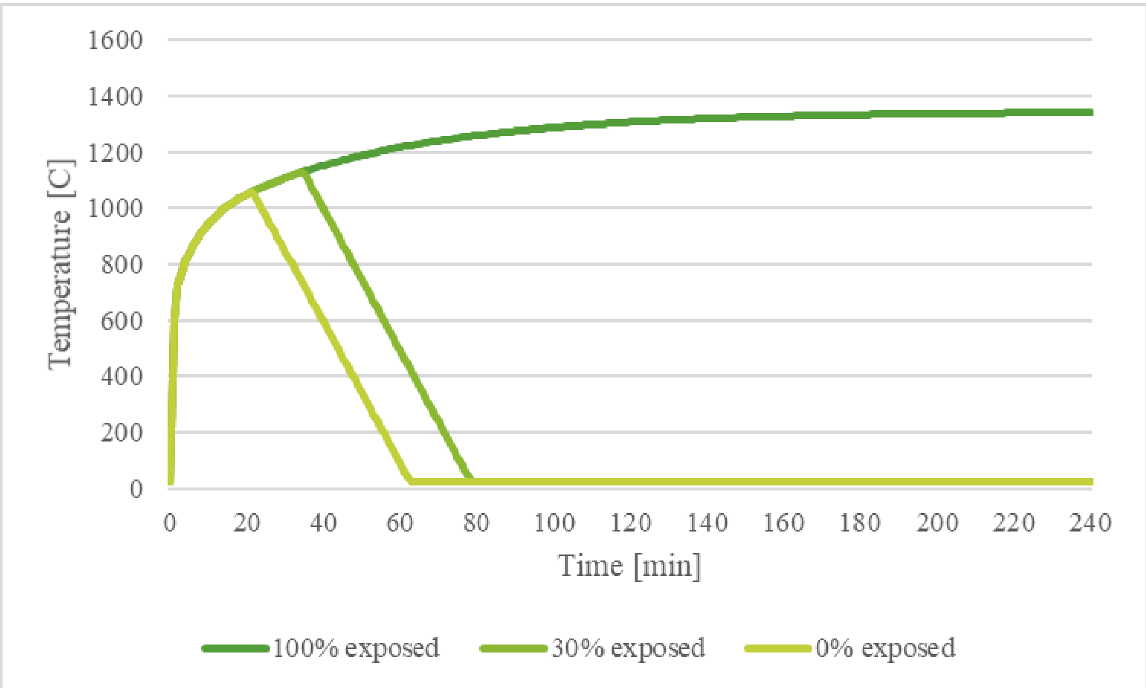


Figure 31: Fire dynamics for different compositions

8.1.1.1 Boundary conditions

Brandon (2018) suggests that the method is only suitable for compartments up to 500 m2. The method describes a homogeneous temperature distribution throughout the compartment and assumes that the char depth on the exposed CLT is similar for every location. Moreover, the method does not account for the effect of delamination, or the effect of gypsum base board failure. Also charring behind the protection is not considered.

8.1.2 Temperature-time calculation equations

The temperature-time curve is calculated based on similar calculation methods as presented in the parametric fire calculation in NEN-EN 1991-1-2 NB (2019). The temperature in the fully developed phase is this way calculated by Eq. 37.

$$\Theta = 20 + 1325(1 - 0{,}324e^{(-0.2t*\Gamma)} - 0{,}204e^{(-1.7t*\Gamma)} - 0{,}472e^{(-19t*\Gamma)}) \qquad \textit{Eq. 37}$$

The temperatures in the decay phase are calculated by:

$$\Theta = \Theta_{max} - 625(t * \Gamma - t_{max} * \Gamma * x) \qquad if \quad t_{max} * \Gamma \leq 0{,}5 \qquad \textit{Eq. 38}$$

$$\Theta = \Theta_{max} - 250(3 - t_{max} * \Gamma)(t * \Gamma - t_{max} * \Gamma * x) \qquad if \quad 0{,}5 < t_{max} * \Gamma < 2 \qquad \textit{Eq. 39}$$

$$\Theta = \Theta_{max} - 250(t * \Gamma - t_{max} * \Gamma * x) \qquad if \quad t_{max} * \Gamma \geq 2 \qquad \textit{Eq. 40}$$

$$With\ x = 1{,}0\ if\ t_{max} > t_{lim}\ or\ x = t_{lim}\Gamma / t_{max}\Gamma\ if\ t_{max} = t_{lim}$$

For this, the parameters presented in Table 9 are required.

Table 9: Equations for fire dynamic calculations

Parameter	Equation	Unit
Opening factor	$O = \left(\frac{A_v}{A_t}\right)\sqrt{h_v}$	$[m^{1/2}]$
Heating rate/time factor	$\Gamma = \left(O/\sqrt{p c \lambda}\right)^2 / (0{,}04/1160)^2$	[-]
Start time of decay	$t^1_{max} = \max\left[\left(0{,}2 * 10^-3 * q_{t,d}/O\right); t_{lim}\right]$	[hour]

The opening factor (O) is calculated by the total ventilation area (A_v) of the window openings, the total compartment surface areas (A_t) of floors, walls, and ceiling, and the weighted average height of the ventilation openings (h_v).

The heating rate/time factor (Γ) is calculated by the opening factor (O) and the thermal inertia of the compartment boundaries ($\sqrt{p c \lambda}$) where p is the density in kg/m^3, c is the specific heat in J/kg and λ is the thermal conductivity in W/mK. The heating rate/time factor calculates the change in heating rate.

The start time of the decay (t^1_{max}) is determined based on fuel load density divided by the compartment boundary area ($q_{t,d}$) expressed in MJ/m^2, the opening factor (O) and the lower limit of the duration of the heating phase (t_{lim}), expressed in hours. In NEN-EN 1991-1-2+C3 (2019), t_{lim} is dependent on the compartment function type which determines if the fire growth is either slow (0:15h), medium (0:20h), or fast (0:25h). t_{max} determines the start of the decay phase, after which the temperature decreases linearly according one of the three equations presented above, until it reaches 20 degrees. Moreover, t_{max} also indicates the moment at which the maximum temperatures are reached.

Until now, the contribution of burning CLT is yet not included in the calculations. Brandon (2018) includes this by a thermal model calculation, described in the next paragraph.

8.1.3 CONTRIBUTION OF CLT

Brandon (2018) accounts for the contribution of CLT to the fire dynamic by considering additional fuel load over time, relating to charring of the timber.

8.1.3.1 CHAR DEPTH CALCULATIONS

As explained in chapter 4, the charring rate varies over time, due to the increased insulation capacity of the char layer. Several equations have until now been developed to determine the charring rate over time. Hadvig (1981) developed a method based on the heating rate factor, and the one-dimensional charring rate (β_0) presented in NEN-EN 1991-1-2 (2019). With this, the initial charring rate is calculated by:

$$\beta_{par} = 1{,}5\beta_0 * \frac{0{,}2\sqrt{\Gamma} - 0{,}04}{0{,}16\sqrt{\Gamma} + 0{,}08} \qquad \textit{Eq. 41}$$

The charring depth at any time is calculated by:

$$d_{char} = \beta_{par} * \mathrm{t} \qquad \textit{for} \quad t \leq t_0 \qquad \textit{Eq. 42}$$

$$d_{char} = \beta_{par}(1{,}5\mathrm{t} - \frac{t^2}{4t_0} - \frac{t_0}{4}) \qquad \textit{for} \quad t_0 \leq t \leq 3t_0 \qquad \textit{Eq. 43}$$

$$d_{char} = 2\beta_{par} * t_0 \qquad \textit{for} \quad t > 3t_0 \qquad \textit{Eq. 44}$$

Where:

β_{Par}	Is the initial charring rate, expressed in mm/min
t_0	Is the time at which the char rate reduces due insulation capacity of the char, expressed in min
d_{char}	Is the final char depth, expressed in mm

With this, the total char depth calculations over time are calculated by the following formulas presented in Table 10.

Table 10: Equations for charring depth

Step	Parameter	Equation	Unit
1	Initial charring rate	$\beta_{par} = 1{,}5\beta_0 * \frac{0{,}2\sqrt{\Gamma} - 0{,}04}{0{,}16\sqrt{\Gamma} + 0{,}08}$	[mm/min]
2	Time at which char rate reduces	$t_0^1 = 0{,}009\frac{q_{t,d}}{O}$	[min]
3	Final char depth	$d_{char}^1 = 2\beta_{par}t_0$	[mm]

8.1.3.2 Steps of iteration to include the contribution of CLT

The contribution of the burning of CLT to the fuel load in the compartment is calculated by an iterative manner, utilizing the formulas in Table 11.

Table 11: Equations for iterative contribution of CLT to fuel load

Step	Parameter	Equation	Unit
1	Total fuel load	$q_{td}^{i+1} = q_{fml} + \frac{A_{CLT} * \alpha_1 * (d_{char}^{i} - 0,7\beta_{par} * t_{max}^{1})}{A_c}$	[$m^{1/2}$]
2	Start time of decay	$\mathrm{t}_{\mathrm{max}}^{\mathrm{i+1}} = \max\left[\left(0,2 * 10^{-}3 * q_{t,d}^{i+1}/\mathrm{O}\right); \mathrm{t}_{\mathrm{lim}}\right]$	[hour]
3	Time at which char rathe reduces	$t_0^{i+1} = 0,009\,\frac{q_{t,d}^{i+1}}{O}$	[min]
4	Final char depth	$d_{char}^{i+1} = 2\beta_{par} t_0^{i+1}$	[mm]

The iterative process continues until the difference in char depth converges below 0,01mm or the fully developed phase exceeds 4 hours. The moment the char depth converges below 0,01mm, the start of the decay phase is initiated. If the fully developed phase exceeds 4 hours, it is considered that the design goes beyond limits and

8.2 THERMAL MODEL CALCULATION

In the previous section a method was presented to calculate the char depth of CLT to allow incorporating the contribution of CLT to the compartment fire dynamics. In this section an alternative method is used to calculate the thermal behaviour of the CLT based on a method presented by Swedish Wood (2019). The reason for this decision is to allow to calculate the influence of delamination and gypsum board protection. The methods are elaborated in the following paragraphs. The values used in design tool calculations are presented in appendix 4.

8.2.1 EFFECTIVE CROSS SECTION

The fire resistance of timber elements depends on the remaining cross section due to the damage after a fire, which is dependent on the burning behaviour and the affected heat zone (Barlett et al., 2019). In the Eurocode, the char rates are defined as fixed nominal values depending on the type of timber. Moreover, methods are provided to calculate and predicting the fire resistance of timber members. This is done by calculating the remaining cross-section after a fire due to the damage from the char layer and a heat affected zone. (NEN-EN 1991-1-2+C3, 2019) To calculate the effective cross section of the CLT therefore the residual cross section is calculated as:

$$h_{ef} = h_{CLT} - d_{ef} \quad \textit{Eq. 45}$$

$$d_{ef} = d_{char} + d_0 \quad \textit{Eq. 46}$$

Where:

h_{CLT}	Is the height of the CLT, expressed in mm, based on the number and thickness of the CLT lamellas
d_{char}	Is the char depth, expressed in mm
d_0	Is the zero-strength layer, expressed in mm

8.2.2 CHAR DEPTH

One dimensional charring should be used if the gap between 2 boards is less then 2mm. This means that charring will only occur from one side. If the boards are positioned such that the gap between the boards is greater than 2mm, nominal charring should be considered (Swedish wood, 2019) It is assumed that this is not the case. According to NEN-EN 1995-1-5+C2 (2011) the nominal charring rate is 0,65 mm/min however, the charring rate is highly dependent on the heat flux that the timber is exposed to (Barlett, 2019). As the 0,65 mm/min from the Eurocode is based on experiments in standard fires, where heat exposure is typically lower than in real mass timber compartment fires, this could potentially be lower than in real fire dynamics. The char depth over time for nominal charring is calculated by:

$$d_{char,0} = \beta_0 * t \quad \textit{Eq. 47}$$

Where:

β_0	Is the nominal charring rate, expressed in mm/min
t	Is the time at which the charring depth is needed, expressed in min

Delamination and encapsulation affect the char-rate. In the tool, therefore a distinction is made between three different types of CLT elements: (1) MUF adhesive, (2) PU adhesive and (3) fire rated encapsulation. These three affect the char depth over time. An example is presented in Figure 32. The calculations are presented in the following sections.

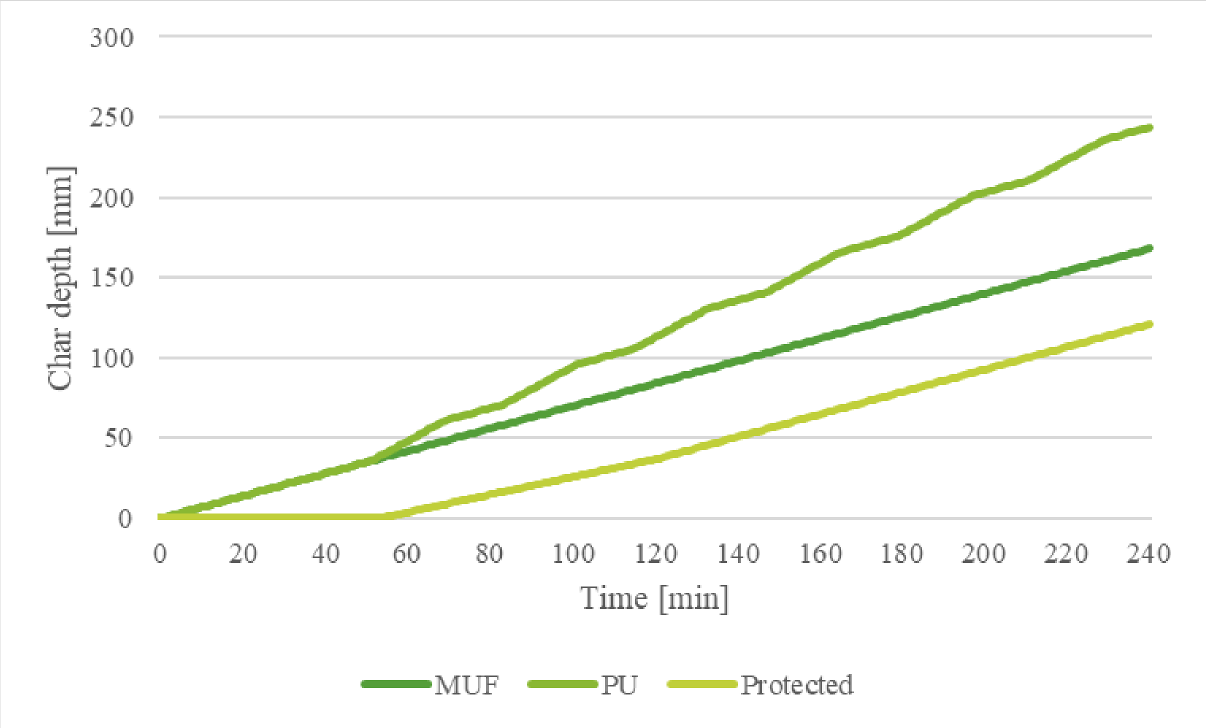


Figure 32: Char depth over time for MUF & PU adhesive and encapsulated CLT element.

8.2.2.1 Delamination

Delamination influences the charring speed, as new uncharred fresh timber suddenly gets exposed to high compartment fire temperatures (McGregor, 2013; Barlett et al., 2019). Whether or not delamination is expected depends on the timber adhesive. An MUF adhesive is fire resistant and will typically not result in delamination. For an CLT element with MUF adhesive, the char depth over time may be calculated according to Eq. 47 .

However, if a non-fire-resistant adhesive is used (typically a PUR adhesive) delamination may occur which results in increased charring for a specific time. Swedish Wood (2019) account for this by an increased charring rate of $2\beta_0$ over the first 25mm of each board after delamination. With this, the char depth over time for delamination of calculated by:

$$d_{char,0} = \beta_0 * t \qquad \textit{if} \quad d_{char} \leq t_{lam} \qquad \textit{Eq. 48}$$

$$d_{char,0} = 2 * \beta_0 * t \qquad \textit{if} \quad t_{lam} < d_{char} < t_{lam} + 25 \qquad \textit{Eq. 49}$$

Where:

β_0	Is the nominal charring rate, expressed in mm/min
t_{lam}	Is the thickness of one CLT lamella, expressed in mm
t_{lam}	Is the time, expressed in min

8.2.2.2 Encapsulated CLT

If a timber element is encapsulated by gypsum boards, the burning will be delayed as the encapsulation will act as an insulating layer. To calculate the delayed effect the method as presented by NEN-EN 1995-1-2+C2 (2011) section 3.4.3.1. and 3.4.3.2. are used. This method assumes that the fire rated gypsum board fails, after which the timber is exposed. However, for new types of fire rated gypsum boards it is expected that these will not fail, and therefore, the charring rate will not likely suddenly increase. In the design tool, this new type of encapsulation is considered in the calculation. With this assumption, the char depth for encapsulated CLT elements is calculated by:

$$d_{char} = 0 \qquad \text{if} \quad t \leq t_{ch} \qquad \text{Eq. 50}$$

$$d_{char} = k_2 * \beta_0 * t \qquad \text{if} \quad t_{ch} < t < t_f \qquad \text{Eq. 51}$$

$$d_{char} = \beta_0 * t \qquad \text{if} \quad t_f < t \qquad \text{Eq. 52}$$

Where:

β_0	Is the nominal charring rate, expressed in mm/min
t	Is the time, expressed in min
t_{ch}	Is the moment at which the timber starts charring due to lack of insulation capacity by the encapsulation panels (see equation Eq. 53), expressed in min
k_2	Is factor for the reduced charring rate at the moment the gypsum is still able to insulate, see Eq. 54
t_f	Is the moment at which the insulation capacity of the total encapsulation is lost, expressed in min

And for which the moment and which the timber starts charring, as well as factor for reduced charring are calculated by:

$$t_{ch} = 2{,}8h_{p,tot} - 14 \qquad \text{Eq. 53}$$

$$k_2 = 1 - 0{,}018h_{p,inner} \qquad \text{Eq. 54}$$

Where:

$h_{p,tot}$	Is the total thickness of the gypsum layers in mm, calculated by the number and thickness of the encapsulation.
$h_{p,inner}$	Is the thickness of the most inner layer

Moreover, for fire rated encapsulation it is assumed that delamination will not occur, as the encapsulation does not fail. This is independent on the adhesive type.

8.2.3 ZERO STRENGTH LAYER

In NEN-EN 1991-1-5 (2011), the zero-strength layer is a fixed value independent on the type of element defined as 7 mm. From previous research follows that this value does not result in a conservative estimation. Alternative zero-strength-layer depths are defined by Swedish Wood (2019). It is assumed that the fire-exposed floor elements are in tension, and the fire exposed wall elements are in compression. Based on this, the zero-strength layer is calculated by the formulas presented in Table 12.

Table 12: Zero strength layer, based on Swedish Wood (2019)

Number of lamellas	Unprotected floor element	Protected wall element	Unit
Floor elements			
3	$d_{0,floor} = \frac{h_{CLT}}{30} + 3{,}7$	$d_{0,floor} = 10$	[mm]
5	$d_{0,floor} = \frac{h_{CLT}}{100} + 10$	If 75< h_{CLT} <100 mm then: $d_{0,floor} = 34 - \frac{h_{CLT}}{4}$ Else: $d_{0,floor} = \frac{h_{CLT}}{35} + 6$	[mm]
7	If: 105< h_{CLT} <175 mm then: $d_{0,floor} = \frac{h_{CLT}}{6} + 2{,}5$ Else: $d_{0,floor} = 10$	Same as unprotected surface	[mm]
Wall elements			
3	$d_{0,wall} = \frac{h_{CLT}}{25} + 3{,}95$	$d_{0,wall} =$ $MIN(13{,}5; \frac{h_{CLT}}{12{,}5} + 7)$	[mm]
5	$d_{0,wall} = \frac{h_{CLT}}{15} + 10{,}5$	$d_{0,wall} = 10$	[mm]
7	If: 105< h_{CLT} <175 mm then: $d_{0,wall} = \frac{h_{CLT}}{6} + 4{,}0$ Else: $d_{0,floor} = 16$	Same as unprotected surface	[mm]

8.3 STRUCTURAL MODEL

In this section, the methods used to calculate the structural fire resistance of the CLT elements in the building are presented. Firstly, the general boundary conditions of the structural scheme are presented including the considered loads and strength calculations under normal non-fire conditions. After this, the methods to calculate the response to fire are presented. The values used in the calculation in the design tool calculations are presented in appendix 4.

8.3.1 STRUCTURAL SCHEME

A simplified structural scheme is created, considering load combinations based on values from NEN-EN 1995-1-2+C2 (2019) and calculation methods based on the document "*The CLT Handbook*" (Swedish wood, 2019). To determine the structural scheme, it is considered that the building is constructed from identical box-shaped compartments stacked on top of each other. The four outer walls are loadbearing façade walls. The CLT elements are transferring loads in one direction only, with panels all with a one-meter width. Moreover, it is assumed that the longitudinal walls carry the floor loads, the perpendicular walls only carry the vertical loads. Figure 33 presents an overview of the scheme.

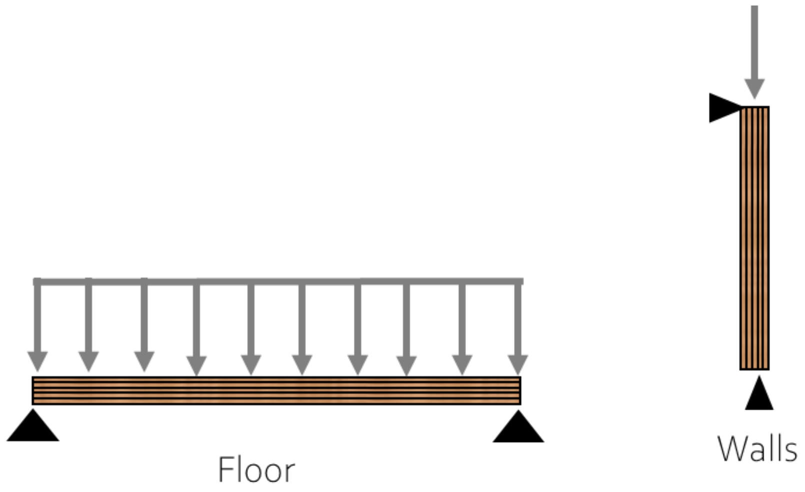


Figure 33: Structural scheme, consisting of characteristics wall and floor elements

8.3.2 DESIGN LOADS

In this research, the effect of wind loads is neglected, although for taller buildings, wind loads may become of significant importance. This neglection is supported by the assumption that for taller buildings a structural core will likely be required, which will provide the load distribution of horizontal loads.

The loads on the structure are simplified and consist of a combination of permanent loads, and self-weight of the CLT. For simplification, it is assumed that every compartment floor carries the same load. With this, the design load for the floor is calculated by:

$$Q_{Ed,floor} = \gamma_G * G_k + \gamma_{Q,1} * Q_{1,k} + \sum \gamma_{Q,i} * \Psi_{0,i} * Q_{i,k} \quad [kN/m^2] \quad \textit{Eq. 55}$$

Where:

Y_G	Is the partial factor for permanent loads
G_{ki}	Is the total permanent load
$Y_{Q,i}$	Is the partial factor for variable loads
Q_{ki}	Is the characteristic value of the leading variable load
$\Psi_{0,i}$	Is the factor for combination of variable load i with the leading variable load
Q_{ki}	Is the characteristic value of variable load.

The values for the load factors are determined as presented in Table 13 for two characteristic load combinations.

Table 13: Load factor values

Combination	Y_G Unfavorable	Y_G Favorable	$Y_{Q;1}$	$Y_{Q;i}$	Ψ_G
1	1,35	0,9	-	1,5	0,4
2	1,2	0,9	1,5	1,5	0,4

8.3.2.1 FLOOR LOADS

For the floor load, a permanent and variable load is considered as well as the deadweight of the floor elements themselves. The loads are calculated by:

$$M_{Ed} = \frac{1}{8} * Q_{Ed,floor} * L^2_{CLT,floor} \quad [kNm] \quad \textit{Eq. 56}$$

Where:

$Q_{ED,floor}$	Is the partial design floor load following from Eq. 55
$L_{CLT,floor}$	Is the length of the floor panels

The partial design load is calculated as the maximum of Eq. 57 and Eq. 58:

$$Q_{Ed,floor,1} = 1{,}35 * (G_{k,cement} + G_{k,CLT}) \quad \textit{Eq. 57}$$

$$Q_{Ed,floor,2} = 1{,}2 * (G_{k,cement} + G_{k,CLT}) + 1{,}5 * Q_{1,k} \quad \textit{Eq. 58}$$

Where:

$G_{k,cement}$	Is the self-weight of a considered cement screed
$G_{k,CLT}$	Is the self-weight of the CLT calculated by the thickness and number of lamellas and with a density
$Q_{1,k}$	Is the variable floor load, which complies with the distributed load of 1,75 kN/m^2 for floor loads in residential areas as presented by (NEN-EN-1991-1-1+C1+C11, tale 6.2, 2019)

8.3.2.2 WALL LOADS

It is assumed that throughout the building, the walls carry the normative load, consisting of half of the loads from the floor panels, as well as the load from the deadweight of the wall-panels of one building storey. This simplification is supported by the assumption that, although loads on the walls increase for the lowest compartments in the building, this is dealt with by a relative increase in the strength of the CLT, this way considering a consistent load-resistance ratio throughout the building. For simplification, wind loads are not considered. With these assumptions the characteristic load combination is the following:

$$F_{Ed,wall} = 1{,}35 * (G_{k,floorload} + G_{k,wallload}) \quad \textit{Eq. 59}$$

Where:

$G_{k,floor}$	Is the floor load distributed to one wall panel which is calculated by $\frac{q_{d,floor}}{2}$ in which $Q_{Ed,wall}$ is the characteristic floor load from Eq. 55
$G_{k,wall}$	Is the load of the one wall panel

With this, and considering the thickness of the panels, the design load is calculated as follows:

$$N_{Ed} = F_d * h_{clt} \quad \textit{Eq. 60}$$

Where:

h_{CLT}	Is the thickness of the wall panels, calculated by the number and thickness of the lamellas

The location of windows influences the load distribution, which may result in a wall panel carrying more load. This is incorporated in an additional factor, such that the characteristic load for structural wall panel may be manually altered with a factor: f_{load}.

8.3.2.3 LOADS DURING FIRE

The design loads for an element in fire are considered to be accidental loads, which means that the design loads may be reduced. A simplified method for the reduced load is presented in Swedishwood (2019) using the following formula:

$$E_{d,fi} = \eta_{fi*} E_d \quad \textit{Eq. 61}$$

Where:

E_d	Is the design load in ambient temperatures
η_{fi}	Is the reduction factor for the design load in the event of a fire, which for residential areas is recommended to be 0,6 as presented in Eurocode 1.

8.3.3 STRENGTH CALCULATION

To calculate the stresses of the elements, cross section properties of the CLT are calculated by using the formula's presented in Table 14 and visualized in Figure 34.

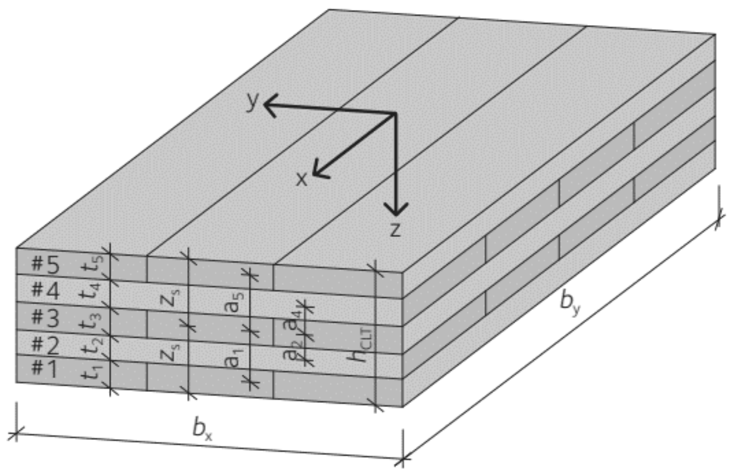


Figure 34: Cross-section characteristics (Figure by Swedish Wood, 2019 p.40)

Table 14: Cross-section property calculations

Parameter	Equation	Unit	Eq.
Effective height in x-direction	$h_x = t_1 + t_3 + t_5 + ..$	[mm]	Eq. 62
Effective height in y-direction	$h_y = t_2 + t_4 + ..$	[mm]	Eq. 63
Total height	$h_{CLT} = h_x + h_y$	[mm]	Eq. 64
Centre of gravity	$z_s = \frac{h_{CLT}}{2}$	[mm]	Eq. 65
Gross area	$A_{x,bruto} = b_x * h_{CLT}$	[mm²]	Eq. 66
Net area	$A_{x,net} = b_x * h_x$	[mm²]	Eq. 67
Net, moment of inertia	$I_{x,net} = \sum \frac{b_x * t_i^3}{12} + \sum b_x * t_i * a_i^2$	[mm³]	Eq. 68
Net, section modulus	$W_{x,net} = \frac{2I_{x,net}}{h_{CLT}}$	[mm³]	Eq. 69
Gamma values	$\gamma_i = \frac{1}{1 + \frac{\pi^2 E_{x,mean} t_i}{l_e^2} \frac{t_{i-1}}{G_{9090}}}$	[-]	Eq. 70
Effective moment of resistance	$I_{x,ef} = \sum \frac{b_x * t_i^3}{12} + \sum \gamma_i * b_x * t_i * a_i^2$	[mm³]	Eq. 71
Effective Radius of gyration	$i_{x,ef} = \sqrt{\frac{I_{x,ef}}{A_{x,net}}}$	[mm³]	Eq. 72
Slenderness factor	$\lambda_y = \frac{l_e}{i_{x,ef}}$	[m]	Eq. 73

Where:

$t_{1,2,3,etc}$	Is the thickness of the lamellas, expressed in mm
b_x	Is the width of the CLT panels, considered to be 1000mm
a_i	Is the distance between the local centre of gravity of a lamella and the centre of gravity of the total element, expressed in mm

8.3.3.1 FLOOR BENDING CAPACITY

It is assumed that the floor panels will fail due to bending stress. The formula used to calculate the bending stress in the floors is:

$$\sigma_{m,y,d} = \frac{M_{y,d}}{W_{x,net}} \leq f_{m,xlay,d} = k_{sys} * k_{mod} \frac{f_{m,xlay,k}}{\gamma_m} \qquad \textit{Eq. 74}$$

Where:

$M_{y,d}$	Is the design bending moment as calculated by Eq. 56
$W_{x,net}$	Is the net section modulus as calculated by Eq. 69
K_{sys}	Is the system strength factor
K_{mod}	Is the modification factor that takes into account service class and load duration
$f_{m,xlay,k}$	Is the bending strength of the loadbearing CLT panels, which is related to the strength class of the CLT
Y_m	Is the partial factor from material properties

8.3.3.2 WALL BUCKLING CAPACITY

It is assumed that the CLT wall panels will fail due to buckling. For this, it is assumed that there are only vertical loads and wind-loads are neglected. Moreover, only linear buckling is assumed for simplification reasons. With this, the formula used to calculate buckling stress in the walls is:

$$\sigma_{mcy,d} = \frac{N_d}{k_{c,y} * A_{x,net}} \leq f_{c,0,xlay,d} = k_{mod} \frac{f_{c,xlay,k}}{\gamma_m} \qquad \textit{Eq. 75}$$

Where:

$N_{y,d}$	Is the design vertical load as calculated by Eq. 60
$k_{c,y}$	Is the buckling factor, see Eq. 57
$A_{x,net}$	Is the net section area as calculated by Eq. 67
K_{mod}	Is the modification factor that takes into account service class and load duration
$f_{c,0,xlay,k}$	Is the compression strength of the loadbearing CLT panels
Y_m	Is the partial factor from material properties

Moreover, the buckling related factors are calculated by the following equations:

$$k_{c,y} = \frac{1}{k_y + \sqrt{k_y^2 - \lambda_{rel,y}^2}} \qquad \textit{Eq. 76}$$

$$k_y = 0,5 * (1 + 0,1(\lambda_{rel,y} - 0,3) + \lambda_{rel,y}^2) \qquad \textit{Eq. 77}$$

$$\lambda_{rel,y} = \frac{\lambda_y}{\pi} * \sqrt{\frac{f_{c,o,k}}{E_{0,05}}} \qquad \textit{Eq. 78}$$

8.3.4 STRUCTURAL FIRE RESISTANCE CALCULATIONS

In CLT elements the effective thickness of the element is dependent on the lamella thickness for the load bearing direction. The cross section over time reduces when timber is burning, which affects the strength. Figure 35 shows an overview of the affected residual strength due to increased char depth, in which h_{CLT} is the total height of the CLT, h_{lam} is the height of the lamellas, h_x is the total height of the lamellas with load bearing capacity in x-direction, and d_{char} is the char depth over time.

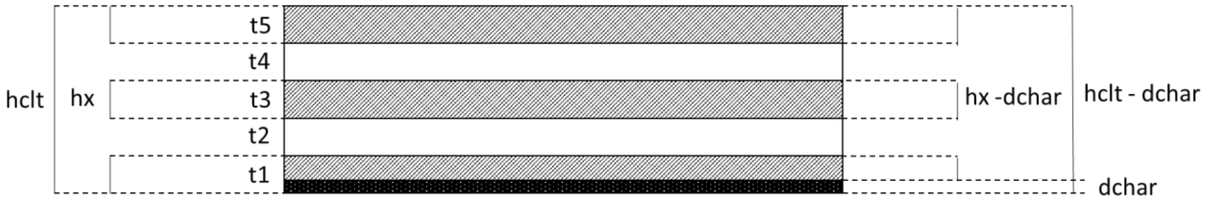


Figure 35: Cross-section calculations of charring CLT (Own figure)

For a homogeneous CLT element with five lamellas of similar thickness, the effective load bearing height for any given time is the following:

$$h_{eff,x} = h_x - d_{char,t} \quad \text{for} \quad d_{char} \leq h_{lam} \qquad \text{Eq. 79}$$

$$h_{eff,x} = h_x - h_{lam} \quad \text{for} \quad h_{lam} \leq d_{char} \leq 2h_{lam} \qquad \text{Eq. 80}$$

$$h_{eff,x} = h_x - (d_{char,t} + h_{lam}) \quad \text{for} \quad 2h_{lam} \leq d_{char} \leq 3h_{lam} \qquad \text{Eq. 81}$$

$$h_{eff,x} = h_x - 2h_{lam} \quad \text{for} \quad 3h_{lam} \leq d_{char} \leq 4h_{lam} \qquad \text{Eq. 82}$$

$$h_{eff,x} = h_x - (d_{char,t} + 2h_{lam}) \quad \text{for} \quad d_{char} > 4h_{lam} \qquad \text{Eq. 83}$$

The moment of structural failure is calculated by calculating the stress increase over time due to capacity loss. The calculation equations to determine the strength over time are similar as discussed in section 0, however, due to the char increasing over time, the cross-section properties from Table 14 must be modified in compliance with Figure 35. Beside the effective height ($h_{eff,x}$), the thickness of the board layers changes, the location of the centre of gravity (z_s) changes as well as the distance between the centre of the board layer and the CLT's neutral axis (a_i). With this, the structural strength over time can be calculated. Examples of the results of the calculations are presented in Figure 36 and Figure 37 for bending and buckling respectively.

From these results, the difference between the fire resistance for either fire resistant (MUF) or non-fire resistant (PU) adhesive is clearly shown, leading to a quicker moment of failure due to increased charring rate by delamination (PU). Also, the effect of protected CLT is clearly observed, in which the moment that timber starts burning is delayed.

It is noted that in the bending calculations, when the damage (char + zeros strength layer) is in a non-loadbearing layer, the stress reduces rather than remain constant which would be expected. This is explained by the combination of reducing structural height (h_{clt}) and the shift of a_i and t_i due to the burning of the CLT. This affects Wxnet and consequently the stress line. This is therefore not accurately accounted for in the calculation methods by Swedish Wood (2019).

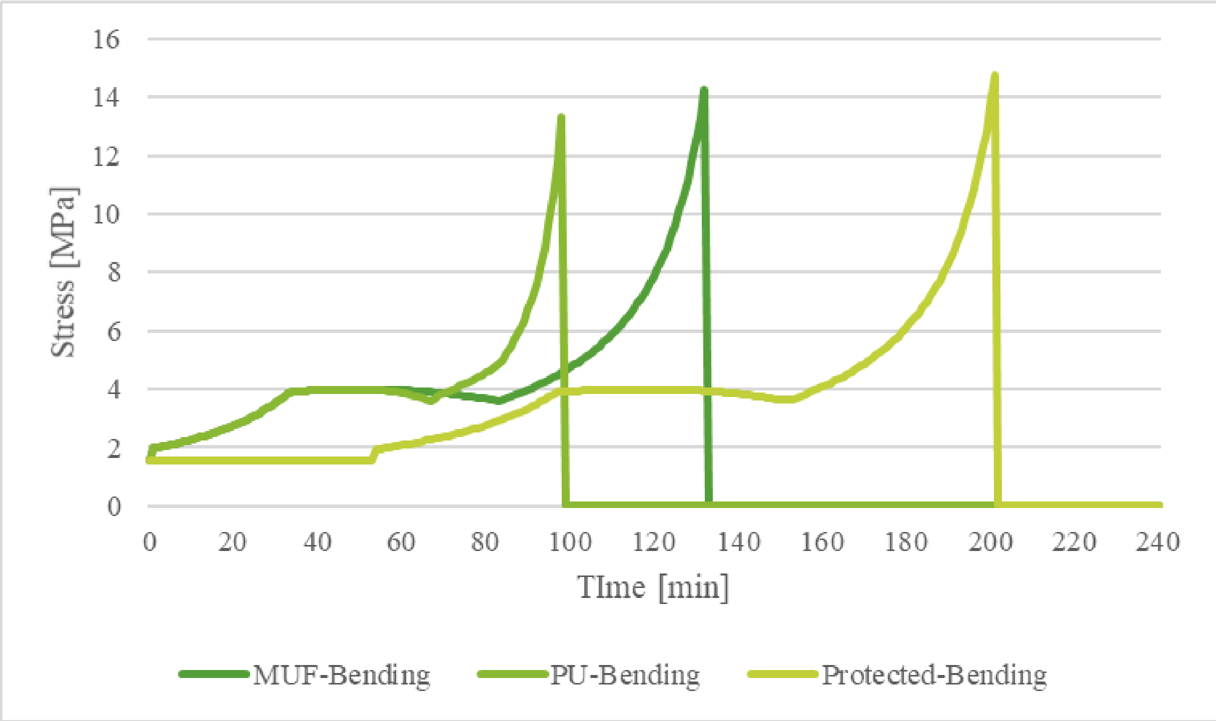


Figure 36: Examples of structural fire capacity for bending

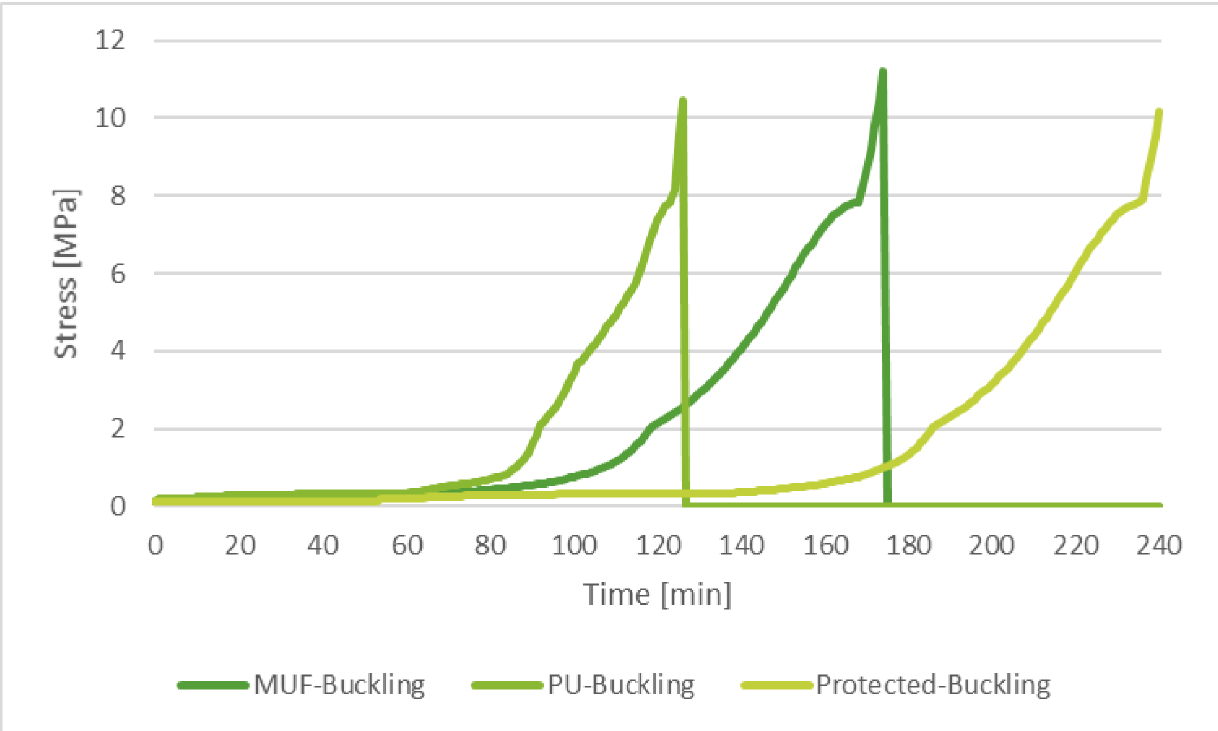


Figure 37: Examples of structural fire capacity for buckling over time

9 THE DESIGN TOOL

In this chapter the design tool is presented, in which previous methods are integrated such that material use and fire risk of the fire safety design in mass timber buildings is quantified. This chapter will show how to use the tool, and how the results can be interpretated. The use of the tool is presented by means of an example, which is then used to perform a variant study and this way provide results. With this chapter, it will be possible to answer the second research question which follows:

Q2: ***How can a circular design approach be used to quantify the relation between material use and fire risk for the fire safety design in mass timber buildings?***

In the design tool, the circular design approach from chapter 3 and integrated with the methods presented in chapters 6, 7 and 8. The main output is a quantification that provides the balance between material use and fire risk for the fire safety design in mass timber buildings, expressed as economic and environmental impact.

9.1 USE-MANUAL

In this section the steps are presented on how to use the design tool and how to interpret the results. The design tool is created in Excel® and consists of three main parts: (1) The user interface, (2) an overview of the considered parameters, and (3) the calculations.

In the user interface, the user can change certain design parameters. The effect that the change of parameters has on the results is calculated by the (hidden) tabs and presented as a visualized presentation in the user interface. This way, a better understanding of the impact of certain (fire safety) design measures on the balance between material use and fire risk is created.

The design tool can be used by following three steps, which are based on the steps presented in "The circular fire safety approach" flow chart which was earlier presented in Figure 13 in chapter 3. With this, the use of the tool consists of three steps:

Step 1: Implement the design specific parameters for a default (reference) design
Step 2: Analyse the results of the default design
Step 3: Perform a variant study by iteratively adjusting the fire safety design related parameters

By following these steps, the balance between material-use and fire risk is quantified, and comparison of different designs possible. In the following sections, the steps are elaborated based on an example. The overview of the additional data and parameters used in the calculations are presented in Appendix 4. The extended calculation of the presented example is presented in Appendix 5.

9.1.1 STEP 1: IMPLEMENT DESIGN PARAMETERS

The first step is to adjust the input parameters as according to the building specific design, presenting "default" or "starting point" design variant, from which the effect of alternative design choices can be compared. In Figure 38 the input design parameters for an example are presented. The input design parameters are divided into three categories: Building parameters, Compartment parameters and Fire safety design parameters. In the parameter overview, only the user adjustable parameters are presented.

9.1.1.1 BUILDING PARAMETERS

The building parameters define the number of storeys and the expected service life of the building.

- **Number of storeys**
  The focus of the research is residential buildings up to 70 meters. The maximum number of storeys is therefore 25
- **Service life**
  The service life of the building can be adjusted in accordance with the expected service life of the building

9.1.1.2 COMPARTMENT PARAMETERS

The compartment parameters present the dimensions of the considered compartments. In the tool, an overview of the dimensions is visualized in a figure. Besides this, a mid-ceiling beam can be implemented, and the percentage of the opening area adjusted.

- **Storey height**
  The storey height presents the height of one compartment, expressed in meters.
- **Width**
  The width of the compartment is defined as the distance that the floor/ceiling panels are spanning.
- **Length**
  The length of the compartment is the total length of the surfaces perpendicular to the width.
- **Mid-ceiling beam**
  From testing the structural calculations followed that the bending capacity of the floor elements is highly influenced by the span of the elements. Therefore, a mid-ceiling beam can be integrated in the design, this way dividing the span of the floor elements.
- **Opening height**
  The opening height is the average opening height of the total openings in the compartment
- **Total opening length**
  The total opening length is the total length of all openings of one compartment combined
- **Percentage open**
  The ventilation rate has a large influence on the fire dynamics. In normal building use situations, it is not expected that the openings are fully open. The expected opening percentage can therefore be adjusted.

9.1.1.3 CLT CHARACTERISTICS

The CLT characteristics are both building as fire safety related parameters, as CLT is part of the structure, though can be increased for additional fire resistance. The parameters defining the CLT characteristics are the adhesive type and cross-section properties.

- **Adhesive type**
  The type of adhesive used in CLT has a large influence on the expected fire dynamics and structural fire resistance, due to the potential effect of delamination. In the tool, a choice can be

made based on either fire-resistant adhesive (presented as MUF) or non-fire-resistant adhesive (presented as PU).

- **Floor and wall lamellas**
  The number of floor and wall lamellas can be independently defined by either 3, 5 or 7 lamellas.
- **Lamella thickness**
  The lamella thickness can be independently defined for floor and wall lamellas, though assuming identical thickness for all lamellas.

9.1.1.4 Sprinkler characteristics

The sprinkler characteristics in the design tool are defined by whether a sprinkler is available.

- **Sprinkler availability**
  The effect of a sprinkler can be considered by adjusting the input to “Yes”. If no sprinkler is considered in the design, the input should be changed to “No”.

9.1.1.5 Encapsulation characteristics

The encapsulation characteristics consist of percentage of encapsulated area, type, number of layers and thickness.

- **Percentage of encapsulation**
  If no encapsulation is available, the percentage of encapsulation should be defined as 0. If encapsulation is considered, the percentage can be changed. This is dependent of the location of the encapsulation.
- **Location of encapsulation**
  The location of the encapsulation can be defined as: “Ceiling”, “Walls” or “Ceiling and Walls”, and relates to the percentage of encapsulation. By this, if encapsulation is only located at the walls, the input should be changed to “Walls”. This indicates that the ceiling is fully exposed. If a certain percentage of the total surfaces (ceiling and walls combined) is encapsulated, the input should be changed to “Ceiling and Walls”.
- **Type of encapsulation**
  The type of encapsulation used in the design affects the fire risk relating to probability of extinguishing and structural fire resistance if the encapsulation can fail and this way expose fresh unburned timber to high temperatures. This effect can be considered by adjusting the type of encapsulation “Normal” in case the encapsulation can fail, or “Fibre reinforced” in case a specific type of encapsulation is used which will not fail. If no encapsulation is used, the input should be changed to “None”. It must be noted that the type of encapsulation only affects the risk in the design, the material use is considered to be the same, defined by “Fibre reinforced” encapsulation from Promat.
- **Thickness of encapsulation layers**
  The thickness of the encapsulation can be chosen to either be 10 or 12mm. In case no encapsulation is available the thickness should be defined as 0.
- **Number of encapsulation layers**
  The number of encapsulation layers can be defined as 1,2 or 3. In case no encapsulation is applied, the number of layers should be defined as 0.

Design parameters

In this sheet, the user defines the design specific parameters. By changing the fire safety design measures, it is possible to determine how this affects the results on the banalce between material use and fire risk.

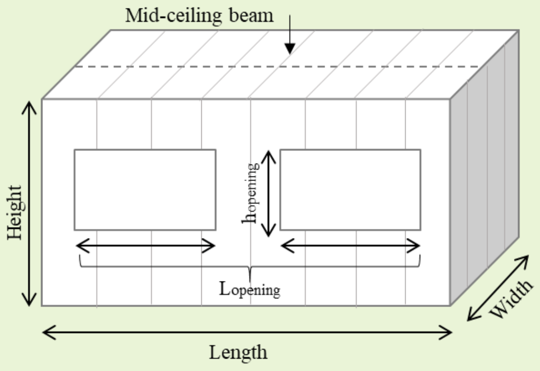
Building dimensions and characteristics

Building characteristics

Parameters	**Value**	**Unit**
Number of storeys	25	[-]
Service life	100	[years]

Compartment characteristics

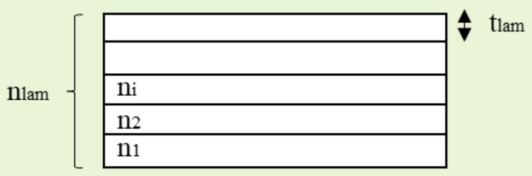
Parameters	**Value**	**Unit**
Storey height	2,73	[m]
Width	7	[m]
Length	20	[m]
Mid ceiling-beam	Yes	[-]
Opening height	1,78	[m]
Total opening length	11,5	[m]
Percentage open	100	[%]



Fire safety design relating measures

CLT characteristics

Parameters	**Value**	**Unit**
Adhesive type	MUF	[-]
Floor lamellas	5	[-]
Wall lamellas	5	[-]
Thickness floor lam.	35	[mm]
Thickness wall lam.	35	[mm]



Sprinkler availability

Parameter	**Value**	**Unit**
Sprinkler availability	Yes	[-]

Encapsulation characteristics

Parameters	**Value**	**Unit**
Percentage	70,00	[%]
Location	Ceiling & walls	[-]
Type	Fibre reinforced	[-]
Number of layers	2	[-]
Thickness	12	[mm]

Figure 38 ; Example of design input parameters for design tool step 1

9.1.2 Step 2: Analyse results for default building design

In step 2, the results of the default building design are analysed. The user interface in the design tool provides an overview of the most important results, which can either be presented for economic or environmental impact. In Figure 39 and Figure 40 the overview of the results from the design tool for the considered example is presented, representing the economic impact.

The general interpretation of the overview of the results is explained in the following sections. The elaborate interpretation of the results of the example is presented in Appendix 5.

9.1.2.1 Resistance results

The fire resistance results present an overview of the values for the amount of time that fire resistance is required according to the Eurocode (NEN-EN 1991-1-2+C3, 2019) and the fire duration and fire resistance time calculated by the design tool.

This overview immediately presents whether the design meets the resistance requirements presented by the regulations, meaning that the required structural resistance should at least be lower than the calculated moment of failure of floor and wall elements. The moment of calculated extinguishing provides an idea of the risk of the design. If the calculated values exceed 240 min, the moment of extinguishing is not calculated, and the result states “>240” for the extinguishing time and the moment of failure.

9.1.2.2 Total impact results

The total impact results present the balance between material use and fire risk of the design, which can be either expressed in economic or environmental impact. In Figure 39, the economic impact is considered. The costs and benefits represent the material use of the building, and the risk the relating fire risk. The total impact presents the “total circular fire safety value” which presents the threshold value which will allow comparison of the impact of different fire safety design alternatives.

9.1.2.3 Material use results

An elaborate output of the material use results is resented by showing the contribution of the building elements based on material costs and material benefits. Here, the costs present the economic or environmental cost for the total material needed during the service life of the building. The benefits present the end-of-life value of the building elements. The costs and benefits combined present the total material use impact.

This way it is possible to compare the effect of linear and circular design on the total impact.

9.1.2.4 In depth risk-results

To increase the understanding of the risk-calculation, the design tool presents an overview of the most important results of the fire risk calculation. The output of the results is presented in Figure 40. The sheet answers the questions on the left by presenting the probability of the specific answer. With this, the total probability of the fire scenarios is presented, followed by the impact, and relating fire risk.

Moreover, the tool visualizes the calculated fire dynamics and fire resistance, presenting conditions without a sprinkler.

Result analysis

This sheet summarizes the main results if the design tool. The first results relate to fire resistance. The total impact reaults present the balance between material use and fire risk. Moreover, in depth results of the material use calculations is presented.

Overview of results

Resistance results

Parameters	**Value**	**Unit**
Required resistance (EC)	120,0	[min]
Moment of calculated ext.	82	[min]
Moment of floor failure	133	[min]
Moment of wall failure	175	[min]

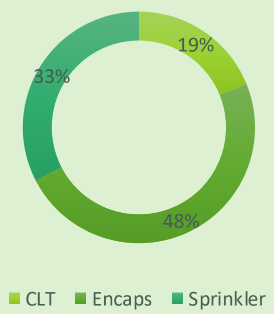
Total impact results

Impact:		**Economic**
Costs	€	3.092.547,95
Benefits	€	-1.537.656,98
Risk	€	44.665,42
Total	**€**	**1.599.556,39**

In depth results for material use

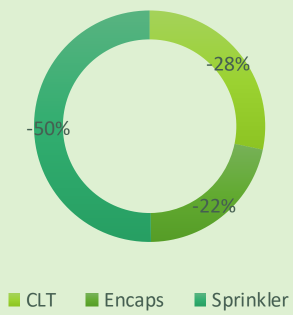
Material cost

Impact:		**Economic**
CLT	€	583.953,13
Encaps	€	1.501.094,83
Sprinkler	€	1.007.500,00



End-of-life benefit

Impact		**Economic**
CLT	€	-434.315,14
Encaps	€	-331.591,85
Sprinkler	€	-771.750,00



Total material impact

Impact		**Economic**
CLT	€	149.637,99
Encaps.	€	1.169.502,98
Sprinkler	€	235.750,00

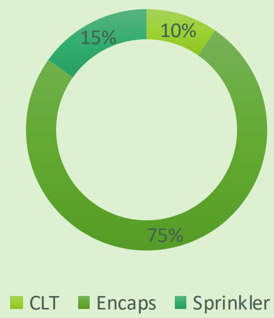


Figure 39: Example of step 2 of design tool

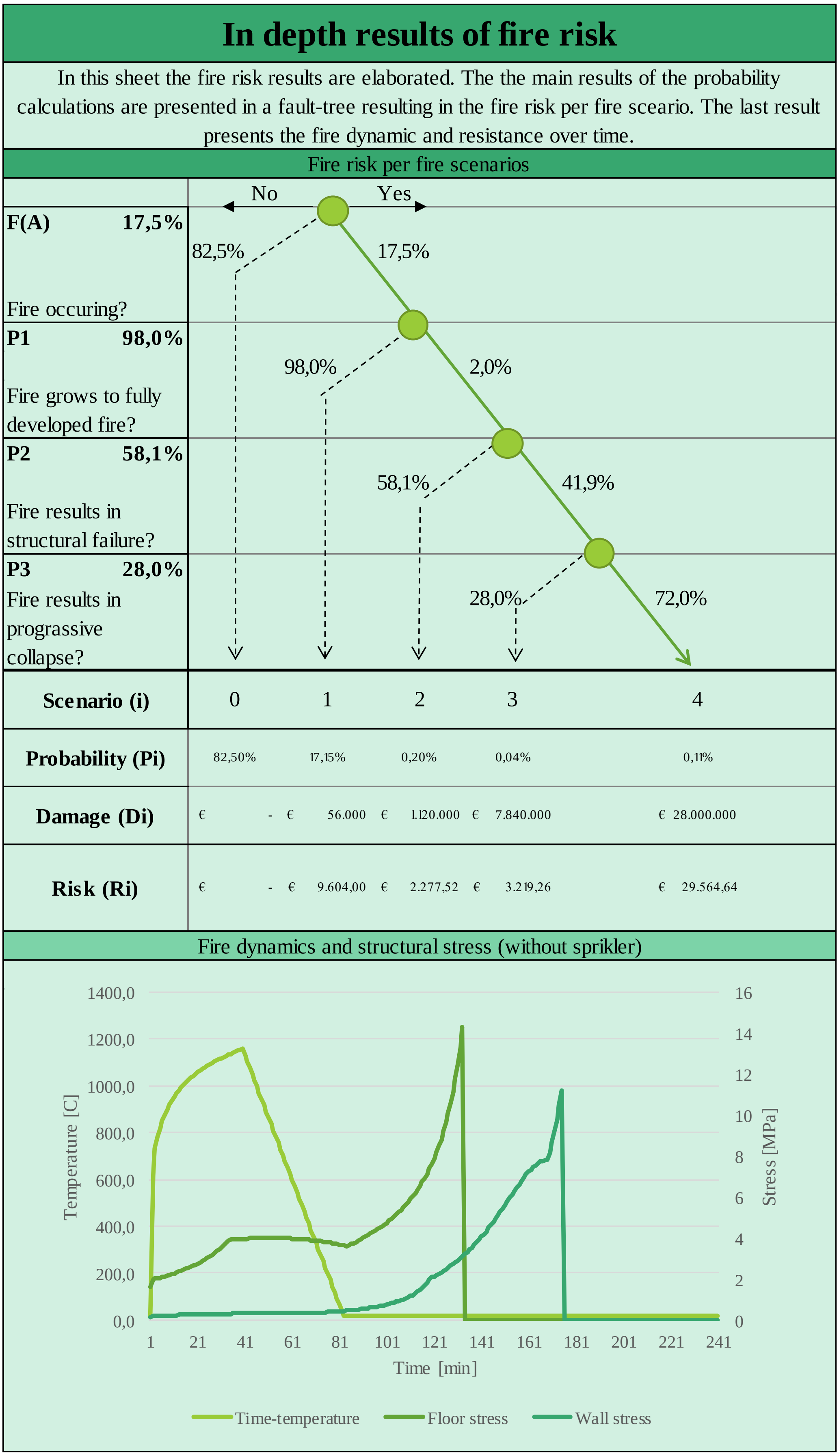


Figure 40: Example of design tool step 2: In depth results of fire risks

9.1.3 Step 3: Variant study

In the third step, a variant study can be done. In this step, the effect of different or alternative fire safety measures on the results can be examined, by iteratively changing the input parameters. This step therefore consists of two extra steps:

Step 3.1: Adjusting parameters for fire safety measures and
Step 3.2: Analysis of the effect on the results

In section 9.2, an elaborate variant study is done, based on two building designs. In the following sections, the steps are shortly discussed.

9.1.3.1 Step 3.1: Adjust fire safety related parameters

The adjustment of the fire safety measures can be done by changing the fire safety related parameters as presented in Figure 38. This consists of CLT, encapsulation and sprinkler related input.

9.1.3.2 Step 3.2: Analyse the effect on the results

By iteratively changing the fire safety design related parameters, the results in the user-interface change. This presents the influence of a certain measure on the balance between material use and fire risk, which can go either up or down.

If the calculated impact for material use increases due to a change in design, the design measure negatively effects the impact on material use. If the calculated risk increases, the design measure negatively affects the fire risk.

The balance between material-use and fire risk is integrated to one value: “circular fire safety impact value”. This value can go up or down, in which up presents a negative impact of a design considering material-risk relation. If the value goes down, the design has a positive effect on the material-risk relation. It is this way possible to compare different fire safety designs and this way define the ultimate fire safety design for the building specific design. The optimal design variant is the combination of design measures leading to the lowest total “circular fire safety impact” value.

**It should be noted that comparison of the fire safety design on the impact is only sufficient if comparison is done between designs with similar building and compartment characteristics.*

9.2 DESIGN VARIANT STUDY

In this section, the influence of different fire safety design variants is tested by using the design tool. Here, six different fire safety design variants are tested for two different building designs. Design 1 has a compartment area of 48 m^2. Design 2 is the building design presented as input example in Section 9.1, with a compartment area of 140 m^2. The study is done for a varying building height up to 25 storeys. This will allow comparison between the influence of design variants for different building size and height.

This section focusses on the main results provided the design tool user-phase. For an elaborate generation of results, refer to the example presented in Appendix 5, in which all results and calculation steps performed by the design tool is presented for one example design variant.

9.2.1 DESIGN CHARACTERISTICS

Design 1 and 2 are, apart from compartment size and ventilation opening, similar, such that the influence of compartment size on the results can be investigated. Design 1 has a building length of 6,85 m, which results in a compartment GFA of 48 m^2 and Design 2 has a building length of 20 m, which result in a compartment GFA of 140 m^2. Besides this, the total opening length deviates, which is 4,5m for Design 1 and 11,5 m for Design 2. The adjustment of the opening length is done to represent similar ventilation rates in the two designs such that the fire dynamics are similar for both designs. The number of storeys is iteratively changed to allow understanding of the impact relating to building height. Table 15 presents an overview of the input parameters of both building designs.

Table 15: Overview of design input parameters for Design 1 and Design 2

Parameter	Unit	Design 1	Design 2
Building characteristics			
Number of storeys	[-]	1-25	1-25
Service life	[year]	100	100
Compartment characteristics			
Storey height	[m]	2,73	2,73
Width	[m]	7,0	7,0
Length	[m]	6,85	20,0
Mid-ceiling beam	[-]	Yes	Yes
Opening height	[m]	1,78	1,78
Total opening length	[m]	4,5	11,5
Percentage open	[%]	100	100

9.2.1.1 Design variants

Six different fire safety design variants are investigated. The different variants are visualized in Figure 41, in which variant 1 presents a building with fully exposed surfaces, variant 2 presents a variant in which 30% of the surfaces are exposed (both ceiling and walls) and variant 3 is a fully encapsulated compartment. Variant 4 to 6 present similar fire safety designs, though including an automatic sprinkler system. It is assumed that the CLT characteristics for all variants is similar. The input parameters for the six variants in the design tool are presented in Table 16: Characteristics of design variantsTable 16.

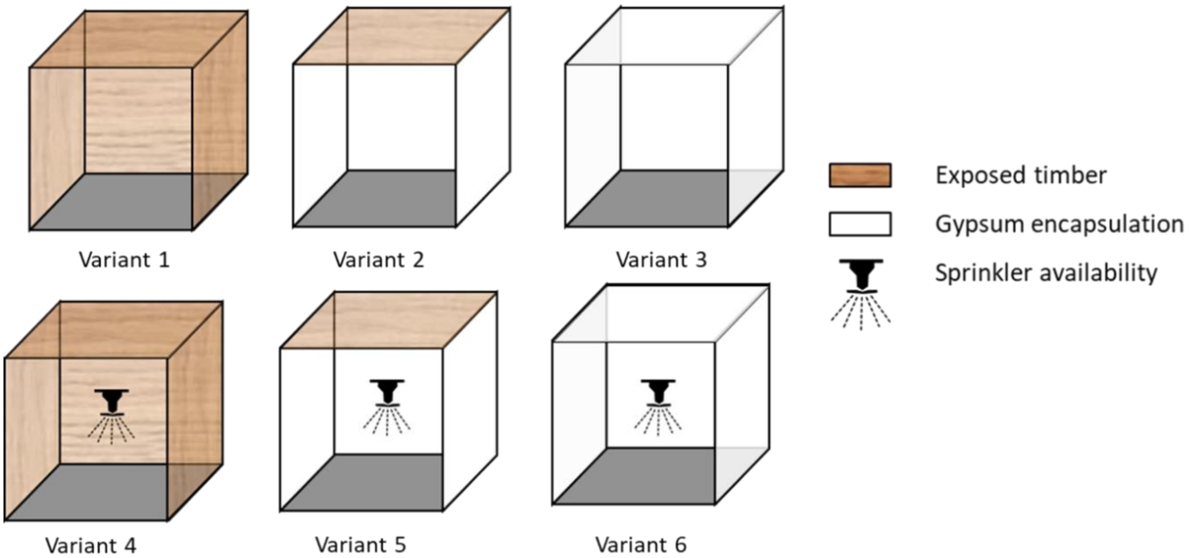


Figure 41: Design variants

Table 16: Characteristics of design variants

Parameter	Unit	Variant 1	Variant 2	Variant 3	Variant 4	Variant 5	Variant 6
CLT characteristics							
Adhesive type	[-]	MUF	MUF	MUF	MUF	MUF	MUF
Floor lamellas	[-]	5	5	5	5	5	5
Wall lamellas	[-]	5	5	5	5	5	5
Lamella thickness floor	[mm]	35	35	35	35	35	35
Lamella thickness wall	[mm]	35	35	35	35	35	35
Sprinkler availability							
Sprinkler availability	[-]	No	No	No	Yes	Yes	Yes
Encapsulation characteristics							
Percentage	[%]	0	70	100	0	70	100
Location	[-]	-	Ceiling & walls	Ceiling & walls	-	Ceiling & walls	Ceiling & walls
Type	[-]	-	Fibre reinforced	Fibre reinforced	-	Fibre reinforced	Fibre reinforced
Number of layers	[-]	-	2	2	-	2	2
Thickness	[mm]	-	2	2	-	2	2

9.2.2 Results of Design 1: Compartment GFA of 48 m2

In this section, the results of the six design variants of Design 1 are analysed, based on the output presented by the user-interface of the design tool. The design variants are tested for different building heights, varying between 1 and 25 storey buildings.

9.2.2.1 Resistance results

The first results that are presented in the tool are the fire resistance related results. An overview of the results is presented in Table 17. The results of variant 1&4, 2&5 and 3&6 are similar, as the tool does not consider the effect of the sprinkler on these results.

Table 17: Fire resistance results Design 1

Parameter	Unit	Variant 1&4	Variant 2&5	Variant 3&6
1-storey building				
Required resistance (EC)	[min]	60	60	60
Moment of calculated ext.	[min]	>240	79	63
Moment of floor failure	[min]	133	133	202
Moment of wall failure	[min]	175	175	>240
25-storey building				
Required resistance (EC)	[min]	120	120	120
Moment of calculated ext.	[min]	>240	79	63
Moment of floor failure	[min]	133	133	202
Moment of wall failure	[min]	175	175	>240

From Table 17 follows that the required resistance (as stated by NEN-EN 1991-1-2) varies between 60 minutes for a one-storey building up to 120 min for a 25-storey building, independent on the design variant. The moment of calculated extinguishing is more than 240 minutes for design variant 1, 79 minutes for variant 2, and 63 minutes for variant 3. The reduction in moment of extinguishing is due to the decreased percentage of exposed CLT surfaces. The moment of calculated extinguishing is independent of the building height. The moment of calculated floor and wall failure are similar for design variants 1&4 and 2&5, which is explained by the failure time of the most dominant CLT elements, which are not encapsulated for variant 1&4 and 2&5. For variant 3&6, the moment of structural failure increases, as all structural elements are encapsulated (100% encapsulated for Ceiling & floor, see Table 15). The moment of structural failure is independent on building height, due to considered constant load on elements.

It is observed that the moment of structural failure for floor and wall elements for all design variants meet the requirements stated by NEN-EN 1991-1-2 regarding the fire resistance time, for a 1-, as well as a 25-storey building. The calculated fire dynamics and resistance of the variants are visualized in Figure 42, Figure 43 and Figure 44.

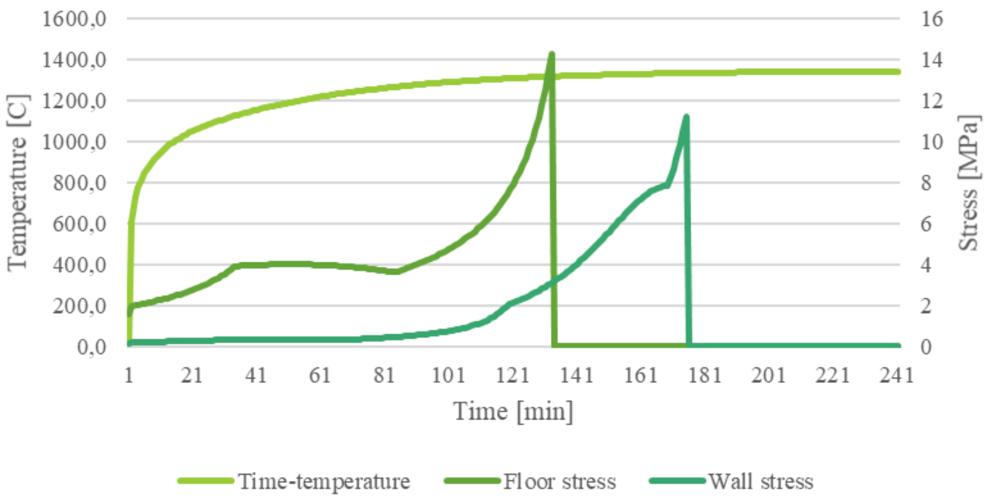


Figure 42: Results fire dynamic and resistance for Design 1 variant 1 & 4

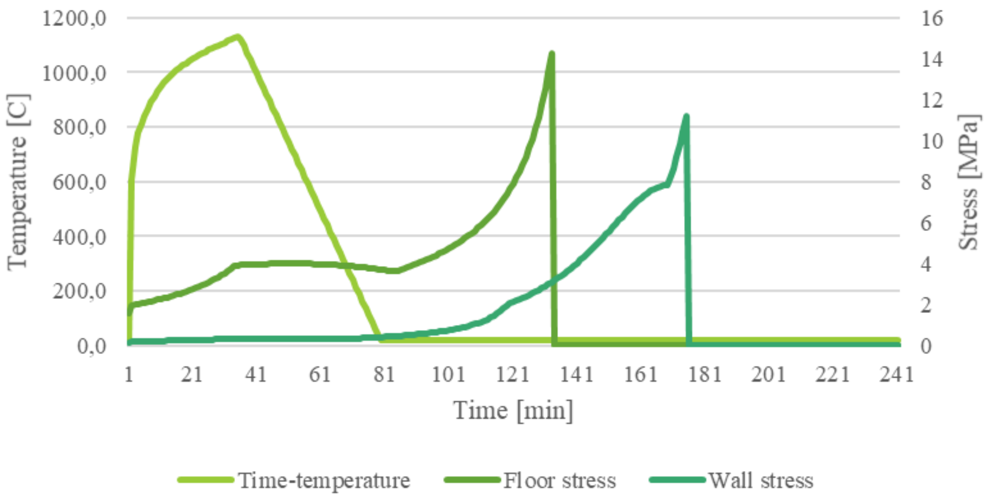


Figure 43: Results fire dynamic and resistance for Design 1 variant 2 & 5

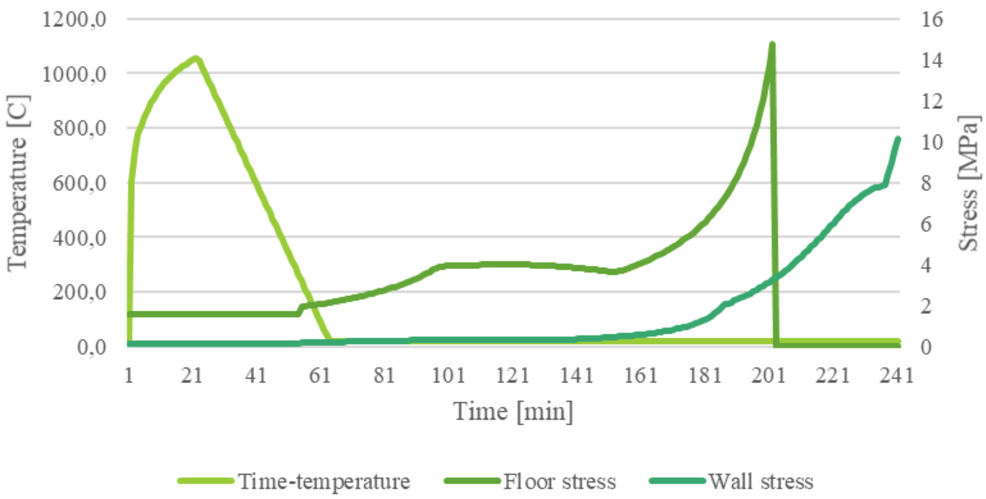


Figure 44: Results fire dynamic and resistance for Design 1 variant 3 & 6

9.2.2.2 Material use for fire safety measures

The impact on material use for the fire safety measures is determined by a life cycle analysis of the elements, in which the costs for material input and the benefits for end-of-life element value are integrated to one value representing the material use. The design tool calculates the material cost and end-of-life circularity benefit of the different building materials for both economic and environmental impact.

The results are generated for the six design variants, for a 1- and a 25-storey building. The results of the economic impact for the material use of the designs are summarized in Table 18, in which the impact per fire-safety elements is presented. The results are visualized in Figure 45 and Figure 46 the next page.

Table 18: Results of economic material use of design variants

Parameter	Unit	Variant 1	Variant 2	Variant 3	Variant 4	Variant 5	Variant 6
Costs							
1-storey building							
CLT	[€]	10.112	10.112	10.112	10.112	10.112	10.112
Encapsulation	[€]	0	23.668	30.036	0	23.668	30.036
Sprinkler	[€]	0	0	0	161.748	161.748	161.748
Total	[€]	10.112	33.779	40.148	171.859	195.527	201.896
25-storey building							
CLT	[€]	252.790	252.790	252.790	252.790	252.790	252.790
Encapsulation	[€]	0	591.697	750.908	0	591.697	750.908
Sprinkler	[€]	0	0	0	443.694	443.694	443.694
Total	[€]	252.790	844.487	1.003.698	696.483	1.288.181	1.447.391
Benefits							
1-storey building							
CLT	[€]	-7520	-7520	-7520	-7520	-7520	-7520
Encapsulation	[€]	0	-5228	-6635	0	-5228	-6635
Sprinkler	[€]	0	0	0	-10573	-10573	-10573
Total	[€]	-7520	-12749	-14156	-18093	-23322	-24728
25-storey building							
CLT	[€]	-188012	-188012	-188012	-188012	-188012	-188012
Encapsulation	[€]	0	-130706	-165876	0	-130706	-165876
Sprinkler	[€]	0	0	0	-264324	-264324	-264324
Total	[€]	-188012	-318718	-353888	-452337	-583043	-618212
Total material use							
1-storey building							
CLT	[€]	2592	2592	2592	2592	2592	2592
Encapsulation	[€]	0	18440	23401	0	18440	23401
Sprinkler	[€]	0	0	0	151175	151175	151175
Total	[€]	2592	21032	25993	153767	172207	177168
25-storey building							
CLT	[€]	64778	64778	64778	64778	64778	64778
Encapsulation	[€]	0	460991	585032	0	460991	585032
Sprinkler	[€]	0	0	0	179370	179370	179370
Total	[€]	64778	525769	649810	244146	705138	829179

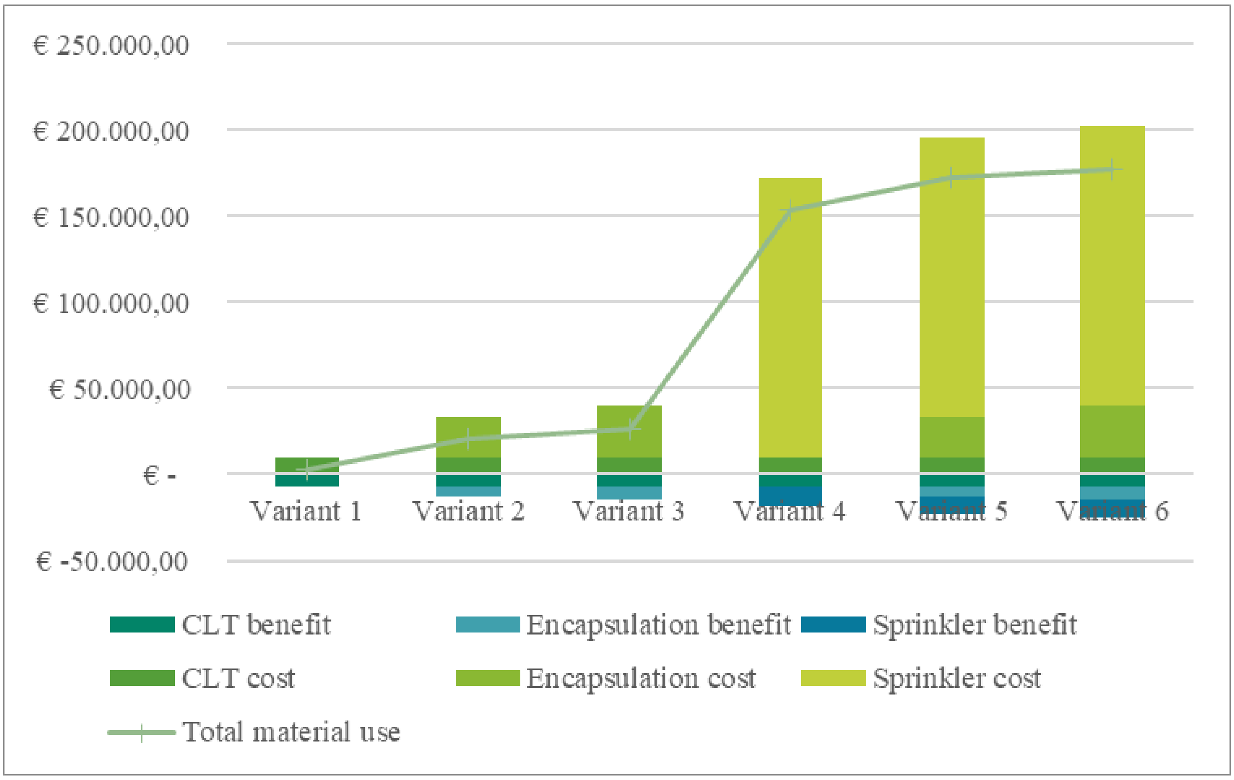


Figure 45: Economic impact for material use - Design 1 - 1-storey building

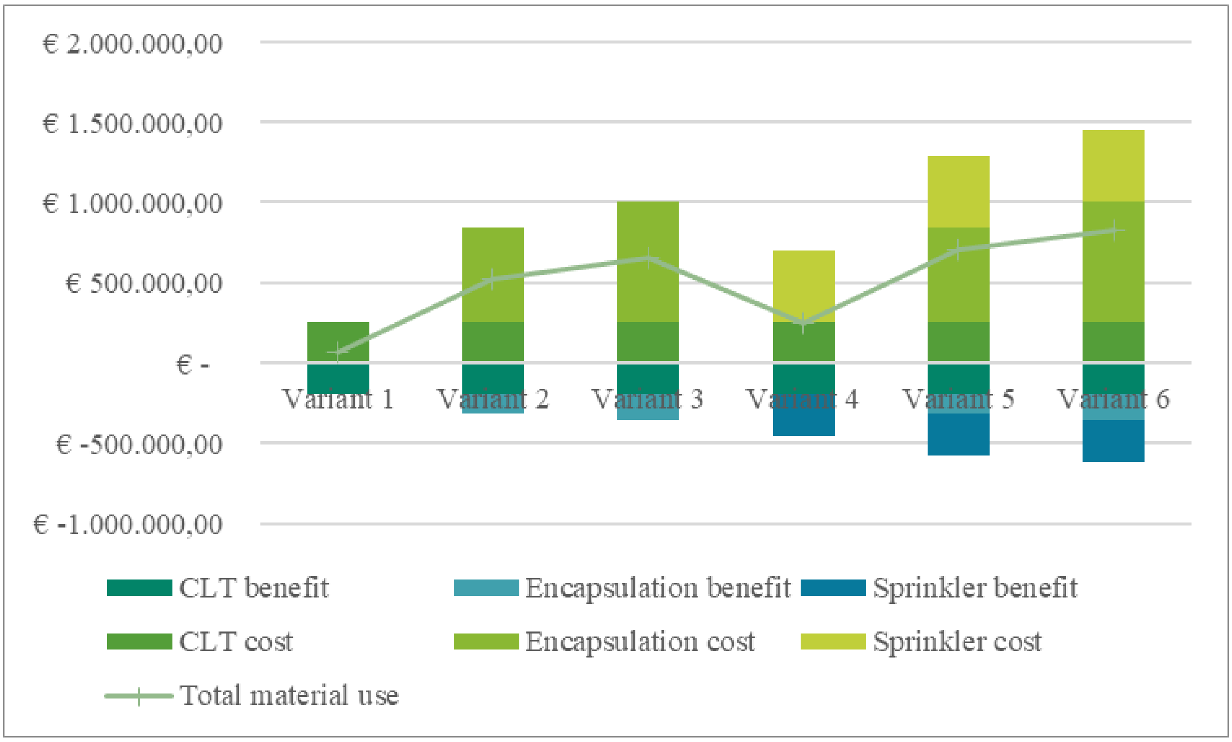


Figure 46: Economic impact for material use - Design 1 – 25-storey building

From the results follows that the cost for all design variants increase linearly over the building height, though with higher initial cost for the variants in which a sprinkler is available. It is observed that the encapsulation costs accounts for a significant part of the costs for the non-sprinklered design variants. For both 1- and 25-storey buildings, the contribution of encapsulation to the costs is significant, accounting for 70% of the costs for variant 2 and 75% for variant 3.

Moreover, it is observed that for a one storey building the availability of a sprinkler has a significant effect on the total costs, accounting for 94% of the costs for variant 4, 83% of the costs for variant 5 and 80% for variant 6. For the buildings with 25 storeys, the share of the sprinkler to the total costs decreases, resulting in 64% for variant 4, 34% for variant 5, and 31% for variant 6. For variant 5 and 6 for a 25-storey building, the encapsulation accounts for the biggest share in cost of 46% and 52% respectively.

Comparing the costs of a 1- and 25-storey building, it is observed that for a 1-storey building, the additional cost of a sprinkler is very high, whereas for a 25-storey building the cost of a sprinkler is only a relative part of the total cost. This is explained by the high initial costs of a sprinkler system due to the central unit that is required for a sprinkler installation, and the reduced relative increase of costs for increased building height. Comparing variant 2, 3 and 4 of the 25-storey building, it is observed that a sprinkler installation even is preferred over the cost of encapsulation as variant 4 results in a smaller total cost compared to variant 2 and 3.

The results of the benefits shows that all variants result in a linear increase of benefits for building height, which is due to the considered linear increase of material per building storey and the neglected effect of the central unit of the sprinkler. It is observed that the benefit of the CLT is dominant over the benefit of encapsulation, by 59% for variant 2 and 53% for variant 3. Moreover, it is observed that for the variants including a sprinkler, the sprinkler provides the highest end-of-life benefit, resulting in 58%, 45%, and 43% for variant 4, 5, and 6 respectively.

When looking at the total impact for material use of the designs (cost – benefit), it is observed that variant 1 presents the most favourable design variant for both a 1- and 25-storey building, which is a reasonable outcome considering that for the other designs a similar amount of CLT is used, though with additional fire safety measures, and thus increased material use. It is observed that for a 1-storey building, the variants without a sprinkler are favourable over the designs without a sprinkler, whereas for a 25-storey building variant 4 (with a sprinkler) is favourable over design 2 and 3 (without sprinkler with encapsulation).

In Figure 47, the economic impact for the material use for a building with 1- up to 25-storey buildings is presented. It is observed that, from a material use perspective, a sprinkler is beneficial compared to encapsulation for the examined building design in case the building is higher than 8 storeys (21,8m).

Besides the economic impact, the tool also calculates the environmental impact. The results of the environmental for the design for 1- up to 25-storey building is presented in Figure 47. It is observed that the environmental impact is comparable to the economic impact, though design variant 4 becomes favourable after 7-storey (19m). Based on both economic and environmental results, it can be stated that, from a material circularity perspective, the benefits of a sprinkler compared to encapsulation is dependent on the building height, in this case above 7 storeys if considering both environmental and economic impact.

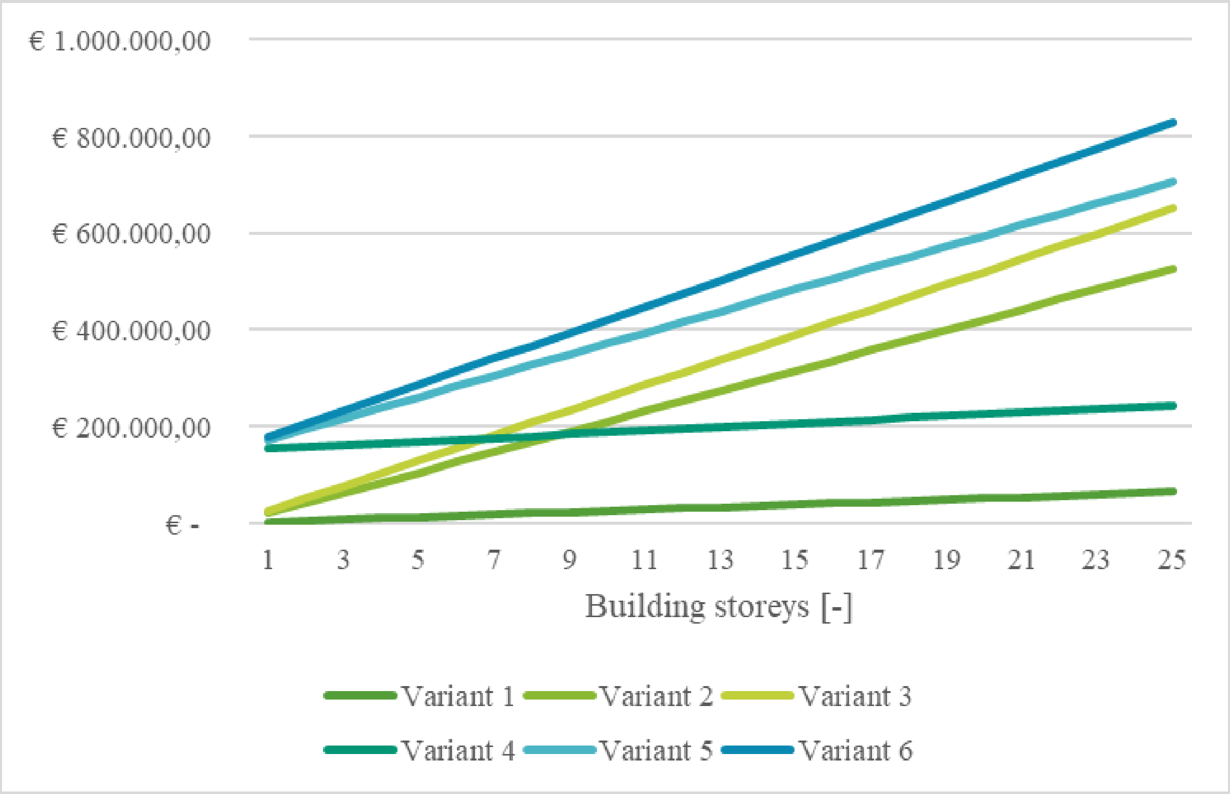


Figure 47: Economic impact for material use (Cost – Benefit) - Design 1

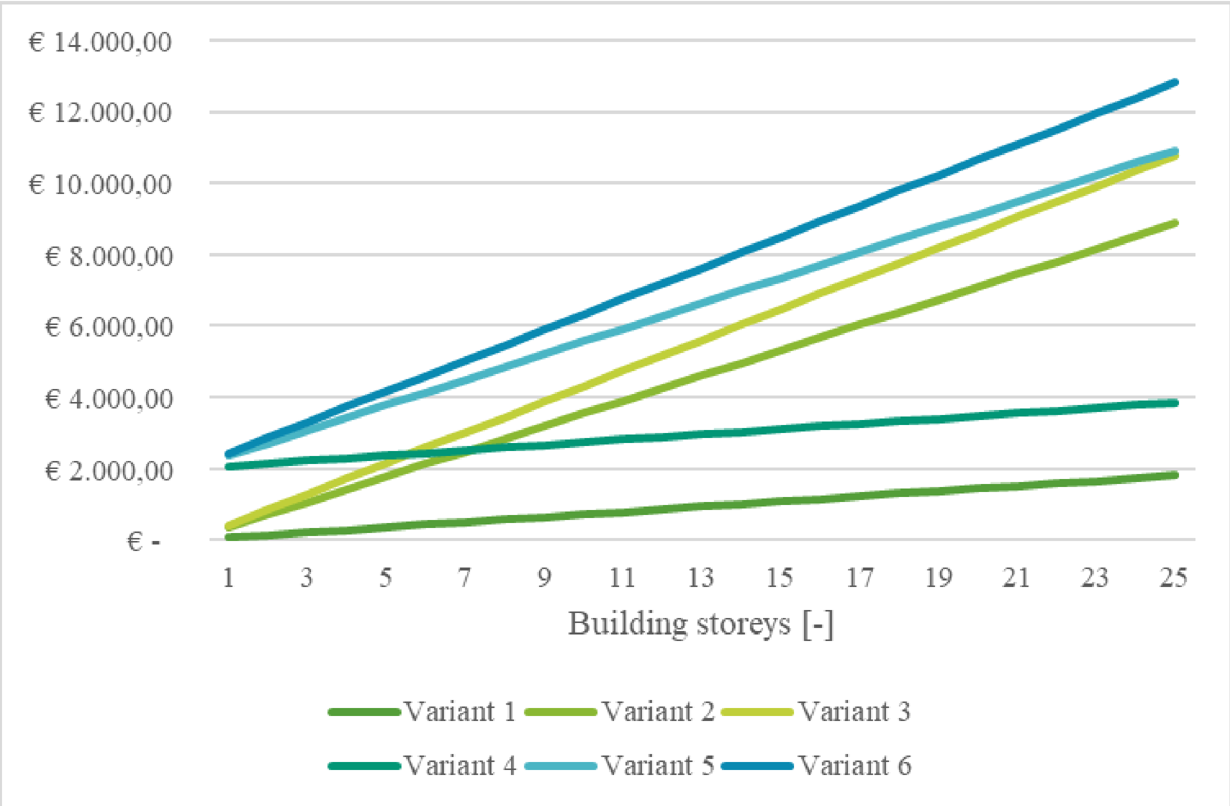


Figure 48: Environmental impact for material use (Cost – Benefit) - Design 1

9.2.2.3 Fire risk/resilience results

The design tool calculates the fire risk and presents the most important results in the user-interface as a fault-tree, in which the probability of different fire scenarios is presented. The results of the probability calculations are similar for economic and environmental impact. The damage and risk are calculated for both economic and environmental impact.

In Table 19, the results of the economic risk-calculations for the different design variants for a 1-storey building are presented, further visualized in Figure 49. In Table 19, the results of the economic risk-calculations for the different design variants for a 25-storey building are presented, further visualized in Figure 50.

Table 19: Results of economic fire risk calculations- Design 1 - 1-storey building

	Unit	Variant 1	Variant 2	Variant 3	Variant 4	Variant 5	Variant 6
Probability factors							
F(A)	[%]	0,24%	0,24%	0,24%	0,24%	0,24%	0,24%
P1	[%]	0,0%	0,0%	0,0%	98,0%	98,0%	98,0%
P2	[%]	0,0%	83,0%	100,0%	0,0%	83,0%	100,0%
P3	[%]	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%
Probability per fire scenario*							
F0	[%]	99,76%	99,76%	99,76%	99,76%	99,76%	99,76%
F1	[%]	0,0%	0,0%	0,0%	0,23%	0,23%	0,23%
F2	[%]	0,0%	0,20%	0,24%	0,0%	0,0%	0,0%
F3	[%]	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%
F4	[%]	0,24%	0,04%	0,0%	0,01%	0,01%	0,01%
Damage per fire scenario							
D0	[€]	0	0	0	0	0	0
D1	[€]	19180	19180	19180	19180	19180	19180
D2	[€]	383600	383600	383600	383600	383600	383600
D3	[€]	0	0	0	0	0	0
D4	[€]	383600	383600	383600	383600	383600	383600
Risk per fire scenario							
R0	[€]	0	0	0	0	0	0
R1	[€]	0	0	0	45	45	45
R2	[€]	0	763	920	0	15	18
R3	[€]	0	0	0	0	0	0
R4	[€]	920	156	0	18	3	0
RTotal	**[€]**	**920**	**920**	**920**	**63**	**63**	**63**

**Note that the probability for scenarios becomes so small, that a clear difference in the results is not always observed in the probability results. The difference is however observed the final risk-results, see results variant 4,5 and 6.*

Table 20: Results of economic fire risk - Design 1 - 25-storey building

	Unit	Variant 1	Variant 2	Variant 3	Variant 4	Variant 5	Variant 6
				Probability factors			
F(A)	[%]	6,0%	6,0%	6,0%	6,0%	6,0%	6,0%
P1	[%]	0,0%	0,0%	0,0%	98,0%	98,0%	98,0%
P2	[%]	0,0%	58,1%	70,0%	0,0%	58,1%	70,0%
P3	[%]	28,0%	28,0%	28,0%	28,0%	28,0%	28,0%
				Probability per fire scenario			
F0	[%]	94,01%	94,01%	94,01%	94,01%	94,01%	94,01%
F1	[%]	0,0%	0,0%	0,0%	5,87%	5,87%	5,87%
F2	[%]	0,0%	3,48%	4,20%	0,0%	0,07%	0,08%
F3	[%]	1,68%	0,70%	0,50%	0,03%	0,01%	0,01%
F4	[%]	4,32%	1,81%	1,29%	0,09%	0,04%	0,03%
				Damage per fire scenario			
D0	[€]	0	0	0	0	0	0
D1	[€]	19180	19180	19180	19180	19180	19180
D2	[€]	383600	383600	383600	383600	383600	383600
D3	[€]	2685200	2685200	2685200	2685200	2685200	2685200
D4	[€]	9590000	9590000	9590000	9590000	9590000	9590000
				Risk per fire scenario			
R0	[€]	0	0	0	0	0	0
R1	[€]	0	0	0	1127	1127	1127
R2	[€]	0	13358	16094	0	267	322
R3	[€]	45064	18882	13519	901	378	270
R4	[€]	413856	173406	124157	8277	3468	2483
RTotal	**[€]**	**458921**	**205646**	**153771**	**10305**	**5240**	**4202**

For the results regarding the calculated probability factors (F(A), P1, P2, P3) as presented by Table 19 and Table 20 follows that F(A) (which is the probability of a fire occurring) is constant for each variant of a 1-storey building. Similarly, F(A) is constant for each variant of a 25-storey building. F(A) for the 25-storey building is however 25 times larger than for a one storey building, which is explained by the increase in total GFA of the building.

P1 is the probability that in case there is a fire, this results in extinguishing before flashover, which is dependent on the availability of a sprinkler. The design variants without a sprinkler (variant 1,2 and 3) therefore result in a P1 of 0%. The variants where a sprinkler is available (variant 4,5 and 6) result in a P1 of 98%, indicating that when there is a fire, there is a 98% chance that the fire will be extinguished (with post-sprinkler extinguishing by fire fighter services of 100%). P1 is independent of the building height.

P2 is the probability that in case there is a fully developed fire, this does not result in structural failure of the CLT. From the results follows that variant 1 and 4, 2 and 5, and 3 and 6 result in similar probabilities for P2. This is explained by the identical design characteristics, as P2 indicates the influence in case a sprinkler does not result in extinguishing. Variant 1 and 4, result in a P2 of 0%, due to the calculated continuous burning of the compartment, which is independent on the building height (see results of fire dynamic calculations presented in Figure

42). For the other variants, the building height affects the calculated P2, which is explained by the considered fire fighter accessibility due to building height in relation to post-fire extinguishing. For this, increased building height negatively affects the expected post fire extinguishing and this way the probability of extinguishing before structural failure. The difference regarding the probability between variant 2 and 5, and 3 and 6 for similar building heights is explained by the effect of encapsulation on moment of extinguishing and structural failure.

P3 is the probability that in case there is structural failure, this does not result in total collapse of the building. P3 is independent of the design variant, though dependent on the building height. For the designs with 1-storey, P3 is 0%, as the building only consists of one storey, and therefore in case there is structural collapse due to a fire, the chance is 100% that this will occur in the one compartment the building exists from. For the design variants for a 25-storey building, P3 is 28%, which is based on the calculation for structural collapse, which will only occur if the fire is located below storey floor 17 (see extensive example in Appendix 5). If the fire occurs above this floor, it is assumed that the building will not result in progressive collapse.

Based on the calculated probability factors, the probability of each fire scenario is calculated. The economic damage due to specific fire scenarios is independent on the design variant, though dependent on the building height. This is explained by the increased GFA for increased building height and therefore increased damage. D0 is 0, as this presented the fire scenario where no fire is expected.

For the 1-storey building variants, D1 is 5% of the value of one compartment, in this case of the total building. For this building height, D2 and D4 are similar, as the damage due to the loss of one compartment (D2) is similar as the loss of the total building (D4), as the building only consists of one compartment. D3 is 0 in the 1-storey building, as only the total building can be lost in case of structural failure. For the 25-storey compartment, D1 is 5% of the value of one compartment. D2 is the loss of 1 compartment, D3 is the loss of the compartments at which structural collapse will not occur, and D4 is the damage due to loss of the total building.

With the probability and damage per fire scenario, the fire risk is calculated. The results of the fire risk per scenario is presented in Table 19 and Table 20 and further visualized in Figure 49 and Figure 50 on the next page. From the results follows for a 1-storey building, variant 1,2 and 3, as well as variants 4,5, and 6 result in the same total economic fire risk. The total risk of variant 1 is entirely due to fire scenario 4, presenting total loss of the building. Variant 2, results in risk partially due to fire scenario 2, referring to risk of loss of only one compartment (and in this case thus the total building) and partially by scenario 4. The risk of variant 3 is completely because of fire scenario 2. For design variants 4, 5 and 6, similar results are obtained, though drastically decreased by 93,2% due to the availability of sprinklers.

For the results of a 25-storey compartment, the total risk deviates between the different design variants. It is observed that the risk of variant 1 presents the highest risk, with a value that is 2,2 times higher than the risk of variant 2. It is observed that the availability of a sprinkler decreases the total risk of the building by over 97% for all variants compared to their non-sprinklered variant.

In Figure 51 and Figure 52, the results of the total risk of the design variants are presented for a building varying from 1 to 25 storeys for economic and environmental impact calculations.

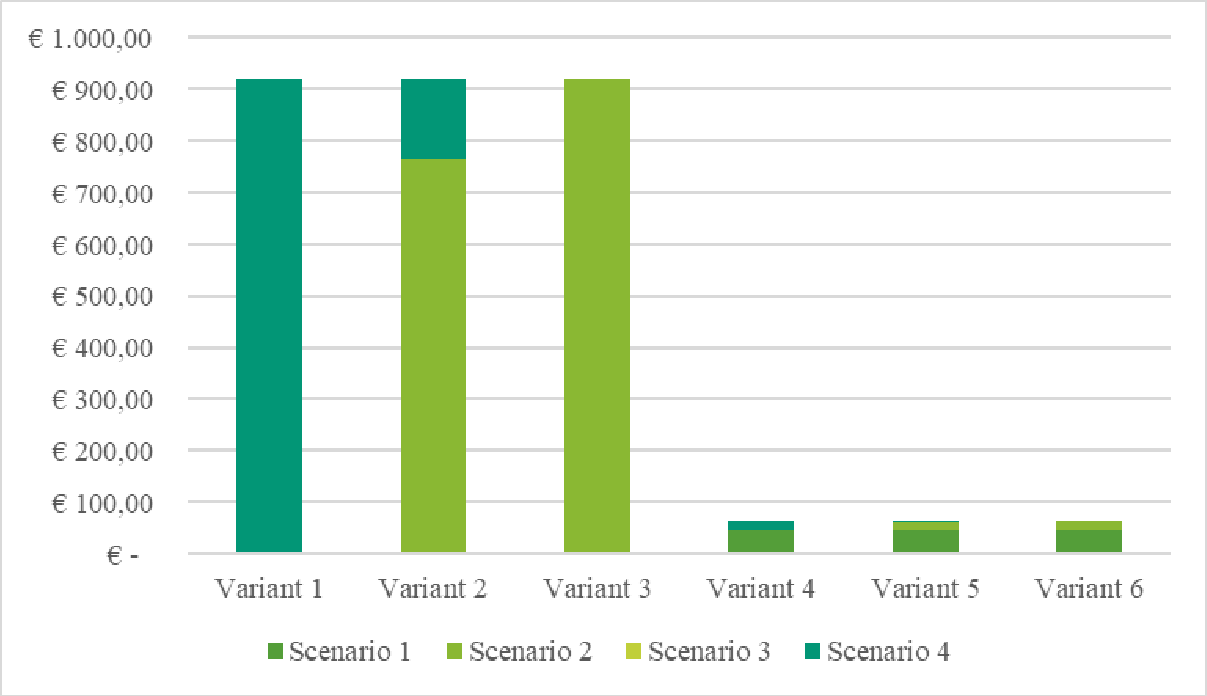


Figure 49: Economic impact for fire risk – Design - 1-storey building

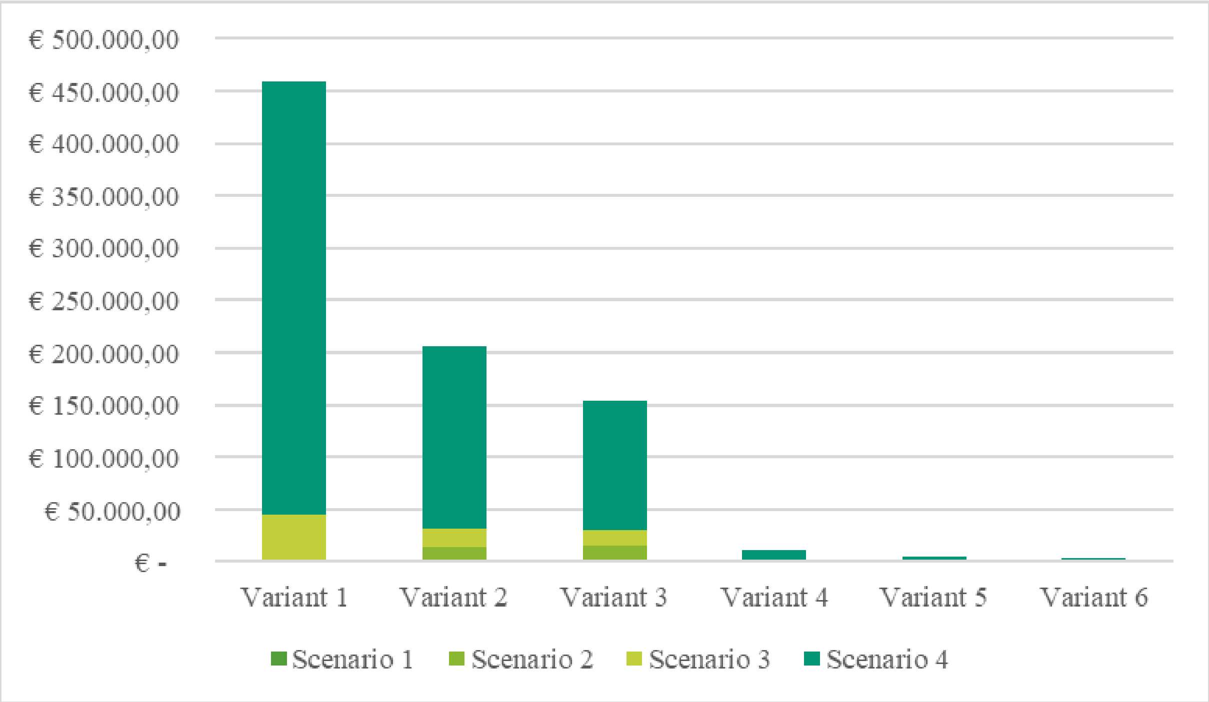


Figure 50: Environmental impact for fire risk – Design 1- 25-storey building

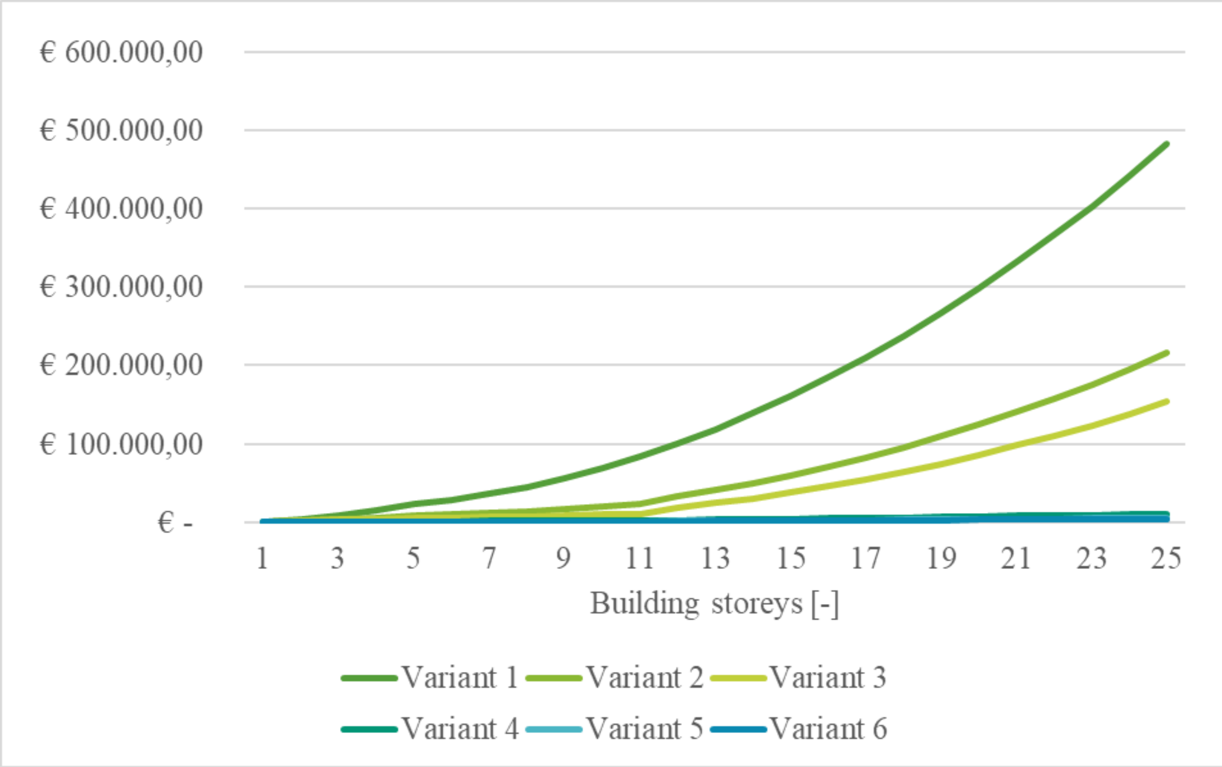


Figure 51: Economic fire risk – Design 1

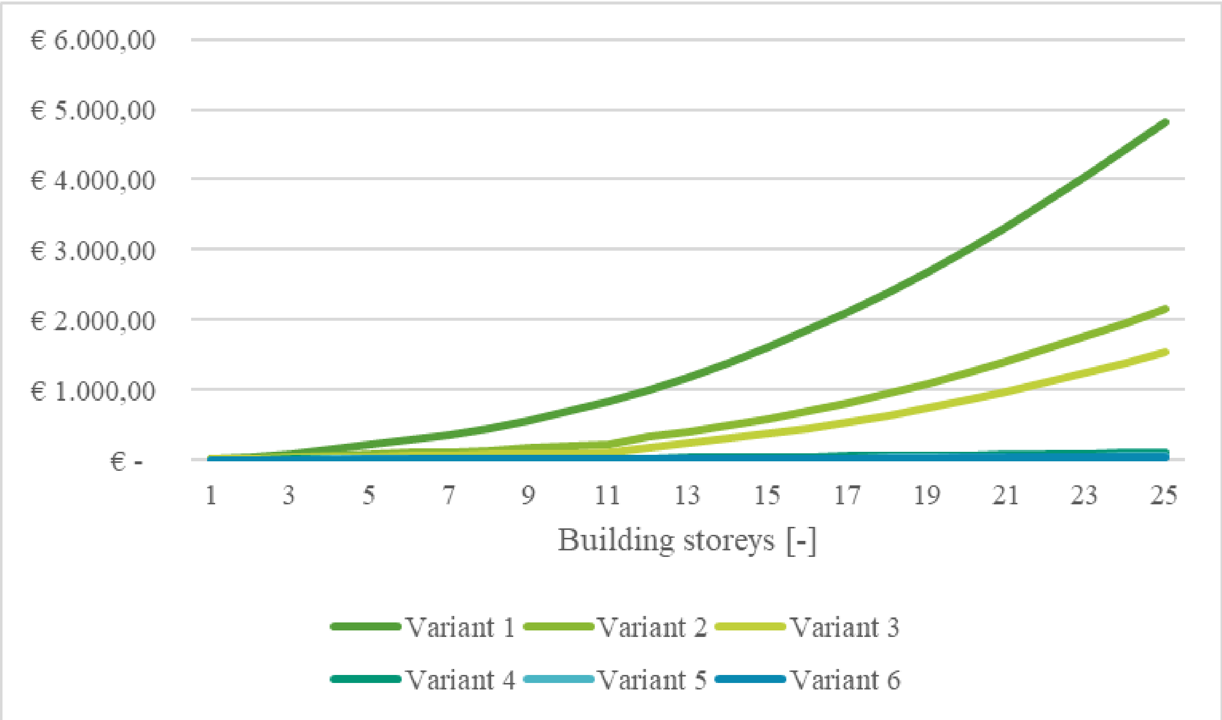


Figure 52: Environmental fire risk - Design 1

Comparing the results presented in Figure 51 and Figure 52 it is observed that the graphs present similar results, though with a factor of 100 in difference. This is because the only difference between economic and environmental impact calculations is due to the considered building value. This was chosen to be €8000 per m2 for the economic building value, and 0,8 per year per m2, for 100 years (80 in total) for the environmental value, resulting in a factor of 100 in difference.

It is observed that the risk grows exponentially with height, where the exponential growth rate depends on the design variant. Variant 1 has the highest exponential growth rate, meaning that per building storey, the risk increases more compared to the other variants. For the variants in which the encapsulated area increases (variant 2 and 3) the growth rate decreases significantly, resulting in a total risk reduction of 55,2% for variant 2 and 66,5% for variant 3 compared to variant 1 for a 25-storey building. It is observed that the effect of a sprinkler on the fire risk is significant, leading to a reduction of 97,8% for variant 4, 98,9% for variant 5 and 99,1% for variant 6 compared to variant 1.

From both graphs it is observed that variants 2 and 3 have buckle in the risk-rate at 11 storeys (30m building height). This is also the case for variant 5 and 6 though not visible in the figure. This is explained by the additional risk calculated for the accessibility by fire fighter services and the relation to post-fire extinguishing. The reason the buckle in not observed in variant 1 and 4 is because the calculated probability of extinguishing before failure is 0 (P2 in Table 19 and Table 20).

9.2.2.4 Material-risk balance

The aim of the research is to understand the balance between material use and fire risk in mass timber buildings. The balance is presented by the material use and fire risk as calculated in the previous sections and integrated to one "circular fire safety impact" value. The results are generated for the six design variants, for a 1- and a 25-storey building. The results of the economic impact of the designs are summarized in Table 18. The results are visualized in Figure 53 and Figure 54 on the next page. The material use is divided into cost and benefit impacts, to allow comparison between the influence of a linear and a circular design approach on the results.

Table 21: Results of material-risk balance – Design 1

Parameter	Unit	Variant 1	Variant 2	Variant 3	Variant 4	Variant 5	Variant 6
1-storey building							
Cost	[€]	10111,59	33779,48	40147,9	171859,3	195527,2	201895,7
Benefit	[€]	-7520,49	-12748,7	-14155,5	-18093,5	-23321,7	-24728,5
Fire risk	[€]	919,681	919,681	919,681	63,45799	63,45799	2329,649
Total impact	[€]	3510,775	21950,43	26912,07	153829,3	172269	177230,6
25-storey building							
Cost	[€]	252789,7	844486,9	1003698	696483,4	1288181	1447391
Benefit	[€]	-188012	-318718	-353888	-452337	-583043	-618212
Fire risk	[€]	482832,5	215665,2	153770,7	10783,26	5439,913	2329,649
Total impact	[€]	547609,9	741433,9	803580,4	254930	710577,9	833381,1

The main goal of the quantification of the "circular fire safety impact" is to determine the most advantageous fire safety design, for which the balance between material use and fire risk is minimized. This means that the most advantageous design is the design that results in the lowest total impact value. The result interpretation can be done for both a linear approach, in which only material cost and fire risk are considered (the positive numbers presented in Figure 53 and Figure 54) and a circular approach, for which also the end-of-life benefits are included in the calculation.

From the results presented in Table 21 and Figure 53 follows that for a 1-storey building, the most advantageous design variant is variant 1, for both a linear as a circular approach, as cost and benefit outweigh the risk. This means that the reduced risk of additional material used for fire safety measures relating to encapsulation and sprinkler does not weight up against the cost (+benefit) of the additional material. Especially the additional costs of a sprinkler installation are not beneficial from a material perspective for a 1-storey building.

Based on the results for a 25-storey building (Table 21 and Figure 54), the most advantageous design variant both considering a linear and circular design approach is variant 4, as the reduced risk due to a sprinkler outbalances the additional material cost (+ benefit) compared to variant 1. Comparing a linear and a circular approach, it is observed that the end-of-life circularity benefits of a sprinkler result in an additional preference for variant 4 compared to variant 1. It is observed that the additional risk-reduction of encapsulation in an already sprinklered compartment is not significant such that it outbalances the additional material costs.

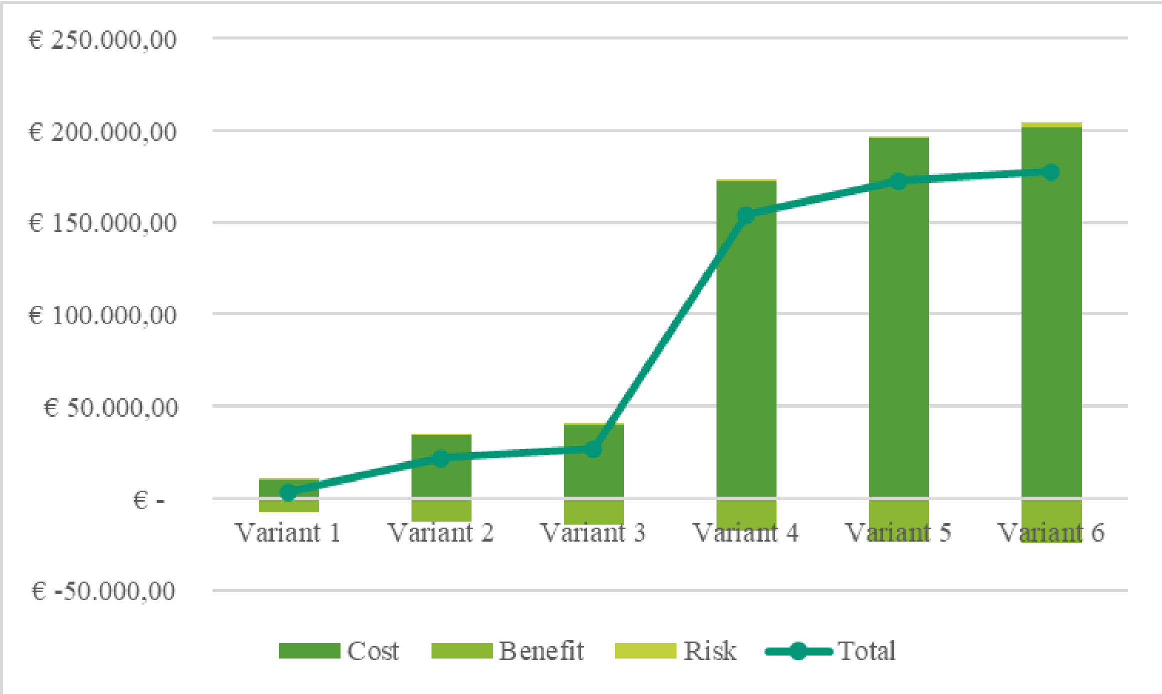


Figure 53: Total economic material-risk balance - Design 1 - 1-storey building

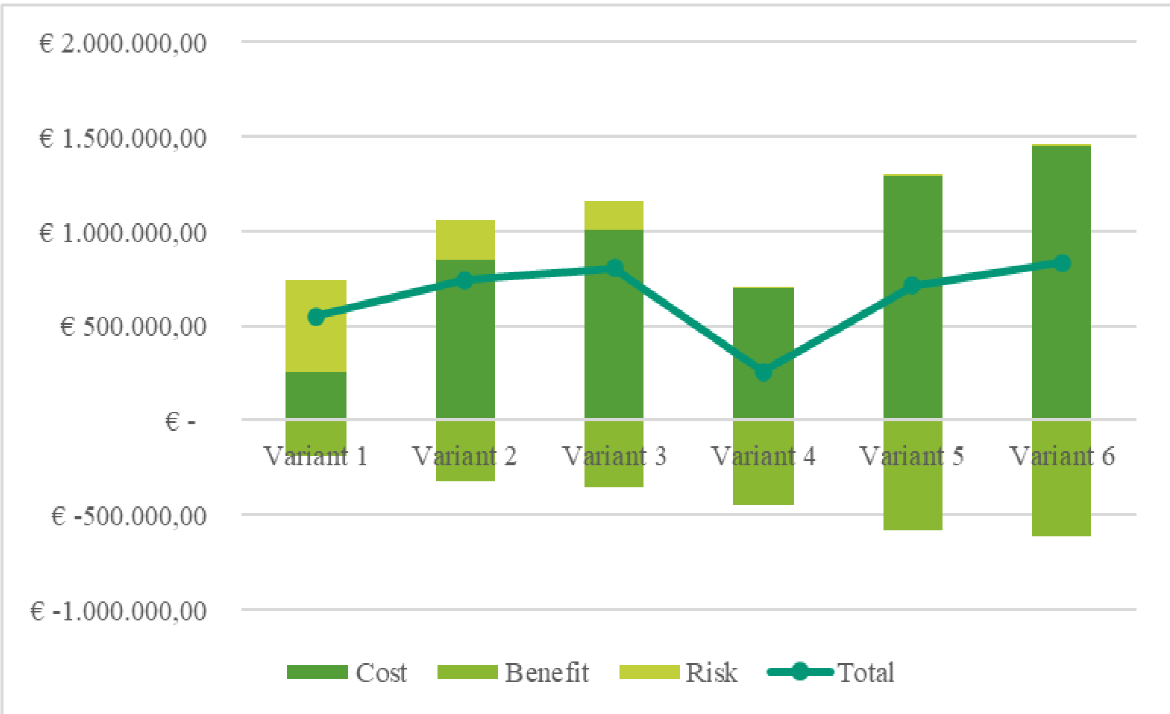


Figure 54: Total material-risk balance - Design 1 - 25-storey building

In Figure 55, the total circular fire safety impact for the six design variants for 1- to 25-storey buildings are plotted, representing a circular design approach. In Figure 56, the total impact based on only cost and risk is plotted, which represents a linear approach.

By comparing the two graphs it is observed that the circular material approach (Figure 55) has an increased slope rate compared to the results for a linear material approach. This is explained by the linear contribution of the benefit, and results in a reduction of the influence of the material use for fire safety measures, which increases the influence of the risk on the results. Based on this, it is observed that when considering the total impact for a circular approach, variant 4 is preferred for a building with more than 15 storeys (40 m height), whereas for a linear approach (Figure 56) variant 4 is preferred for building with a storey number higher than 24, which presents a building height of 65,5 m.

Based on this, it observed that the current linear approach may result in a sprinkler being beneficial from a larger building height, whereas, changing the approach to a circular approach, considering the end-of-life benefits of fire safety measures, might result in alternative most favourable fire safety designs.

In Figure 57 and Figure 58, the environmental impact results are plotted for both a circular as well as a linear design approach. It is observed that the environmental impact results are rather similar to the economic impact results, though with reduced slope rate. This is explained by the higher impact for material use compared to fire risk, resulting in reduced slope. For the environmental impact results for a circular design approach, this results in a most optimal design variant 1 up to 16 building storeys (43,7m), after which variant 4 becomes most beneficial. For a linear approach (Figure 58), variant 1 is the most optimal design up to 17 storeys (46,4m), after which variant 4 becomes more optimal.

Comparing the economic and environmental results, it follows that the most optimal approach differs between environmental and economic impact results, which can be explained by the difference in cost- and benefit-values which are used to determine the material cost and benefits. Especially the difference between economic and environmental costs for sprinkler pipes varies, as accurate EPD data is lacking for sprinkler installations. The assumptions affect the share in costs and benefit, especially for sprinkler pipes used in the economic and environmental impact calculations, which affects the slope rate of the total impact calculations. This makes that a sprinkler becomes more optimal for an economic circular approach, compared to environmental circular approach.

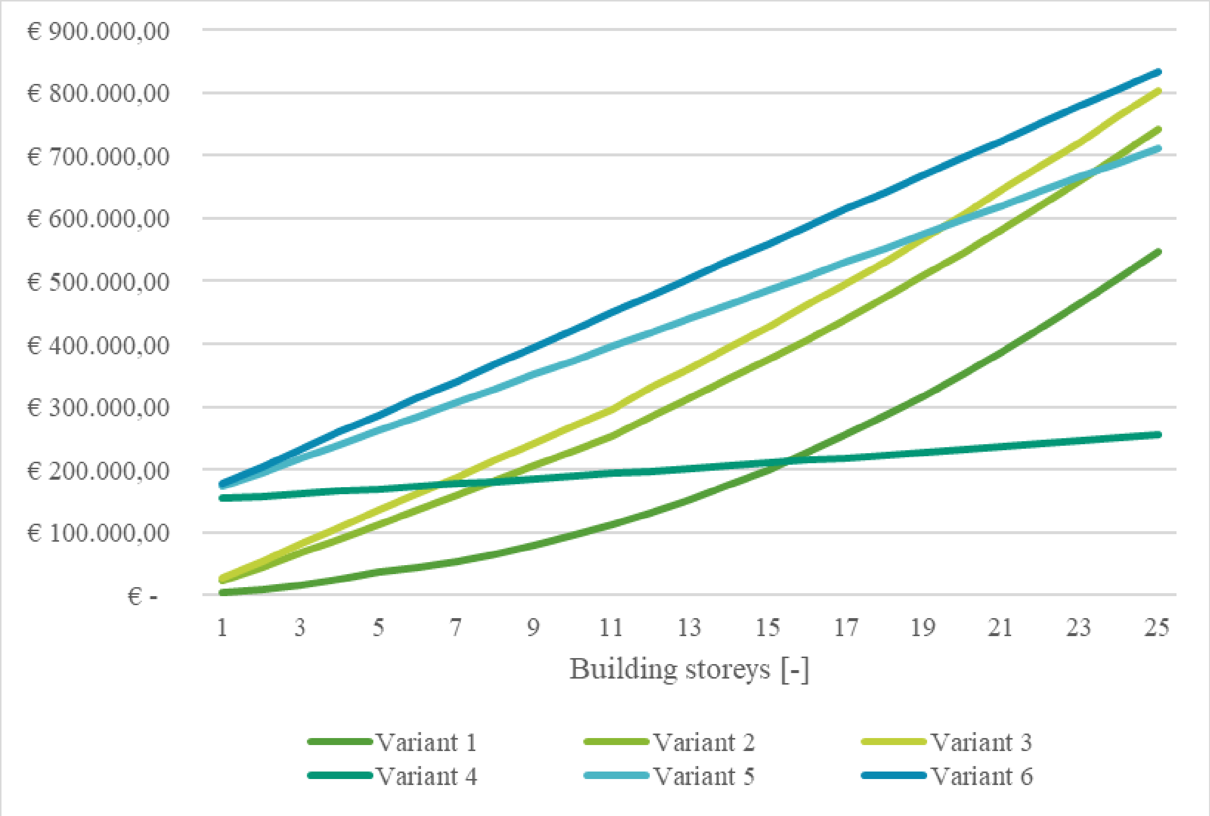


Figure 55: Total economic "circular fire safety impact" – Circular material use– Design 1

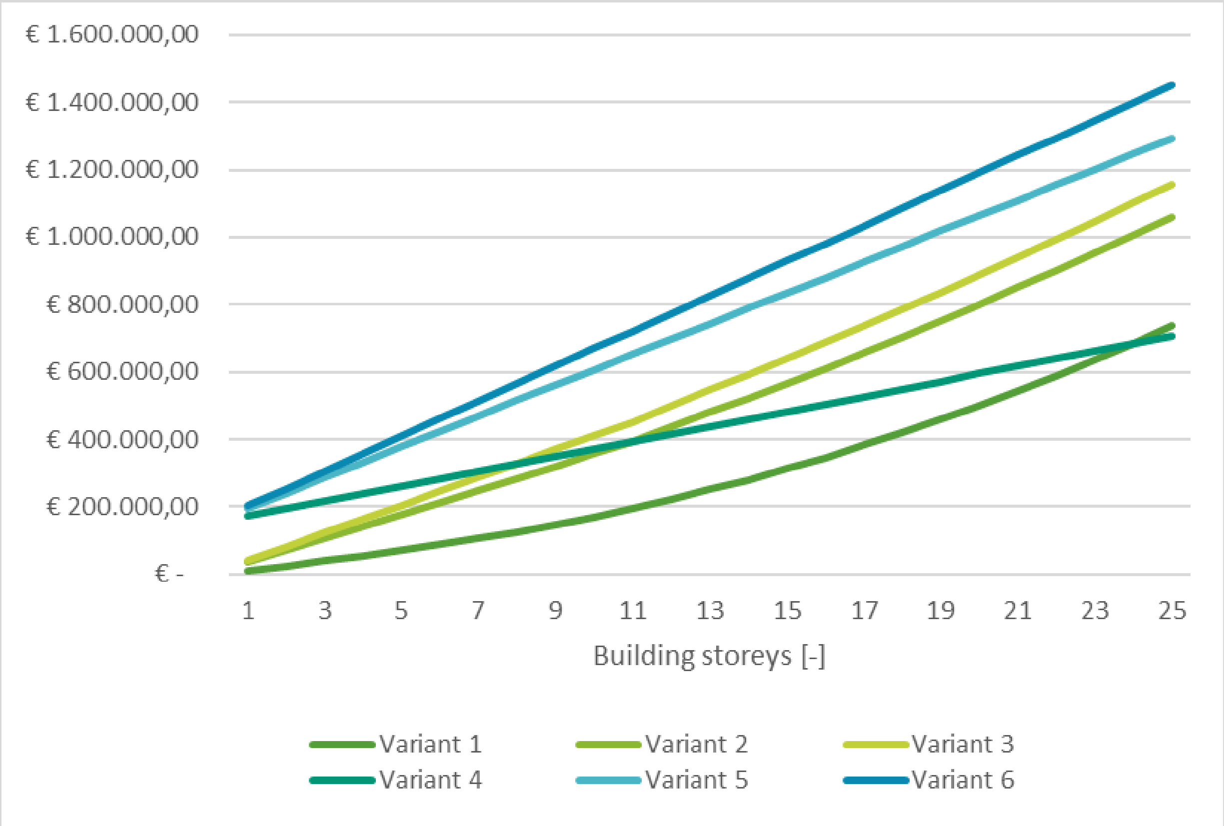


Figure 56: Total economic impact cost-risk based – Linear material use- Design 1

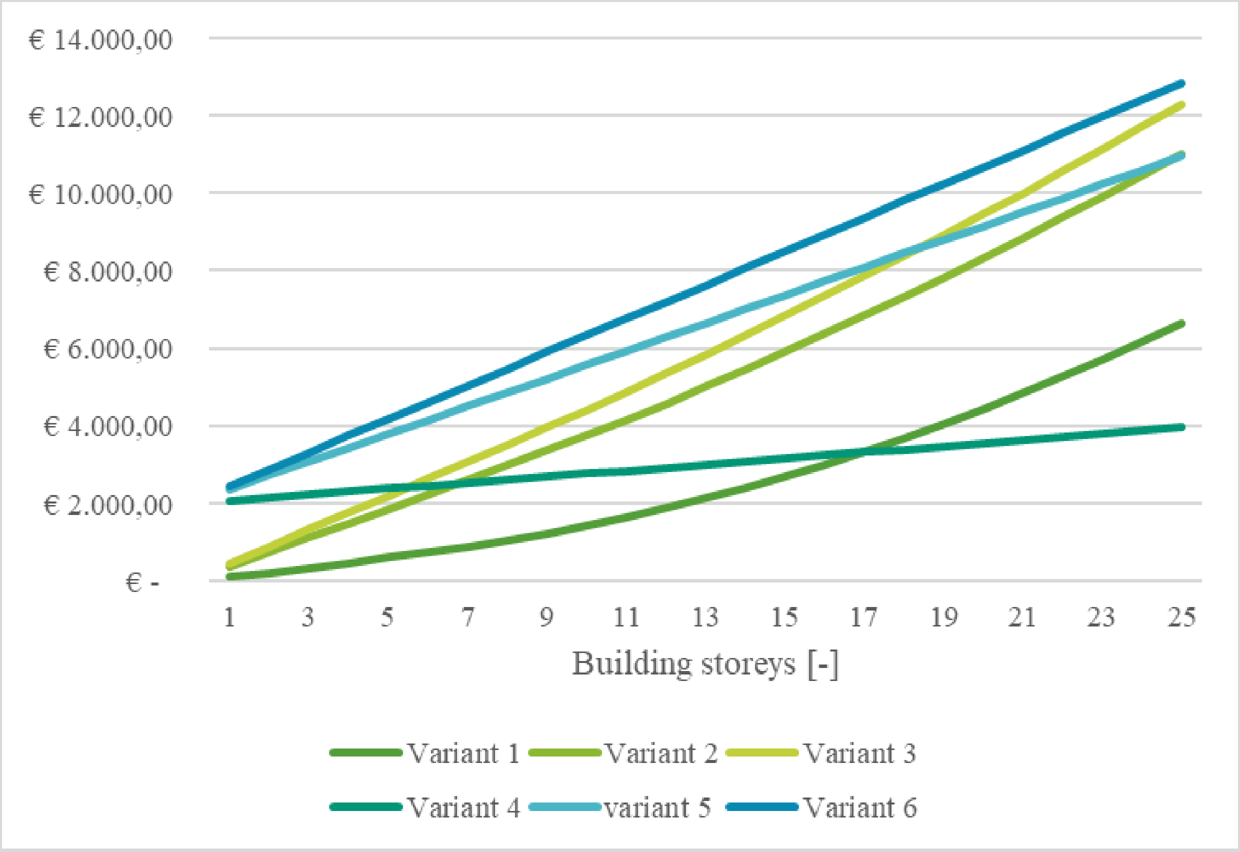


Figure 57: Total environmental "circular fire safety impact" – Circular material use – Design 1

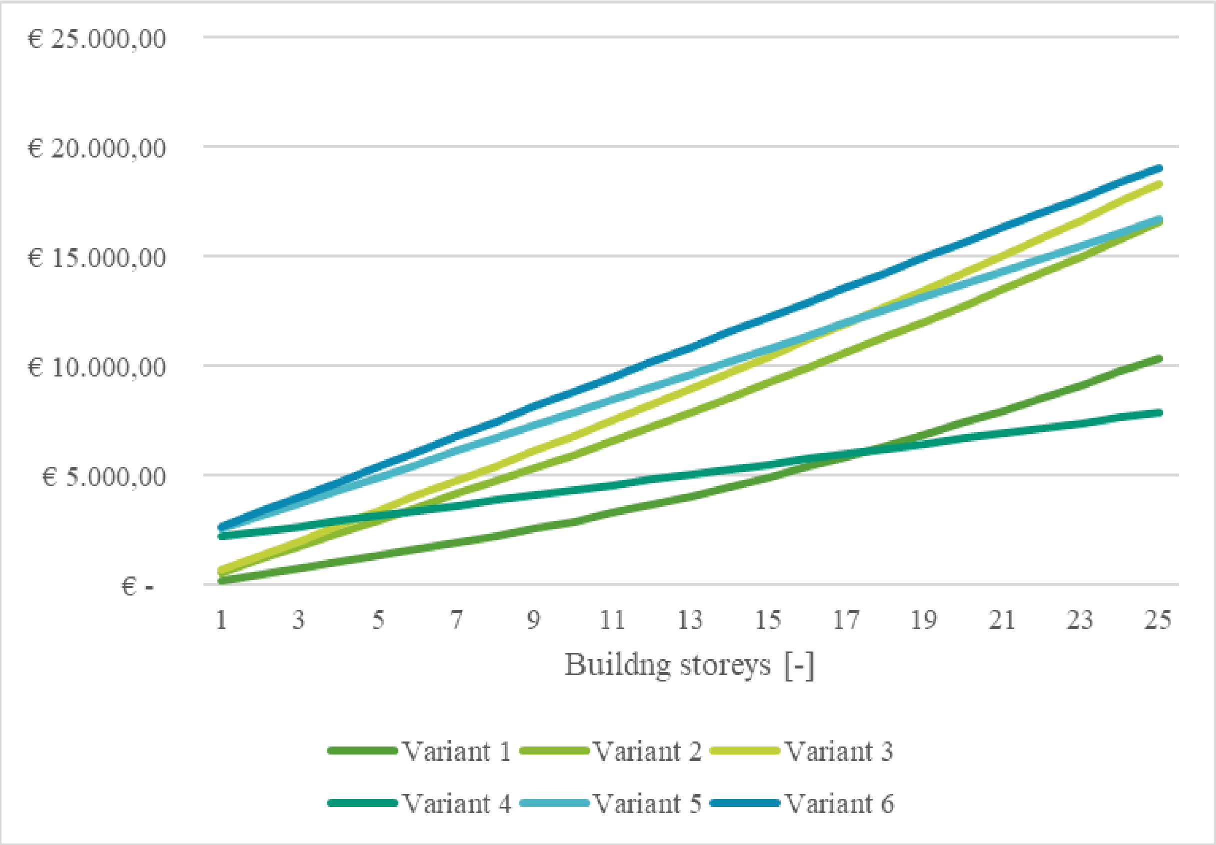


Figure 58: Total environmental impact cost-risk based – Linear material use – Design 1

9.2.3 Results of Design 2: Compartment GFA of 140 m2

In this section, an overview of the results of Design 2 is presented. Design 2 is a design like Design 1 though with increased floor and opening area. The characteristics of the design have been presented in Table 15 in section 9.2.1Design characteristics. The design has been tested for the same design variants are presented in section 9.2.1.1. The main goal of this section is to allow comparison between the influence of the compartment size on the most favourable fire safety design variant.

9.2.3.1 Economic impact results

The total economic impact results are presented in Table 22 for each design variants for a 1 and 25-storey building design. Figure 59 and Figure 60, the results are visualized.

Table 22: Economic impact results - Design 2

Parameter	Unit	Variant 1	Variant 2	Variant 3	Variant 4	Variant 5	Variant 6
1-storey building							
Cost	[€]	23358,13	83401,92	98113,21	207658,1	267701,9	282413,2
Benefit	[€]	-17372,6	-30636,3	-33886	-48242,6	-61506,3	-64756
Fire risk	[€]	7840	7840	7840	540,96	540,96	540,96
Total impact	[€]	13825,52	60605,64	72067,21	159956,5	206736,6	218198,2
25-storey building							
Cost	[€]	583953,1	2085048	2452830	1591453	3092548	3460330
Benefit	[€]	-434315	-765907	-847150	-1206065	-1537657	-1618900
Fire risk	[€]	4006240	1792491	1310848	89728,8	45453,81	35820
Total impact	[€]	4155878	3111632	2916528	475116,8	1600345	1877251

Based on the results from Table 22 and Figure 59, it is observed that for a 1-storey building, the most advantageous design is variant 1, as the risk reduction of additional fire safety measures does not add up to the additional material costs and benefits.

From Table 22 and Figure 60 follows that the most advantageous design for a 25-storey building is variant 4. It is observed that the reduced risk due to implementation of a sprinkler balances out the additional costs and benefits, such that applying a sprinkler becomes more beneficial over the use of encapsulation.

Figure 61 and Figure 62Figure 62 present an overview of the economic and environmental impact calculations for 1- up to 25-storey buildings. From Figure 61 follows that the most optimal design is design variant 1 up to 4 building storeys (10m), after which variant 4 becomes the most optimal. In case a sprinkler is not desired, Figure 62variant 2 becomes more optimal after 10 storeys (27,3 m) and variant 3 after 12 storeys (32,8m). Variant 3 compared to variant 2 is beneficial after 14 storeys (38,2 m).

For the environmental impact, presented by Figure 62 follows that up to 5 storeys (13,7m) design variant 1 is the most optimal, after which variant 4 becomes the most optimal. In case a sprinkler is not desired, Figure 62variant 2 becomes more optimal after 19 storeys (51,9 m) and variant 3 after 20 storeys (54,6 m). Variant 3 compared to variant 2 is beneficial after 23 storeys (62,8 m).

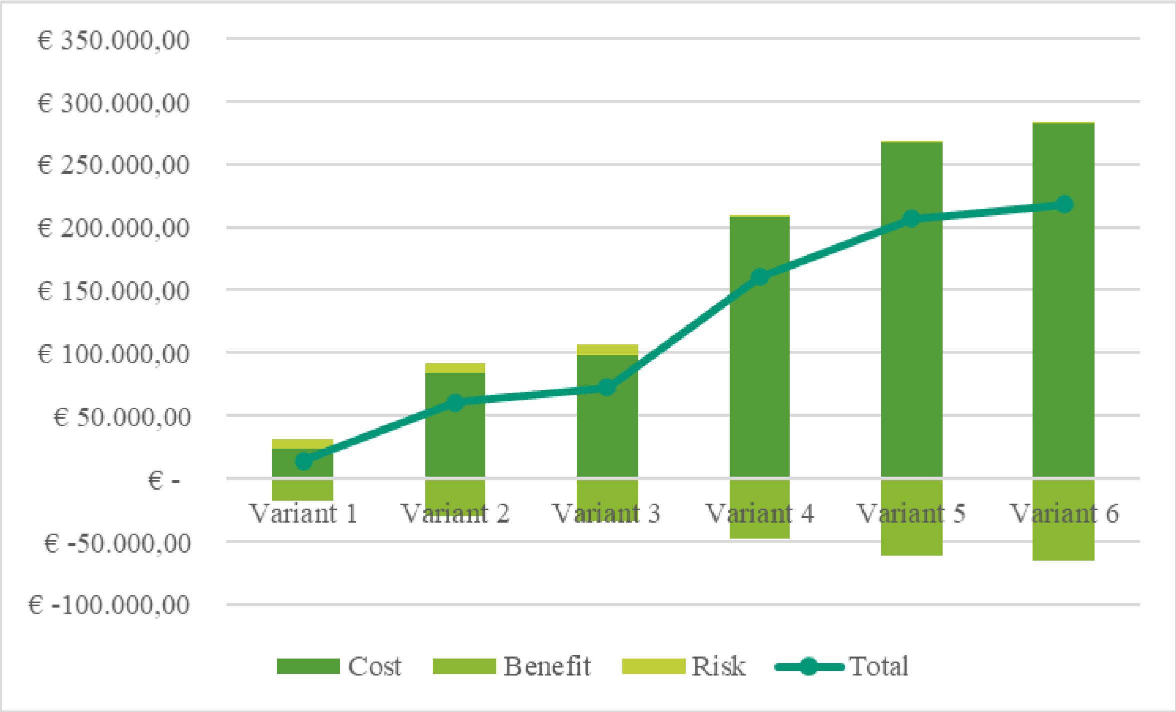


Figure 59: Total economic impact results material -risk balance- Design 2- 1-storey building

Figure 60: Total economic impact results – material-risk balance – Design 2 - 25-storey building

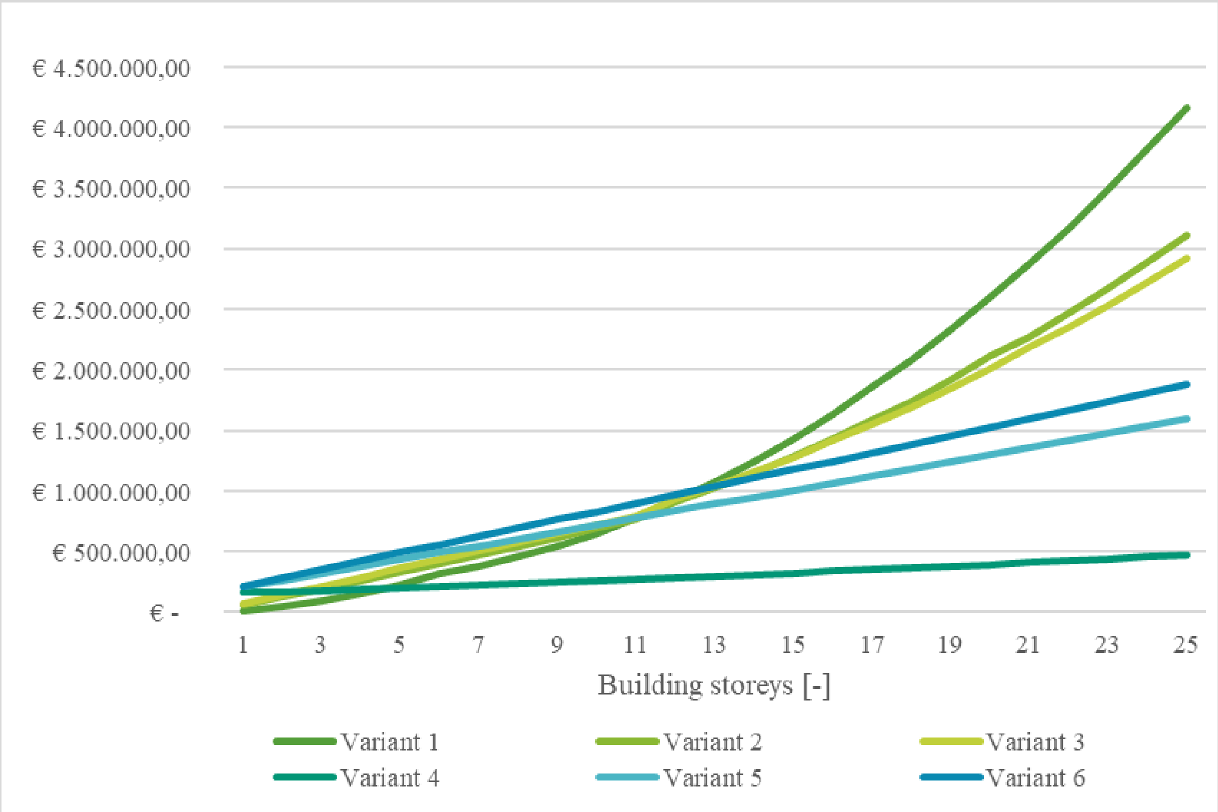


Figure 61: Total economic "Circular fire safety impact"- Circular material use - Design 2

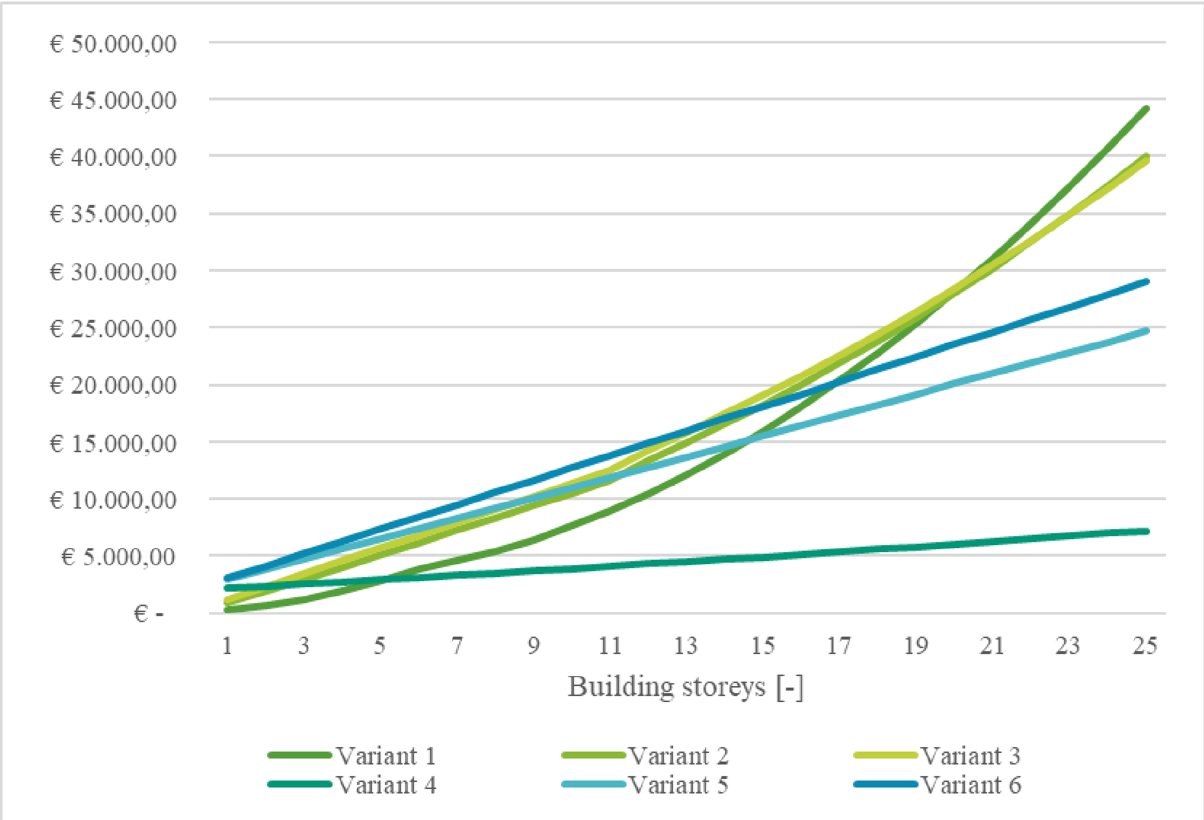


Figure 62: Total environmental "Circular fire safety impact" – Circular material use - Design 2

9.2.4 COMPARISON OF RESULTS

In this section the results if the two building designs: Design 1 and Design 2 are compared, which presents the influence of the compartment size on the results.

9.2.4.1 TOTAL RESULTS ECONOMIC IMPACT

Figure 63 presents the total circular fire safety impact results for design 1 and 2 for different building heights. On the horizontal axis, the number of floors is presented. On the vertical axis, the impact is presented in monetary value. It is observed that for increased compartment size, the slope rate of the designs is steeper. It is observed that especially the buildings variants without a sprinkler result in a significant difference between the total impact. This is explained by the higher considered value of the building (the Economic price per m2) per meter squared compared to material cost, which results in an increase in building risk compared to material cost or benefit when compartment size increases. It is observed that for an increase in compartment size, variant 4 becomes the most optimal design for a shorter building height compared to a smaller compartment size.

9.2.4.2 TOTAL RESULTS ENVIRONMENTAL IMPACT

Figure 64 presents the total environmental impact results. The graphs present rather similar results as the economic impact calculations though with slopes that are slightly less steep compared to the results for the economic calculations.

Figure 63: Economic "Circular fire safety impact" - Design 1 and 2

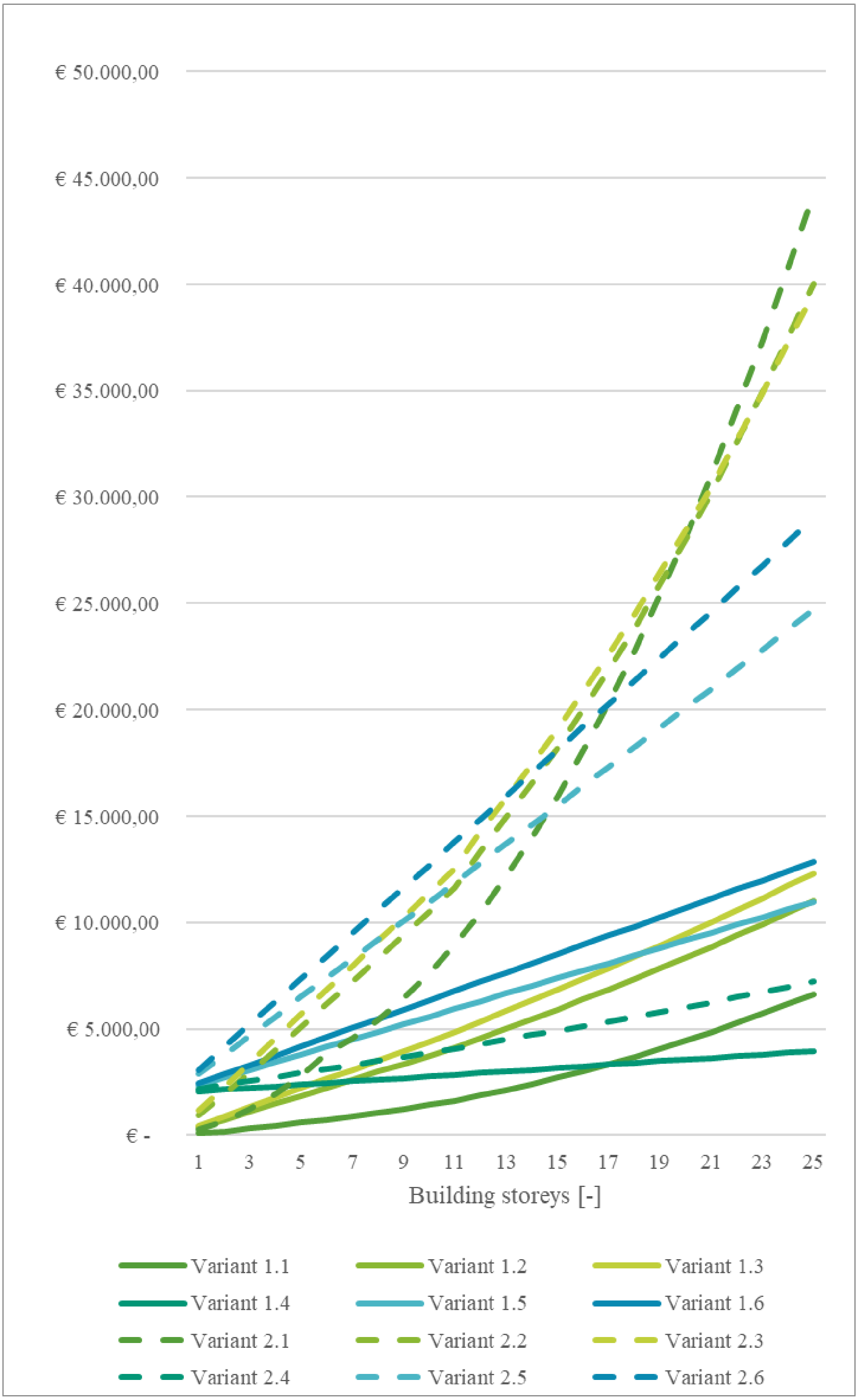


Figure 64: Environmental "Circular fire safety impact" - Design 1 and 2

9.3 Conclusions

With the results presented in this chapter, the second sub-question can be answered:

Q2: How can a circular design approach be used to quantify the relation between material use and fire risk for the fire safety design in mass timber buildings?

Timber design is one of the sustainable solutions which has high potential to contribute to reaching a circular build environment, as timber is natural and renewable and the forests in which it is harvest functions as a carbon sink. Moreover, it has high potentials to be reused or recycled. However, timber is combustible, which affects the characteristics of the fire dynamics and structural capacity, and this way the fire risk of the building. To reduce this risk, fire safety measures are applied, of which encapsulation and sprinklers are the most used measures.

The fire dynamics in mass timber buildings are affected by the design. It is observed that there are some aspects that have a significant influence on the characteristics, of which some are related to the building (ventilation and fuel load density) and some to the fire safety design. For the fire safety design, it is observed that especially the number of exposed CLT surfaces, the CLT adhesive type, the type of encapsulation, the number of encapsulation layers and the availability of a sprinkler installation has a significant influence on the fire dynamics and thus the severity of the fire. The fire resistance of the structural elements is mainly related to the structural scheme, heat flux exposure time, the encapsulation, number and thickness of timber lamellas and the adhesive type.

Because of the increased risk of timber design, general prescriptive regulation may not suffice for fire safety design, as these are based on “standard” non-combustible building materials. Therefore, the fire safety design should be based on a risk-based approach that considers the effect of the fire safety design on the fire dynamics and (structural) fire resistance.

By integration of the theory on fire safety design in mass timber buildings and the circular fire safety design approach, a method is developed that quantifies the material use of fire safety measure and the relating fire risk.

The defined quantification methods are integrated in a design tool in Excel. This tool provides insight in the influence of fire safety design in mass timber buildings on the material use and fire risk, by quantification into economic and environmental impact value. By summing the material use and fire risk, one “circular fire safety impact” value is calculated. This allows comparison between different fire safety designs. The most optimal design from a material perspective is determined by the design with the lowest total impact.

The calculation methods are integrated in a design tool created in Excel which allows changing the design parameters. The tool calculated the effect on material use and fire risk. The use of the tool consists of three main steps:

1. Implementation of design parameters
2. Analysis of the results
3. Variant study

This way, the tool gives insight in the influence of the fire safety measures on material use, fire risk and the combined “circular fire safety impact”. By changing the fire safety design, the most optimal design variant can be determined. This is the variant with the lowest total impact value.

PART 3

CONCLUSIONS

In this part of the research the results are discussed, and conclusions drawn. With this, the main objective of the research is reached which is defined as:

Enhance the understanding of the influence of the fire safety design on the balance between material use and fire risk in mass timber buildings.

10 DISCUSSION

In this chapter, the obtained results of the research are analysed. In this research a design approach is formulated that presents the relation between the objectives and methods of circular building design and fire safety design. This approach presents a guideline which can be used for quantification and comparison of different fire safety designs and their relation to the objectives of circular building design.

With the design approach as a guideline, a design tool is created that quantifies material use for fire safety measures and the relating fire risk for mass timber building design. The quantification methods and values of the design tool are gained by literature review, expert judgement and using available databases. The discussion is presented based for both parts of the research: (1) Circular fire safety design approach and (2) Circular fire safety design tool for mass timber buildings.

10.1 CIRCULAR FIRE SAFETY DESIGN APPROACH

In the first part of the research, a design approach is created in which circular design is related to fire safety design and integrated to one design approach for circular fire safety design. The integration is based on relating the different objectives and methods for circular and fire safety design, which is gained from literature review.

The design approach presents a first step towards circular fire safety design. The approach presents the important contradiction between circular and fire safety design, by balancing the impact of material use for fire safety measures and its relation to fire risk. The approach can be used as a guideline for different types of fire safety designs. The method can be used to determine both economic and environmental impact, based on material use.

10.1.1 FUTURE RESEARCH

Due to the time frame of the research, the approach presents limitations and further improvement should increase the usability and insight of the approach. The design approach presents the risk of a fire occurring during the use phase only. However, a building fire can also occur during the construction phase of a building.

10.2 Circular fire safety design tool for mass timber buildings

In the second part of the research, a design tool is created in Excel that quantifies the balance between material use and fire risk for the fire safety design in mass timber buildings. The quantification is done by utilizing the circular fire safety design approach as a guideline. The calculation methods are defined based on literature review. The input data is gained from literature and product data.

10.2.1 Result description

The result is a design tool created in Excel which allows comparison between different fire safety designs in mass timber buildings and their effect on the balance between material use for fire safety measures and fire risk. In the tool, the design of the building can be adjusted and the influence of CLT, encapsulation and sprinkler installation can be determined.

The user-interface presents the most important results, relating to fire dynamics and resistance, material of fire safety design measures, and fire risk. By integration of the impact on material use and fire risk the “total circular fire safety impact” value is calculated as one value. This represents the total material impact of the design, which allows comparison of different design and this way defining the most favourable design from a material perspective by choosing the design with the lowest total value.

The main results are obtained by testing the design tool based on a variant study, representing 6 different fire safety design variants, for two building designs: (1) a compartment with a GFA of 48 m2 per building storey and (2) a compartment with a GFA of 140 m2 per building storey. The test was done for different building heights up to 25 storeys. The results can be divided into four groups: (1) Fire resistance results, (2) Material use for fire safety measures, (3) Fire risk results, and (4) total circular fire safety impact.

10.2.1.1 Fire resistance results

From the elaborate variant tests follows that all the fire resistance calculations comply with the requirements stated by NEN 1991-1-2+C3 (2019). However, it is observed that the moment of calculated extinguishing increases for increased CLT exposure, exceeding the threshold value of 60 minutes on which the values in the regulations are based. From this follows that though the resistance may suffice, the structure may not be able to withstand the additional length of the fire due to exposed CLT and result in severe property loss.

10.2.1.2 Material use

Considering the results of material use of fire safety measures, it is observed that the material use increases linear for increased building height. It is observed that a fully exposed mass CLT compartment presents the most optimal design in terms of material, as this results in the lowest impact, for all building heights. This result is expected, as the alternative designs consider the same design, though with additional fire safety measures and thus increased material use.

Moreover, it is observed that for smaller building height, the use of encapsulation compared to sprinkler is preferred. This is explained by the high initial material use (costs) of a sprinkler central unit. For increased building height, the high initial costs of a sprinkler system are balanced out, by the increase in material cost for CLT and encapsulation. Therefore, for increased building height, a fully exposed CLT design with a sprinkler installation is preferred over the variants in which only encapsulation is considered.

10.2.1.3 Fire risk

The fire risk grows exponentially with height, where the exponential growth rate depends on the design variant. It is observed that the increase in compartment size, increases the exponential growth rate. This is expected because, as building height and area increase, the probability of a fire occurring increases, as well as the increase of the impact of the fire.

It is observed that a fully exposed compartment has the highest exponential growth rate. Applying 70% or 100% encapsulation reduces the risk for a 325-storey building by approximately 55 and 70% respectively. Applying a sprinkler reduces the fire risk by approximately 98% independent on the building heights, compared to a non-sprinklered compartment. This is explained by the considered 98% probability of a fire resulting in extinguishing before flashover due to the availability of a sprinkler installation.

10.2.1.4 Circular fire safety impact

The design tool integrates the material use and the fire risk into one impact value. This value shows the balances between the impact of material use for fire safety measures in relation to fire risk, and this way allows to define the most beneficial design from a material perspective.

From the results of the variant study follows that the most favourable fire safety design, both for economic and environmental impact, is dependent on the size and height of the building. It is observed that the total impact of the design variants increases for increased building height. This is explained by the combination of increased material use and increased fire risk. However, it is observed that the rate at which the impact increases differ for the different design variants. This is explained by the balance between material use and fire risk.

For all designs, the material-use, results in a linear impact growth for increased building height. The risk results in an exponential growth. If a design presents a clear exponential growth for increased building height, (which was observed for a fully exposed CLT compartment design) the fire risk presents a relative higher part of the total impact compared to the material use. The variants which show a more linear increase (the variants with a sprinkler) show that the material use presents a relative higher share of the total impact compared to fire risk.

This difference in the growth rate of the total impact explains the observed turning points for increased building height, at which an alternative design becomes favourable over the design for a shorter building.

Results of the variant study indicate that the risk of a smaller or shorter building may be significantly low, so that costs for the additional material for fire safety measures by encapsulation or sprinkler do not result in reduced total impact. Therefore, a fully exposed CLT building without additional fire safety measures may be most optimal for smaller or shorter buildings.

Moreover, it is observed that all calculations show that a design variant with fully exposed CLT surfaces with a sprinkler, provides the most optimal design after the turning point. Although the sprinkler installation results in higher total material use, the reduction of the risk is so significant (98%) that it outweighs the variants with encapsulation.

However, it should be noted that encapsulation is not only beneficial for fire safety but may be needed for other building related issues such as acoustics. In that case, the default design investigated should consider the required amount of encapsulation for the design and compare different design alternatives. Moreover, building regulations state the requirement for residential buildings that a fire may not spread beyond the neighbouring building compartment. This means that the solution in which the compartment is fully exposed, does not meet these requirements as the probability that the fire will spread is high. Therefore, to comply with the building regulations, it is proposed to look at the turning point of (partially) encapsulated design variants, rather than fully exposed variants.

10.2.2 Noteworthy findings

The quantification methods defined in this research provide a first step towards fire safe mass timber building design whilst keeping the objectives of circular design in mind. Apart from this, the results obtained by the design tool presents problems relating to current building regulations in regard to fire safety design in mass timber buildings.

Considering the fire dynamic and resistance calculations, the results show that mass timber building design might provide sufficient fire resistance as stated by the Eurocode (NEN-EN 1991-1-2) without applying encapsulation or additional fire safety measures, meaning that the required resistance time suffices before the structure fails. However, based on the research it is observed that this may lead to significant damage and property loss of the building. Though, the regulations state that for residential compartments damage must be minimized and not spread beyond the neighbouring fire compartment. Therefore, following the general fire safety requirements stated by building codes, may not result in the intended safety regarding minimizing damage when designing a mass timber building.

Moreover, current building regulations do not state requirements for sprinkler installations for residential buildings below 70m. However, the research suggests that the risk reduction by a sprinkler for mass timber buildings is so significant that this outweighs the economic or environmental investment costs for mass timber buildings below 70 meters. Therefore, suggesting sprinkler installations for the fire safety design for timber buildings below 70 meters may enhance mass timber building design, without significant additional fire risks.

10.2.3 Limitations

Due to the timeframe of the research, the methods present limitations. Beside the limitations regarding the defined circular design approach, the quantification methods for material use and fire risk of the fire safety design in mass timber buildings presents limitations.

10.2.3.1 Material use quantification

The material use in this research presents a circular approach. However, methods to determine the circularity impact of design measures are currently being developed by Platform CB’23 (2020). In this research, the current methods are used and further strengthened by literature review. It is observed that especially the end-of-life circularity value quantification of the elements is yet not clearly defined. In the research, therefore a simplified method is created.

The effect of a central unit of a sprinkler system is in the tool only considered in a simplified method, without considering the exact compositions of material or integration in to end-of-life circularity value.

Moreover, the replacement of materials during the buildings service life may require detaching other building components, which is not accounted for in the calculations.

For the quantification, material data was needed. It should be noted that the results are affected by the data, of which economic and environmental monetary values are most likely to be variable for alternative designs. If the monetary values are known in building design, these can easily be adjusted in the design tool, though might slightly change the outcome.

10.2.3.2 Fire risk quantification

The fire risk quantification is the most dominant part of the research and provides a first step to allow quantification of the fire risk in mass timber buildings. However, the method consists of many simplifications and assumptions, which provide limitations regarding the risk-calculation.

An important limitation is the number of considered fire safety measures. Alternative fire safety measures such as the influence of detection and alarm system, fire extinguishers, mist-system and impregnation could influence the fire scenarios.

Moreover, in the current fault-tree the probability of an ignited fire developing into a local fire is neglected. Also, the spreading of a fire is only considered due to failing of the structural resistance (R). The effect of failing of the partition elements by integrity (E) or insulation (I) and external flaming on the fire spread is not incorporated in the approach.

Besides this, the probability of (moment of) natural decay is simplified by looking at the moment that average compartment temperatures drop below 300 degrees. It is noted that this does not indicate the real behaviour of self-extinguishing, however, provides an indication of the moment that potential self-extinguishing could occur by additional fire fighter's suppression. It is expected that this method is sufficient for the goals of the research for preliminary design but should be further investigated for more detailed design.

For the calculations, data input was gained from literature. It is expected that the probability related values as well as the economic and environmental monetary value of the building will have the highest influence on the results. However, it is expected that adjustment of the data will not lead to a significant difference regarding the general conclusions of the research.

10.2.3.3 Value Corrections

In the timber strength calculations used in the design tool, the values for the k_{mod} and materialfactor are based on the values for ambient temperatures rather than fire conditions. When building on this research, these values should be changed to values stated by EN 1995-1-2, which results in a k_{mod} of 1 and a materialfactor of 1 as well as k_{fl} either 1.15 or 1.25. These assumptions change the results of the design tool and should be accounted for when building on this research.

10.2.4 Future research

The scope and boundary conditions of the tool limit the possible insight. Moreover, the assumptions made for data and methods have an effect on the results. Future research would therefore be to improve the tool by more thorough investigation of quantification methods and values and increase the scope of potential fire safety design choices. A short list of the general improvement of the tool for future research is:

- **Increase testing of the tool**
  In the research, only a few design variants are considered, though the tool allows an increased number of adjustments such as the effect of CLT adhesive, increasing the

number of CLT lamellas, and more. Further investigating the effect of these aspects would provide an increased number of conclusions which can be drawn from the tool.

- **Increase scope and research of quantification methods**
  The quantification methods are defined by calculations and values, which consist of several assumptions that influence the outcome. Increasing the scope and more in-depth research on the methods and input values could therefore increase the accuracy of the results.
- **Increased scope of considered fire safety measures**
  In the design tool, only the effect of sprinklers, encapsulation and CLT are considered as fire safety design measures. Increasing the influence of other (fire safety) design measures such as insulation, treated CLT or other type of sprinklers would increase the insight and usability.
- **Increased scope of material for considered fire safety measures**
  Currently, only CPVC sprinklers and fibre reinforced encapsulation are considered. Moreover, the distinction between the environmental impact of timber adhesive is not considered. The effect of alternative materials for these elements would enhance the most sustainable decision from a material perspective.
- **Flexibility of structural scheme**
  The structural scheme in the building is very simplified. Increased accuracy and flexibility of the structural scheme would improve the accuracy of a specific design.
- **Comparison to non-timber building**
  It would be interesting to compare the quantification to a non-timber building, for example concrete and look whether the benefits of timber outweigh the additional risks and required fire safety measures compared to other type of buildings.

Beside this, it is observed that some knowledge and data is lacking which is needed to further improve the tool. An overview of important aspects is:

- Increased transparency in EPD data
- Increased research on the circularity of fire safety measures, for sprinkler systems in particular
- Increased tests for effect of sprinkler (types) on fire behaviour and extinguishing
- Improved definition and increased knowledge on conditions for (self) extinguishing
- Effect of continuous smouldering of CLT
- In depth research regarding the effectiveness of fire fighter extinguishing in mass timber buildings (in and post fire)

11 Conclusions

In this chapter the conclusions of the research are presented by answering the stated research questions. With this, the objectives of the research are reached:

Enhance the understanding of the influence of the fire safety design on the balance between material use and fire risk in mass timber buildings,

By:

Creating a design approach that presents the relation between circular- and fire safety-design,

And utilize this approach to:

Create a design tool for preliminary design phase that quantifies balance between material use and fire risk for the fire safety design in mass timber buildings.

11.1 Sub-questions

The research was divided into two main parts: (1) the circular fire safety design approach and (2) the circular fire safety design tool for mass timber buildings. For these, two sub questions were formulated, which are answered below. The first question was defined as:

How can the relation between circular building design and fire safety design be defined and translated to a design approach for circular fire safety design?

The main objective of circular building design is to reduce the negative impact of material consumption. In the Netherlands three main objectives are stated for circular building design: (1) Protection of material sources, (2) protection of environment, and (3) protection of element/material value.

A building fire can have a large negative impact on building and surrounding, affecting the safety of people, and damaging material, environment, and economy. This way, a building fire negatively affects the objectives of circular building design, as (1) material is lost and this way end-of-life value damaged, (2) a fire results in toxic emissions, affecting the environment, (3) additional material is needed to either rehabilitate or build a new building.

To reduce the negative impact of a fire, fire safety measures are implemented in the design. However, this affects the initial objective of circular design, to reduce the negative impact of material consumption. This means that there is a balance between either affecting the aim of protection of material sources, or protection of fire risk. Where an increased amount of fire safety measures reduces the impact of a fire but increases the impact of material use.

This balance between fire safety design and circular design can be translated to a design approach where the influence of the fire safety design is considered in a circular and resiliency life cycle approach. The approach consists of two main parts: (1) Material use of the fire safety measures, and (2) the fire risk, representing the probability and impact of a fire for a certain fire safety design. By changing the fire safety design, the most favourable design can be determined. The most favourable design is the design with the lowest economic or environmental total value.

The second sub-question relates to fire safety design tool for mass timber buildings. This question was defined as:

How can a circular design approach be used to quantify the relation between material use and fire risk for the fire safety design in mass timber buildings?

Timber design is one of the sustainable solutions which has high potential to contribute to reaching a circular build environment, as timber is natural and renewable and the forests in which it is harvest functions as a carbon sink. Moreover, it has high potentials to be reused or recycled.

However, timber is combustible, which affects the characteristics of the fire dynamics and structural capacity, and this way the fire risk of the building. To reduce this risk, fire safety measures are applied, of which encapsulation and sprinklers are the most used measures.

The fire dynamics in mass timber buildings are affected by the design. It is observed that there are some aspects that have a significant influence on the characteristics, of which some are related to the building (ventilation and fuel load density) and some to the fire safety design. For the fire safety design, it is observed that especially the number of exposed CLT surfaces, the CLT adhesive type, the type of encapsulation, the number of encapsulation layers and the availability of a sprinkler installation has a significant influence on the fire dynamics and thus the severity of the fire. The fire resistance of the structural elements is mainly related to the structural scheme, heat flux exposure time, the encapsulation, number and thickness of timber lamellas and the adhesive type.

Because of the increased risk of timber design, general prescriptive regulation may not suffice for fire safety design, as these are based on “standard” non-combustible building materials. Therefore, the fire safety design should be based on a risk-based approach that considers the effect of the fire safety design on the fire dynamics and (structural) fire resistance.

By integration of the theory on fire safety design in mass timber buildings and the circular fire safety design approach, a method is developed that quantifies the material use of fire safety measure and the relating fire risk.

The defined quantification methods are integrated in a design tool in Excel. This tool provides insight in the influence of fire safety design in mass timber buildings on the material use and fire risk, by quantification into economic and environmental impact value. By summing the material use and fire risk, one “circular fire safety impact” value is calculated. This allows comparison between different fire safety designs. The most optimal design from a material perspective is determined by the design with the lowest total impact.

The calculation methods are integrated in a design tool created in Excel which allows changing the design parameters. The tool calculated the effect on material use and fire risk. The use of the tool consists of three main steps:

4. Implementation of design parameters
5. Analysis of the results
6. Variant study

This way, the tool gives insight in the influence of the fire safety measures on material use, fire risk and the combined "circular fire safety impact". By changing the fire safety design, the most optimal design variant can be determined. This is the variant with the lowest total impact value.

11.2 MAIN-RESEARCH QUESTION

After having answered the sub-research questions, the main research question can be answered:

How can a circular design approach be used as a means to steer fire safety design in mass timber buildings towards a solution that provides economic and environmental safety?

There is a contradiction between circular- and fire safety design. Circular design focusses on reducing the impact of material use, and fire safety design focusses on reducing the fire risk.

Until now, there was no specific method available that relates and quantifies these two aspects of design. This limits the possibility of fire safety design to contribute to a more circular building industry.

By creating a method that allows comparison between the economic and environmental impact of material use and fire risk, a well-founded choice of building materials is easier to make.

The design tool quantifies the impact on material use for fire safety measures relating to CLT, encapsulation and sprinkler availability and their effect on the fire risk in mass timber buildings. This way insight is provided between the balance of material use and fire risk. By the sum of the impact on material use and fire risk, the total "circular fire safety impact" value is calculated. This value represents the total economic and environmental impact of the design based on the choice of building materials. By changing the fire safety design, the most optimal design variant can be determined. This is the variant with the lowest total impact value.

This way, a circular design approach is used to steer fire safety design in mass timber buildings towards a design solution that does not only provide sufficient safety for people, but also provides maximum economic and environmental safety from a material point of view.

11.3 Recommendations

Based on the findings of this research, the following recommendations are made regarding the fire safety design in mass timber buildings:

- Considering the fire dynamic and resistance calculations, the results show that mass timber building design might provide sufficient fire resistance as stated by NEN-EN 1991-1-2+C3 without applying encapsulation or additional fire safety measures, meaning that the required resistance time suffices before the structure fails. However, based on the research it is observed that this may lead to significant damage and property loss of the building. Though, the regulations state that for residential compartments damage must be minimized and not spread beyond the neighbouring fire compartment. Therefore, following the general fire safety requirements stated by building codes, may not result in the intended safety regarding minimizing damage when designing a mass timber building.
- Moreover, current building regulations do not state requirements for sprinkler installations for residential buildings below 70m. However, the research suggests that the risk reduction by a sprinkler for mass timber buildings is so significant that this outweighs the economic or environmental investment costs for mass timber buildings below 70 meters. Therefore, suggesting sprinkler installations for the fire safety design for timber buildings below 70 meters may enhance mass timber building design, without significant additional fire risks.
- For a building with a compartment area of 48 m^2 a fully exposed CLT compartment results in the lowest material impact up to 15 building storeys (41m). However, this solution does not result in the functional requirement for residential buildings stating that the compartment beyond the neighbouring compartment may not be lost. Therefore, it is proposed that only up to 3 building storeys a residential building should be fully exposed. For buildings higher than 3 building storeys, but lower than 8 building storeys, it is suggested to apply 2 layers of fire rated encapsulation for 70% of the compartment surface. Above this height, a sprinkler becomes preferred over the use of encapsulation.
- Similar results are obtained for a compartment with a GFA of 140 m2. From these results follows that a fully exposed CLT compartment is preferred up to a building with 4 building storeys, after which a sprinkler is preferred. Again, considering the requirements it is proposed to construct residential buildings up to 3 storeys without additional fire safety measures. For 4-storey buildings, encapsulation is suggested. For a building higher than 4 building storeys, a sprinkler is preferred over the use of encapsulation.

It should be noted that the quantification methods and input data affect the outcome. Therefore, increased research is suggested to further strengthen the recommendations.

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APPENDIXES

1 LARGE SCALE COMPARTMENT FIRE TESTS

This appendix presents the elaborate analysis of the results of the large-scale compartment fire tests. The results of the tests are used for the theory regarding fire behaviour in mass timber buildings and the definition of fire risk calculations.

First the design characteristics of the tests are presented, after which the results. After this, the influence of the design measures on the fire dynamics are analysed.

1.1 DESIGN CHARACTERISTICS

In this section, an overview of the design characteristics of the compartment tests is presented, followed by a short description of the main focus and conclusions of the test.

1.1.1 INTRODUCTION

Since the beginning of this century, large scale compartment fire test with exposed timber have been examined. The focus and aim of the tests vary widely, and therefore the characteristics of the tests. This influences the results and the usability of the results. In previous documents by e.g., Brandon et al. (2016), Brandon (2018) and Wade et al. (2019), the characteristics and results of the compartment tests have been summarized. With help from these documents and by reading the test reports, an overview of the test characteristics is presented in Table 23. A short description of all the tests is presented in the following sections.

The first large scale compartment fire test which was constructed from CLT elements was done in 2008 by Frangi et al. At that time, some other tests had been done concerning other types of mass timber construction. The tests by Hakkarainen (2002) and Frangi and Fontana (2005) investigated the effect of exposed timber on the fire dynamics. Both test series observed similar results.

The tests by Hakkarainen (2002) showed rather low average gas temperatures for the test without protection, of approximately 700 degrees. This was due to insufficient ventilation and continued until the end of the test, when all movable fuel load was consumed at which the temperature increased. The conclusion was that at the end of the test due to the reduction of pyrolysis gasses, more oxygen could enter the building. Moreover, a big difference was seen regarding the exterior burning, which was approximately 3 times higher for the unprotected tests then for the encapsulated compartment tests.

Similar results were found in the tests by Frangi and Fontana (2005). From their tests was observed that for compartments with exposed timber the flashover time was much shorter, and the external burning more severe than for the encapsulated tests. The temperature height was though not really affected by the exposed timber. Because the tests were ventilation controlled, they concluded that this was the expected result, and is in line with the observations by Hakkarainen (2002). Frangi and Fontana (2005) noted that also for fuel-controlled tests external burning could be observed due to for example flame extension through openings.

From these two tests followed that the fire dynamics in a compartment will be affected by exposed timber surfaces. In 2008, the first large scale compartment fire tests constructed by CLT elements was done by Frangi et al. Since then, multiple more tests series have been done and more are currently being realized.

Table 23: Large scale compartment fire test characteristics

Reference	Test name	Floor area (m2)	Ventilation (m^0,5)	Percentage of exposed surface	Type of CLT	Type and amount of protection	Fuel load density (MJ/m2)	Fuel type
Frangi et al. (2008)	-	11,16	0,032	0%	-		790	Wood cribs + bed
McGregor (2013)	Test 1	15,75	0,042	0%	3-ply CLT 35mm thick PU-adhesive	2x12,7 mm fire rated	486	Propane
	Test 2			**0%**		2x12,7 mm fire rated	**533**	Furniture
	Test 3			100%		None	182	Propane
	Test 4			0%		2x12,7 mm fire rated	533	Furniture
	Test 5			100%		None	529	Furniture
Medina Hevia (2014)	Test 1	15,75	0,042	Back wall + Side wall Total 37%	3-ply CLT 35mm thick PU-adhesive	2x12,7 mm type X	532	Furniture
	Test 2			Opposing side walls total: 42%		2x12,7 mm type X		
	Test 3			Side wall Total: 21%		2x12,7 mm type X		
Su and Logheed (2014)	CLT	52,54	0,031	0%	-	2x12,7mm type X	550	Furniture
Su and Muradori (2015)	-	23,72	0,064	0%	-	2x16mm type X	790	Furniture and wood cribs
Hadden et al (2017)	Alpha-1	7,4	0,042	Back wall + 1 side wall Total: 41,5%	5-pl CLT, 100mm thick PU-adhesive	2x12,5mm type F	132	Wood cribs
	Alpha-2							
	Beta 1			Ceiling + back wall Total: 41,5%				
	Beta 2							
	Gamma			Ceiling + back wall + side wall Total: 62,2%				
Janssens (2017)	Test 1	15,90	0,033	Ceil: 100%	5-ply CLT 35mm thick PU-adhesive	Walls: Non-combustible	456	Propane burner
	Test 2			Ceil: 100%	5-ply CLT 35mm thick MUF-adhesive	Walls: Non-combustible.		
	Test 3			Ceil: 100%	5-ply CLT 35mm thick PU-fire resistant adhesive	Walls: Non-combustible.		
Brandon and Just (2018)	-	15,75	0,077	Walls: 63%		Walls: 2x15mm type F Ceiling: 3x15mm Type F	600	Furniture
Su et al (2018)	1-1	41,9	0,032	0%	5-Ply CLT 35mm thick PU adhesive	3x15,9mm type X.	550	Furniture
	1-2		0,065	0%		2x15,9mm type X..		
	1-3		0,065	1 wall 100% Total: 22,6%		2x15,9mm type x on walls. 3x15,9mm type X on ceiling		
	1-4		0,032	Ceil: 100% Total: 37,3%		3x15,9mm type X.		
	1-5			1 wall 100% Total: 21,9%				
	1-6			1 wall 100% ceil: 100% Total: 61,1%				
Zelinka et al (2018)	Test 1	82,8	0,105	0%	5-Ply CLT 35mm thick PU adhesive	2x15,9mm type X	550	Furniture
	Test 2			Ceil: 18% Total: 10,1%				

	Test 3			66% of two walls Total: 24,7%				
	Test 4		0,105 window closed	100%		None		
	Test 5			100%		None		
Brandon et al. (2021)	Test 1	47,95	0,062	Ceil: 100% Walls: 0% Beams: 100% Total: 44,2	5-ply CLT 35mm each HBX-PU	2x fire rated	560	Wood cribs + bed
	Test 2			Ceil: 100% Beams: 100% 2 walls not adjacent: 100% Total:75%		3x fire rated		
	Test 3		0,25	Ceil: 100% Beams 100% Right wall: 78% Front wall: 100% Column: 100% Total: 79%		3x fire rated		
	Test 4		0,062	Ceiling: 100% Beams: 100% Rightwall: 100% Leftwll: 100% Frontwall: 100% Column: 100% Total: 80%		2x fire rated		
	Test 5			Ceiling: 100% Beams: 100% Rightwall: 100% Leftwall: 100% Frontwall: 60% Column: 100% Total: 80%				

1.1.2 FRANGI ET AL. 2008

The test consisted of a full scale 3-storey building, which prior to the test was exposed to a shaking table, representing the behaviour of an earthquake. The floor area per storey was 49m2 (7x7m) and the building had a total height of 10m. The fire was ignited at one of the rooms on the first floor (Figure 65). This room was surrounded by two outer walls, two other rooms on the same level and the ground floor and the top floor. The dimensions of the ignited room were 3,34 x 3,34 and consisted of 2 windows of 1x1m with double layered glass. 3 walls existed from 85mm CLT and one wall was 142mm CLT. All walls and the ceiling in the room were encapsulated by 2 layers of gypsum board (1 normal board of 12,5 mm and one fireproof layer of 12mm) except for wall 4, which only had 1 layer of normal gypsum board protection of 12,5mm. Behind the gypsum layers, all walls and the ceiling were insulated with 27 mm mineral wool insulation. The door in the room was a 60-minute fire safe door. All floors of the building were constructed by 142mm thick CLT.

At the beginning of the test the window was opened for 0,25%, relating to an area of 0,26x0,94m. Fire fighter intervention extinguished the fire after 60 minutes.

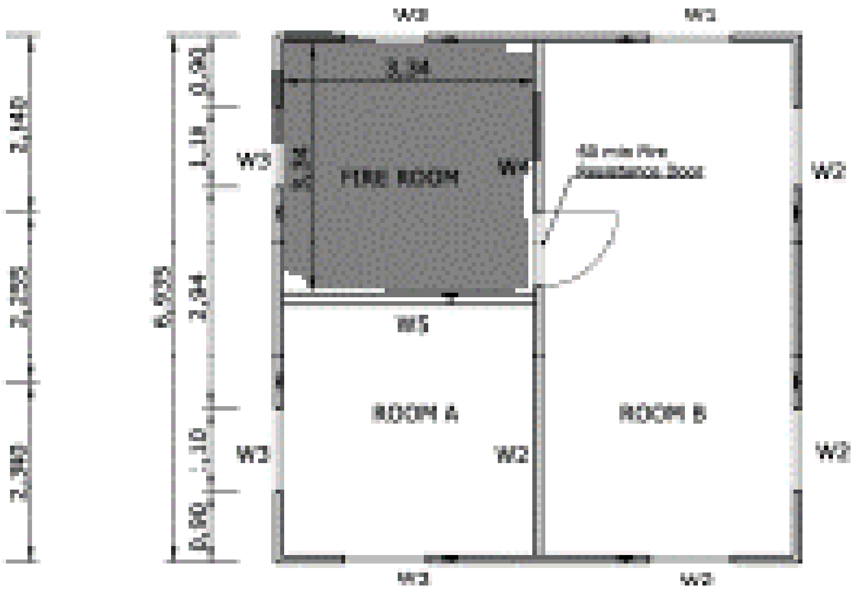


Figure 65: characteristics compartment test by frangi and fontana (2008)

The main conclusion from the tests was that fire spread can be prevented without observing temperature increase or smoke in the compartment above or below.

1.1.3 MCGREGOR (2013) & MEDINA HEVIA (2014)

In 2013 and 2014, a series of large-scale compartment fire tests was done by the Carlton University in Canada. The compartments in the tests had the same dimensions, which allows sufficient comparison and more accurate knowledge on the influence of the parameters on the fire dynamics. The compartment dimensions were 3,5 x 4,5 x 2,5. The compartments had one door opening which was fully open during the experiments of 2,2 m2 (2mx1,1m). In all tests the structural material of walls, floors and ceiling was 3-ply CLT panels (35mm) with a total thickness of 105mm.

McGregor (2013) did 6 tests in total, of which 3 were propane fuelled and 3 were furniture fuelled. The focus of the experiments was to investigate the impact of different configurations of exposed and gypsum protected CLT surfaces on the fire dynamics. All floors were protected with a layer of 15,9mm fire rated gypsum and a 12,7mm cement board.

From the tests by McGregor (2013) was found that all tests had similar peak temperatures, reaching temperatures which may be expected from ventilation controlled fire for these type of compartment characteristics. Moreover, delamination was observed in the tests with fully exposed CLT which resulted in more fuel and energy which prevented flaming extinction.

Medina Hevia (2014) did three additional furniture fuelled CLT compartment fire tests, with similar compartment dimensions as McGregor (2013). The main aim of the research was to study the contribution of CLT on the fire dynamics by looking at different configuration of exposed and protected CLT surfaces. From the tests followed that flaming extinction was only observed in the experiment where one wall was unprotected, and delamination did not occur.

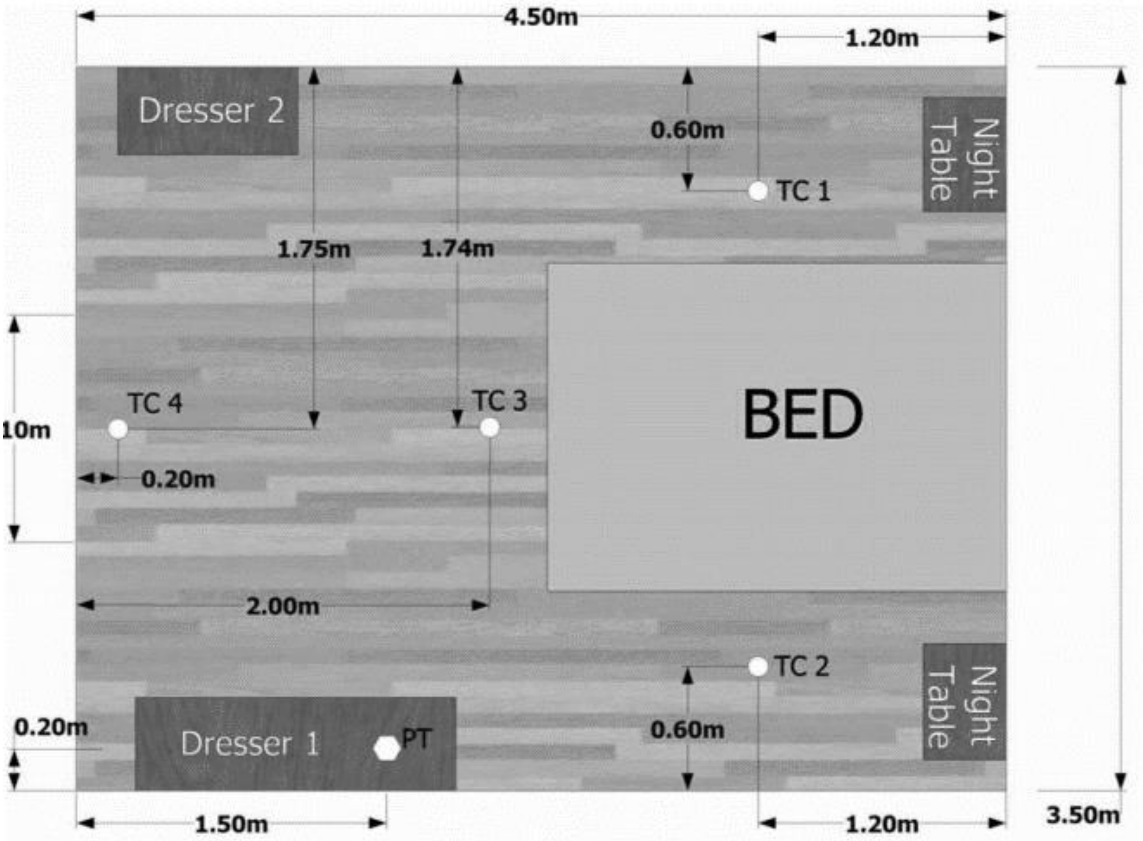


Figure 66: characteristics compartment test by McGregor (2013) and Medina Hevia (2014)

1.1.4 SU AND LOUGHEED (2014)

Su and Lougheed (2014) did four large scale compartment tests with different type of structural building materials. The aim of the research was to assess encapsulation of combustible construction materials as fire protection. Two of the tests considered light wood frame construction, one test was built up by CLT and one tests considered non-combustible materials.

The tests consisted of 3 storey apartment buildings, representing part of a real 6 storey building. The floor area of the storeys was 52,29 m2 (6,3x8,3) and had a height of 2,4m. All storeys represented typical apartment build up including a bathroom, living room and bedroom, completely furnished (Figure 67). Both the living room and the bedroom consisted of a window of 1,5x1,5m. The entrance room was 45 min fire safe. For the test composed out of CLT elements all walls existed of 105mm thick 3-ply CLT. The floors and walls consisted of 175mm thick 5-ply CLT panels. All walls were exposed and insulated by 38mm thick glass fibre insulation. The ceiling was encapsulated with 2x12,7mm gypsum board and the floor was protected by 2x12,7mm cement board with a hardwood cover.

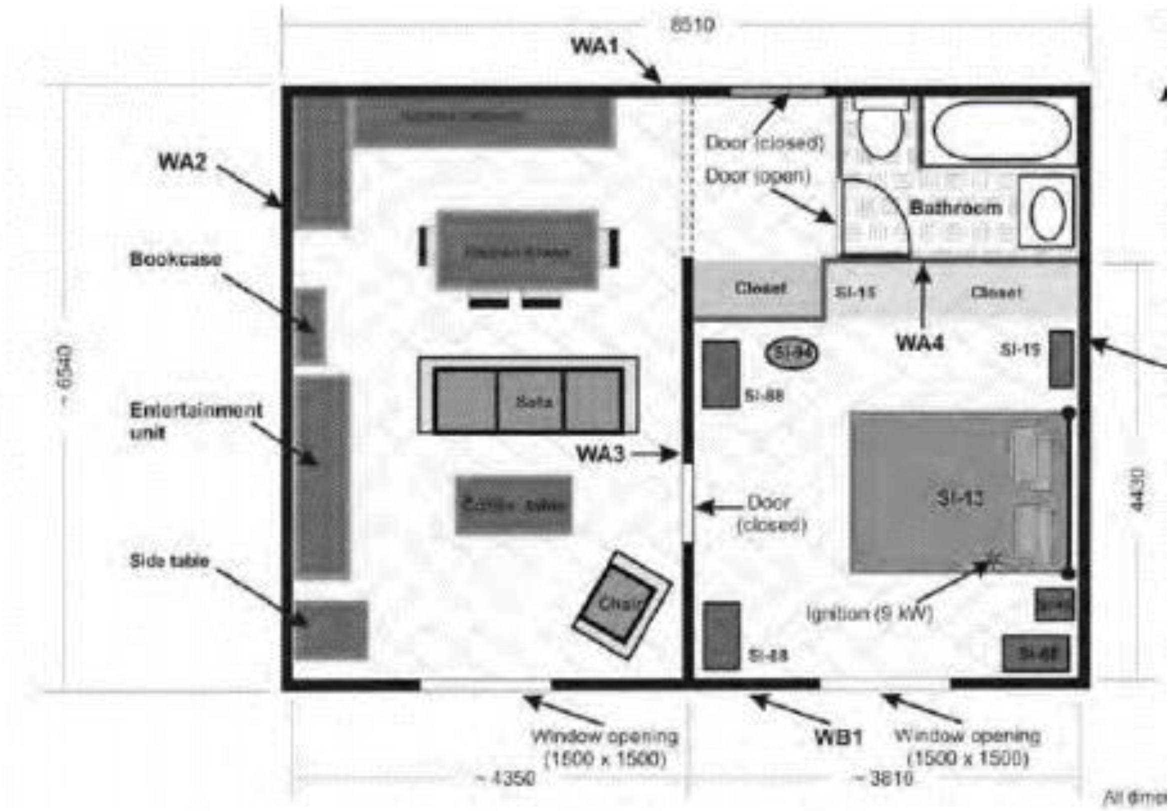


Figure 67: characteristics compartment tests by Su and Lougheed (2014)

From the test constructed from CLT followed that the type X gypsum board protection performed well and stayed in place on most surfaces untill end of test after 180 min.

1.1.5 SU AND MURADORI (2015)

Su and Muradori (2015) did one compartment test representing a section of a 13-storey building. The floor area of the compartment was 23,9m2 (5,2x4,6m) and height was 2,7m. The compartment also consisted of an elevator shaft with dimensions of 4,6x2,5x8,8m. The compartment had one opening of 4,75m2 (2,5x1,9) and had a 45-minute fireproof door. All walls consisted of 175mm thick 5-ply CLT with a protection of 2x16,0mm gypsum board. The wall connecting to the elevator shaft had additional protection with non-combustible rigid mineral wool and a 13mm thick gypsum board. The ceiling was encapsulated by 90mm fiberglass and 1 16 mm gypsum board. The floor was non-combustible.

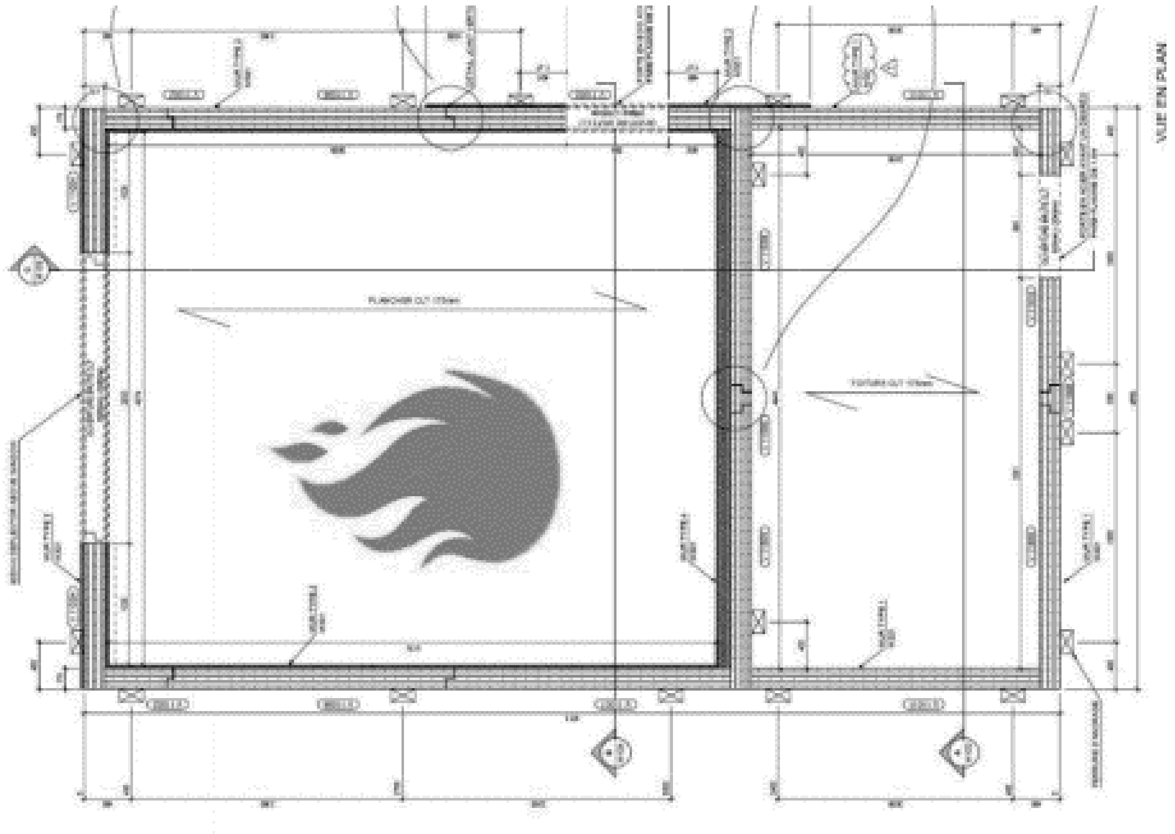


Figure 68: characteristics compartment test Su and Muradori (2015)

1.1.6 JANSSENS (2015)

Janssens (2015) did several tests, of which one of the tests was constructed from CLT. The dimensions of the compartment were 4,46 x 3,25 x 2,38, and had an opening of 1,87x2,07. The walls and ceiling were constructed from 175mm thick CLT and were encapsulated by 2x16mm type X gypsum board. The fuel load in the compartment was 601 MJ/m2. The aim of the experiment was to evaluate the performance of CLT with 2x16mm gypsum board protection. The test was terminated after 2,15 hours.

From tests by Janssen (2015) followed that the protected CLT did not reach 100 degrees C, although the temperatures in the compartment were up to 1222 C. Moreover, generally no charring was observed except from one or two locations near the floor where the wall was exposed to the heat of a pile of smouldering residue of the fuel. This test demonstrated effectiveness of 2 layers of 16 mm type X gypsum board.

1.1.7 HADDEN ET AL. (2017)

Hadden et al. (2017) did 5 compartment fire tests with different configuration to evaluate the impact of exposed CLT on the compartment fire dynamics. All tested compartments had a floor area of 7,4m2 (2,72x2,72m) and a storey height of 2,77m. There was one opening, representing the door, which was 1,4m2 (1,84x0,76m). The main aim of the study was to evaluate the impact of CLT on the fire dynamics for different configurations by focussing on HRR and temperatures.

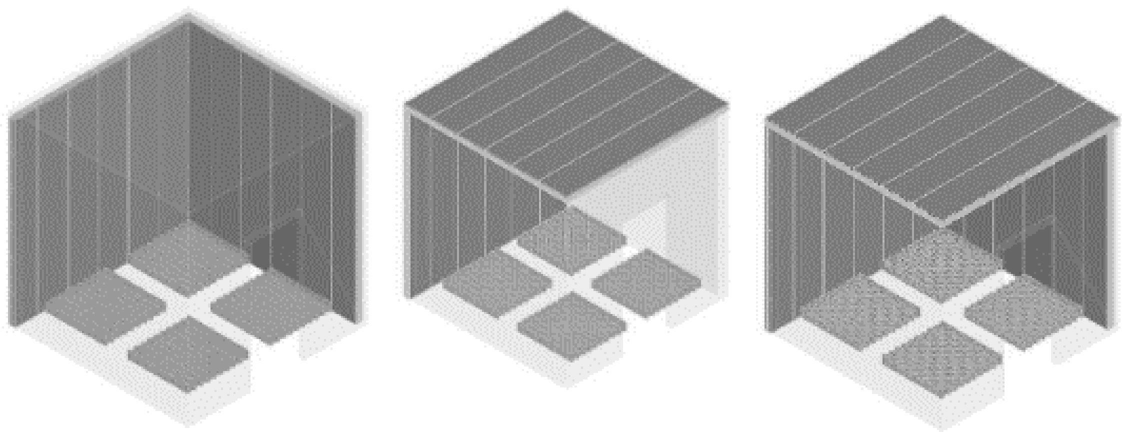


Figure 69: characteristics compartment tests by Hadden et al. (2017)

From the tests followed that self-extinguishing was observed in one of the tests, which consisted of 2 surfaces of exposed CLT. However, when the same test was constructed again, self-extinguishing was not observed. Hadden concluded that self-extinguishing of compartments with 2 adjacent exposed surfaces is possible, but that delamination should be avoided. Moreover, for the experiment with three exposed surfaces, no extinguishing was observed but rather a continuous fully developed fire.

1.1.8 JANSSENS (2017)

Janssens (2017) did tree compartments tests with a floor area of 15,90 m2. The tests consisted of non-combustible walls and exposed 5-ply CLT ceilings. The adhesive types from which the CLT was constructed varied and were PU, MUF and fire-resistant PU respectively. The main aim of the tests was to compare the fire performance of CLT with different adhesive types and the related fire dynamics.

Delamination was only observed from the test with normal PU adhesive. The other two tests did not show delamination and resulted in a natural decay and extinguished. From the test results it was concluded that fire resistant PU adhesive performed sufficiently under real fire conditions. This allowed code change for tall buildings with exposed timber in Canada and the US from 2021 onwards.

1.1.9 SU ET AL (2018)

Su et al. (2018) did six large scale CLT compartments fire tests for compartment dimensions of 9,1 x 4,6 x 2,7. In Figure 70, the compartment layout is presented. The main aim was to quantify the contribution of CLT in compartment fires, which was done by testing six different configurations of exposed timber. In addition to this, the influence of ventilation was considered.

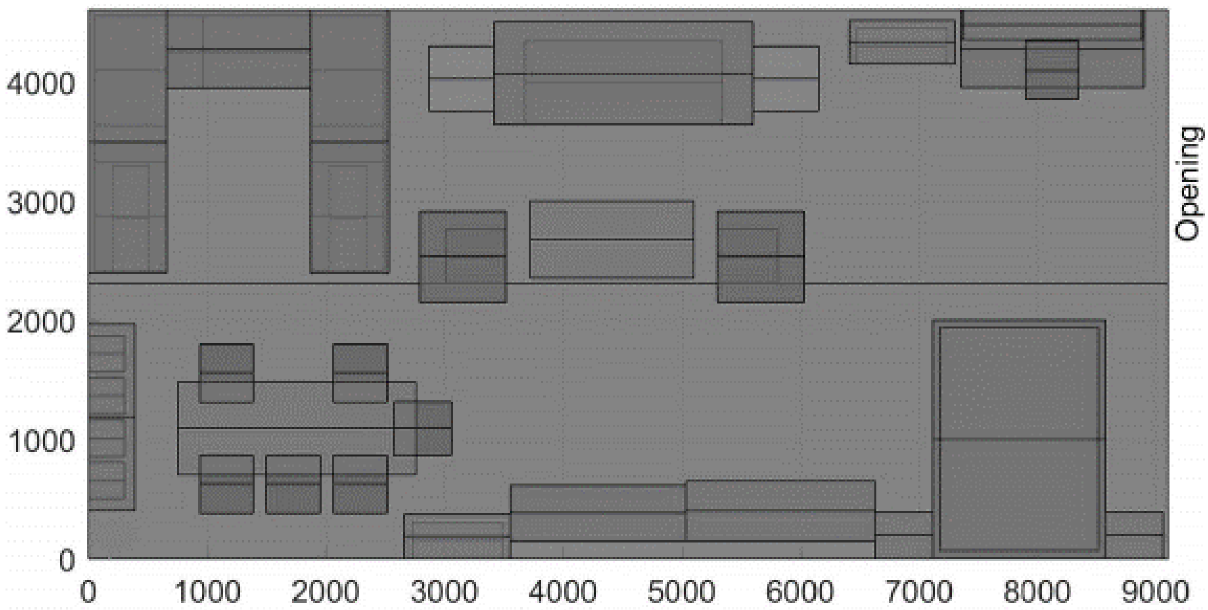


Figure 70: characteristics compartment tests by Su et al. (2018)

The main conclusions from Su et al. (2018) were that the amount of ventilation has a large influence on the temperature exposure in the decay phase (comparison test 1-1 and 1-2, or test 1-3 and 1-5). Moreover, exposed timber showed longer duration of the fully developed phase (comparison test 1-1, 1-4, 1-5, 1-6). Moreover, it is observed that whether

1.1.10 ZELINKA ET AL. (2018)

Zelinka et al. (2018) did five tests for 2 floor specimens. The floor area of the compartments was 82,8m2 (9,1x9,1m) and had a storey height of 2,7m. The tests included corridors. All tests had total windows openings of 3,66x2,44 m. The floor was non-combustible. The main aim of the research was to investigate the impact of exposed CLT on the fire dynamics by comparing different configurations. In addition to this, the last two tests consisted of sprinkler systems to evaluate the effect for this on the fire dynamics.

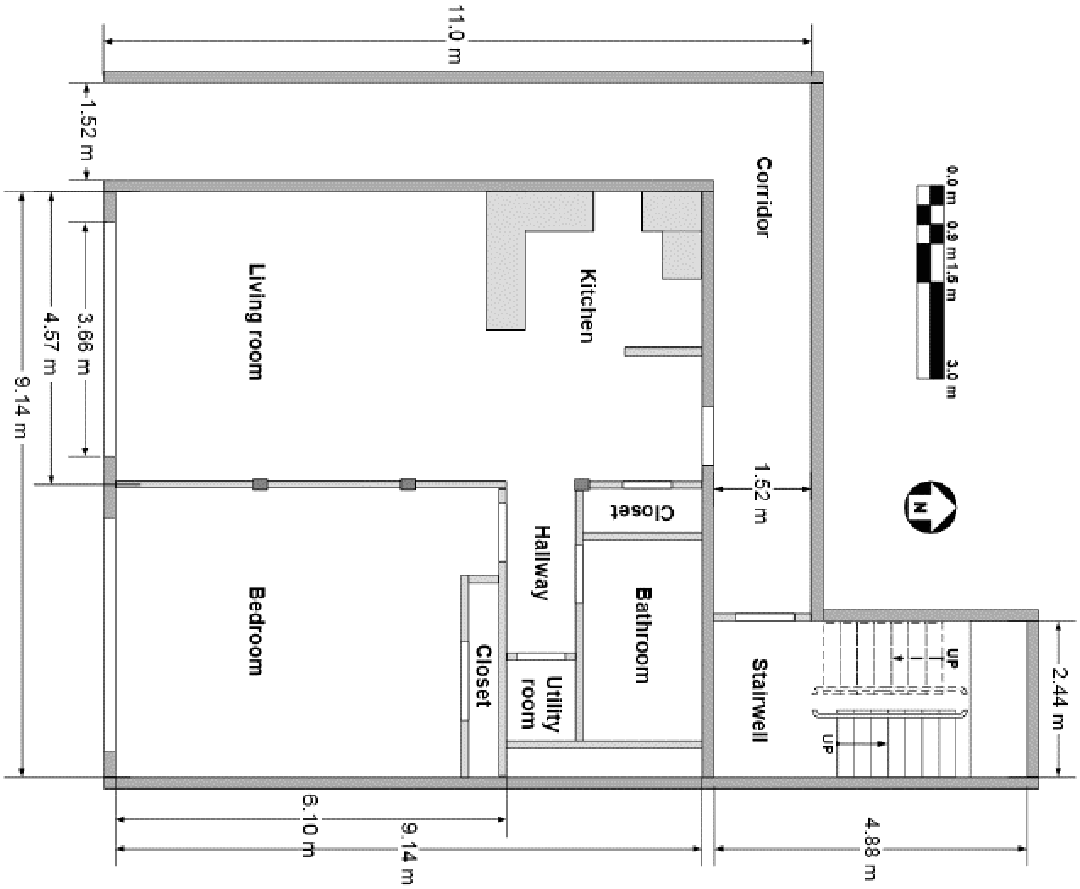


Figure 71: characteristics compartment tests by zelinka et al. (2018)

1.1.11 BRANDON ET AL (2021)

In (the end of) 2020, 5 large scale compartment fire tests were done with the aim to prove the safety of exposed timber ceilings in compartments and this way allow change in the American building code for buildings with exposed timber ceilings up to 12 storeys. The tests were done in Sweden by the Research Institute of Sweden (RISE). Many of the compartment elements were sponsored or gifted by companies. The five tests existed of one storey which had a floor area of 47,95m2 (7x6,85m), a floor height of 2,73 and resembled small residential compartments. The variable fuel load in the compartments was 560 MJ/m2, which was similar to the fuel loads used in the tests done by Su et al. (2018) and Zelinka et al. (2018). For all tests, the walls and ceiling were made from 5-ply CLT panels with a lamella thickness of 35mm. The adhesive type in the CLT was fire resistant HBX-PU. The floor was made from cement board. All tests had different compositions of exposed timber elements and varying opening sizes. The encapsulated parts either had 2 or 3 layers of 16mm gypsum board. Besides test 4, all tests had 2 openings each of 2,25x1,78m (total 8,01m2). Test 4 had 6 openings with a total area of 24,03m2.

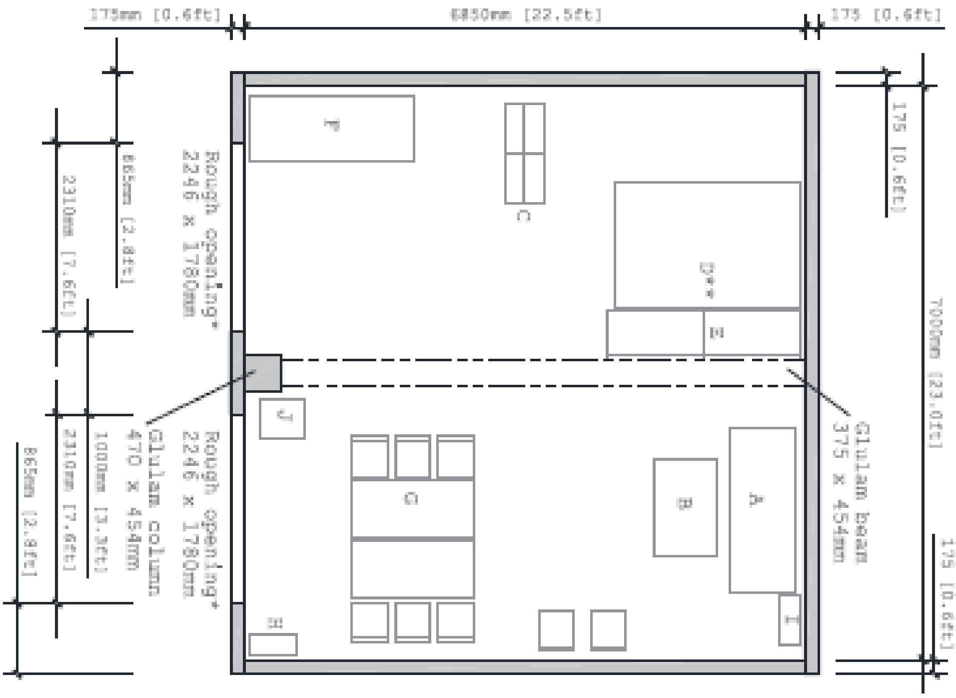


Figure 72: characteristics compartment tests by Brandon et al. (2021); top: test 1,2,3,5; bottom: test 4

1.2 TEST RESULTS RELATED TO COMPARTMENT FIRE DYNAMICS

In this section, the results of the large-scale compartment fire tests are presented. The focus of this section is on the influence of the (fire safety) design measures on the characteristics of the fire dynamics in mass timber compartments.

From the short descriptions of the tests is observed that the characteristics of the compartments as well as the different parameters and focus points vary widely. For this reason, accurately comparing the results and stating conclusions is difficult. However, some similarities in the test characteristics are found and this way of tests in which similarities are found are compared. The following design aspects are considered:

- Amount of exposed CLT
- Compartment size
- Ventilation
- Type of CLT
- Encapsulation measures

The most important test results regarding the fire dynamics are stated in Table 24. Visual comparison between some of the tests is presented in the following section.

Table 24: Large scale compartment fire tests - results

Reference	Test name	Flashover time	Peak temperature	Start of decay	Second flashover	GB fall-off	Delamination	Extinguishing
Frangi et al. (2008)	-	00:35	1100	00:55	No	Yes	-	01:00 manually
McGregor (2013)	Test 1	00:04:57	1200	00:25	Yes	Yes	-	01:59
	Test 2	00:07:30	1100	00:24	No	Yes	-	00:53
	Test 3	00:04:55	1109	00:45	No	-	Minor	00:53
	Test 4	00:09:26	1000	00:26	No	Yes	-	00:53
	Test 5	00:05	1000	no decay	-	-	Yes	01:03
Medina Hevia (2014)	Test 1	00:04	1200	00:20	Yes	-	Yes	02:00
	Test 2	00:05	1100	00:20	Yes	Yes	Yes	00:56
	Test 3	00:06	1100	00:20	No	Yes	No	01:21
Su and Logheed (2014)	CLT	00:03	1100	00:23	Yes	Minor	-	03:05
Su and Muradori (2015)	none	00:02:35	1100	00:45	No	Yes	-	02:00
Hadden et al (2017)	Alpha-1	00:04:40	1236	00:12	Yes	Yes	Yes	01:01
	Alpha-2	00:05	1150	00:20	Yes	Yes	Yes	01:00
	Beta 1	00:08	1150	00:12	No	No	Partial	Auto-extinguishing
	Beta 2	00:04	1114	00:16	Yes	Yes	Yes	01:02 Manual
	Gamma	00:05:35	1190	no decay	-	Yes	Yes	01:18 Manual
Janssens (2017)	Test 1	00:13	1174	01:28 consistent with end propane burner	Yes	-	Yes	03:15 manually when re-growth occured
	Test 2	00:13	1141		No	-	No	03:30 manually
	Test 3	00:13	1172		No	-	No	04:00 manually
Su et al (2018)	1-1	00:13	1200	00:52	No	Yes	-	02:14 manually
	1-2	00:13	1200	00:40	No	Yes	-	01:44 manually
	1-3	00:12	1200	00:43	Yes	Yes	Yes	Natural decay and manual extin.
	1-4	00:11	1200	00:55	Yes	Yes	Yes	Manual when re-growth
	1-5	00:11	1200	00:41	Yes	Yes	Yes	Manual when re-growth
	1-6	00:11	1200	no decay	-	Yes	Yes	02:40 Manual
Zelinka et al (2018)	Test 1	00:14	1080	00:26	No	No	-	Natural
	Test 2	00:11	1130	00:28	No	Yes	No	Natural with manual at 4hr

	Test 3	00:13	1170	00:28	No	Yes	Localized	Natural decay with mantual ate 4 hr
	Test 4	No flashover	-	-	-	-	-	Sprinkler
	Test 5	No flashover	800	-	-	-	-	Delayed sprinkler
Brandon et a. (2021)	Test 1	00:14	1200,00	00:36	No	-	No	04:00
	Test 2	00:08	1250,00	00:36	No	Yes	No	04:00
	Test 3	00:12	1200,00	00:43	Yes	-	No	03:31
	Test 4	00:15	1100,00	00:29	No	-	No	04:00
	Test 5	00:04	1200,00	00:34	No	Yes	No	04:00

1.2.1 Influence of exposed CLT and its location

Many of the compartment tests focused on addressing the influence of exposed timber surfaces on the fire dynamics compared to non-exposed timber compartments. For comparison of the test results and to understand the impact of exposed surface area on the fire dynamics, the tests are further divided based on the number of exposed surfaces. The tests are categorized by:

- Fully encapsulated
- One exposed surface
- Two or more exposed surfaces

Only the tests without sprinkler activation will be considered for now. The division of the tests is presented in Table 25.

Table 25: Overview of extinguihing characteristics

Fully encaspulated		1 surface exposed		Fully exposed	
McGregor (2013)	Test 2	Medina Hevia (2014)	Test 3	McGregor (2013)	Test 5
	Test 4	Janssen (2017)	Test 1	Hadden et al. (2018)	Alpha 1
Su and Muradori (2014)	-		Test 2		Alpha 2
Zelinka et al. (2018)	Test 1		Test 3		Beta 1
Su et al. (2018)	1-1	Su et al. (2018)	1-3		Beta 2
	1-2		1-4		Gamma
			1-5	Su et al. (2018)	1-6
		Zelinka et al. (2018)	Test 2	Brandon et al. (2021)	Test 2
			Test 3		Test 3
		Brandon et al. (2021)	Test 1		Test 4
			120		Test 5

1.2.1.1 General observations

Based on the results from the large-scale compartment fire test follows that an increased amount of exposed timber resulted in faster flashover times. The peak temperatures are not seen to be affected by the amount of exposed timber. However, the duration of the fully developed phase and whether a decay is observed is seen to be related to the number of exposed surfaces.

1.2.1.2 Influence of single exposed surface

For many of the tests with one exposed timber surface, a moment of steady burning was observed after all movable fuel load was consumed (Medina Hevia,(2014), Su et al. (2018), Zelinka et al. (2018) and Brandon et al. (2021)).

The tests by Janssens (2017) shows a fully developed phase which is consistent with the burning pattern of the propane burner. It was observed that when the burner is turned off after 90 minutes, the burning of the timber is not sufficient to sustain the fire.

A decay is observed in all the tests, although half of the test show a regrowth (test 1 by Janssen (2017), test 1-1 by Su et al. (2018)). All other tests showed proper decay although manually extinguished before self-extinguishing really observed. For these tests no delamination was observed. From the results follows that the tests which showed delamination in the decay phase resulted in a second re-growth. Test 1-3 by Su et al. (2018) shows an HRR pattern with cyclic regrowth which is explained by delamination quickly after the start of the decay. In test 1-4 by Su et al. (2018) the regrowth occurred due to delamination in the decay phase. Test 1-5 by Su et al. (2018) also showed a regrowth, this was however a result of the failing of the gypsum board on the ceiling, which occurred when the exposed wall started to delaminate. By this time, now multiple CLT surfaces were exposed which allowed the fire to re-grow.

Moreover, the tests by Janssen (2017) show that delamination only occurs for test 1, which had a ceiling constructed from PU adhesive, this resulted in re-growth. The tests with MUF and fire-resistant PU adhesive don't show delamination. The results by Brandon et al. (2021), for which the compartments were constructed from the PU fire resistant adhesive are in line with the results by Janssen (2017) and don't show delamination. The test by Brandon et al. (2021) confirms the conclusions from Janssen (2017) showing that a fire with a single exposed surface can decay if it is not prone do delamination or gypsum board fall-off.

Thus, from these results follows that in general, a compartment with one exposed CLT surface will prolonged the burning period for some time, however, generally show a decay. In case delamination or gypsum board fall-off does not occur during the (still hot) decay phase, the fire will (probably) self-extinguish. The results of these tests show that where a single surface is exposed, but the fire burns for a prolonged period, the encapsulation can fail, or delamination can occur resulting in the freshly exposed timber surfaces becoming involved in the fire and start re-radiating which can result in a redeveloped fire.

1.2.1.3 Two or more exposed surfaces

For the tests with more than 2 exposed timber surfaces a period of steady continued burning is observed after the fuel load is consumed. Here, the exposed timber contributed to the fuel load, resulting in longer duration fires when compared to a compartment with non-combustible linings. This observation is gained by comparing the test results of e.g., Sue et al. (2018) for different amount of exposed timber (see main report).

Three of the 11 tests (test 5 by McGregor (2013), test gamma by Hadden et al. (2017) and test 1-1 by Su et al. (2018)) maintained steady state burning after all movable fuel was consumed and did not show a decay until manually extinguished. It is concluded that this was due the extended heating periods which resulted in failure of the encapsulation. Following failure of the encapsulation, the remaining timber also became involved in the fire and started to delaminate. Resulting in a cycle of freshly exposed timber.

The other tests showed a start of the decay, which resulted in re-growth after delamination for test 1 and 2 by Medina Hevia (2014), test alpha-1/2 and test beta-2 by Hadden et al (2017). Natural decay was observed in test 3 by McGregor (2013), test beta-1 by Hadden et al (2017) and three of the four tests by Brandon et al. (2021). However, when Hadden et al. (2018) re-generated the composition, no decay was observed but rather a cylindrical HRR pattern.

Different from the other tests, the tests by Brandon et al (2021) were constructed by fire resistant PU adhesive, and therefore in these tests, no delamination was observed. However, test 3 shows a regrowth of the fire without delamination as small flames are observed behind the char layer. This is a concerning observation and more research on this topic is required.

A general conclusion regarding the influence of multiple exposed timber surfaces is that the duration of the fully developed fire is increased. When during this time the protection starts to fail, more timber will be involved in the fire and can lead to a sustained burning. However, as witnessed from the tests by Brandon et al. (2021), if the gypsum protection is maintained during sufficient time and the structure cannot delaminate, self-extinguishing of compartment fire with multiple exposed timber surfaces is possible.

1.2.2 INFLUENCE OF COMPARTMENT SIZE

All the examined and available tests are based on compartments of limited size, reflecting a single bedroom or studio apartment with from floor areas varying from 7,4m2 (Hadden et al., 2018) to 82,8m2 (Zelinka et al., 2018).

The size of the compartment, and whether it is one open space or divided into different spaces by walls influences the homogeneity of the compartment temperatures over time. For comparison of the impact of compartment size on the fire dynamics, the encapsulated tests 1-1 by Su et al. (2018) and test 4 from McGregor (2018) are addressed based on their comparable configuration with different sizes.

From the comparison follows that for the small compartments from the tests by McGregor (2013) there are slight differences between the temperatures within the compartment, however, the temperature development at the different locations is rather similar. The temperature development in the test from SU et al. (2018) however differs throughout the compartment. It is clearly visible that the hottest area moves from the front of the room, near the opening (TC 2 and 3 around) towards the middle of the room (TC5 and 6) to the rear end of the room (TC 1 and 4). The peak temperatures of around 1200 degrees are reached from front to back at approximately 30, 40 and 50 minutes after ignition respectively.

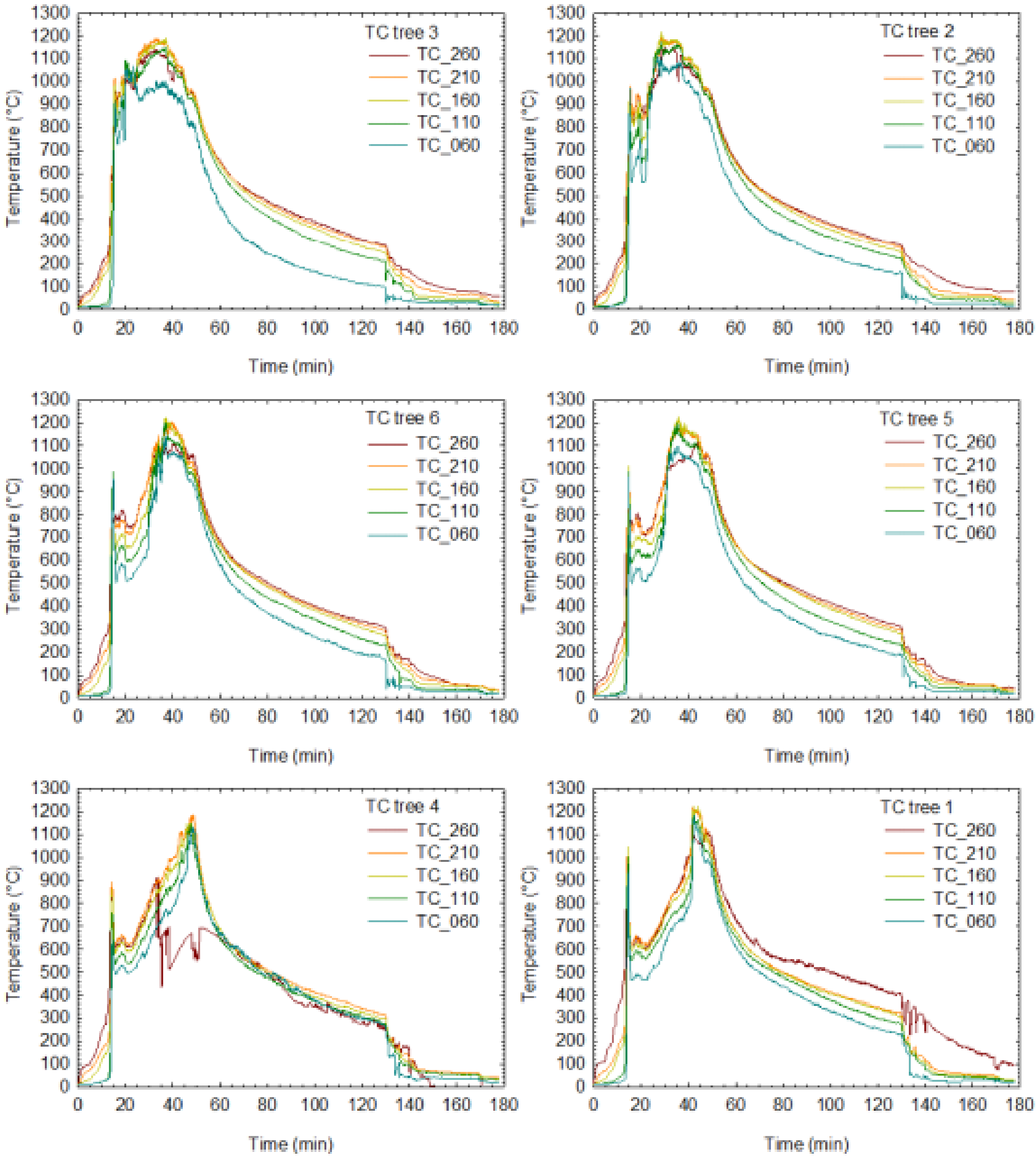


Figure 73: temperature distribution over time for different locations, test 1-1 by Su et al. (2018)

From this observation follows that the size of the room thus affects the gas temperature distribution throughout a compartment, for compartments with non-combustible surfaces. A similar distribution of temperature throughout the compartment is observed in test 1-6 by Su et al. (2018), with an exposed area of 61,1%. It is clearly visible that the peak temperature is reached after approximately 30 minutes for the front of the room, near the opening, and is reached after approximately 80 minutes for the rear end of the room.

From the results follows that for larger compartments, the temperature distribution varies throughout the compartment, depending on the location of the opening. This is explained by the difference between ventilation- and fuel-controlled fire for the different parts of the compartment.

1.2.3 Influence of ventilation

In general, the size of the compartment also influences the amount of ventilation and thus the amount of oxygen in the compartment. All the investigated tests were ventilation controlled, meaning that there was a lack of oxygen rather than fuel. This has an influence on the fire dynamics, which is accurately observed from the tests by Su et al. (2018.). In the fully enclosed tests 1-1 and 1-2, a clear difference is observed. In test 1-2, with larger ventilation openings, the speed of the combustion of the room contents was higher. This "intensified the exterior exposure while shortening the intense burning duration". The ventilation had no effect on the temperatures or heat fluxes, but the fully developed fire was shorter for the well-ventilated compartment. Moreover, the heat release was more intense for test 1-2. The tests were terminated when the temperatures reached below 300 degrees.

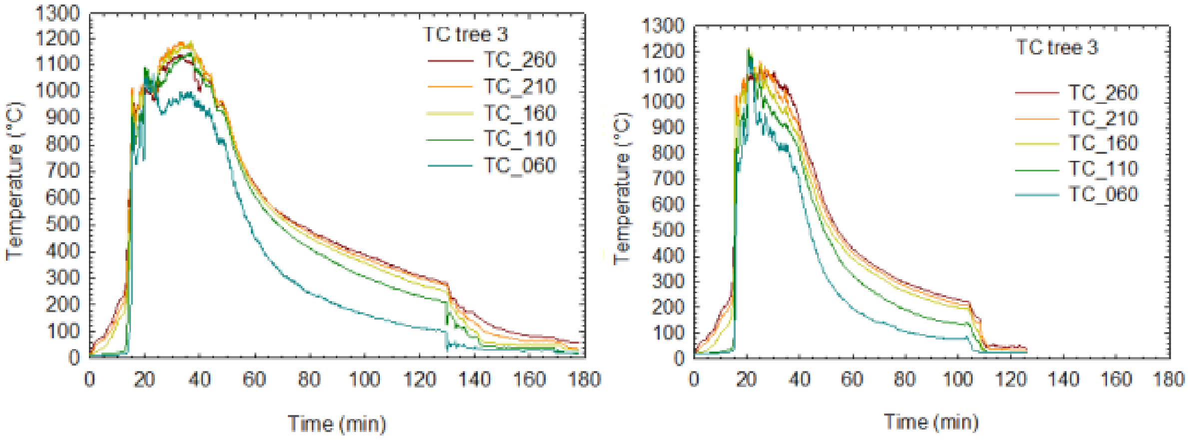


Figure 74: Temperature distribution by Su et al. (2018); left: test 1-1 low ventilation; right: test 1-2 high ventilation

In the same test series, the effect on ventilation for timber exposed compartments is clearly visible from test 1-3 and 1-5, with similar exposed wall. Here, the well-ventilated test was test 1-3. It was observed that increased ventilation results in higher heat release rate, higher external heat fluxes, and more general decay, also more delamination was observed. It is noted that due to smaller openings in test 1-5, the heat of the fire was locked and the temperatures in the decay were much higher, which resulted in delamination in the decay phase and second flashover. It was observed that ventilation does not influence the peak temperature.

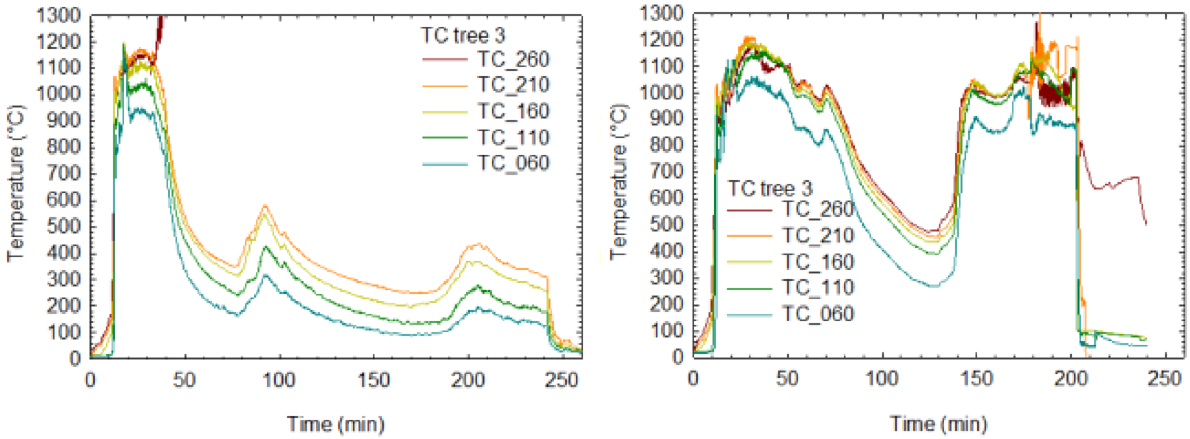


Figure 75: temperature distribution by Su et al. (2018); left: test 1-3 high ventilation; right: test 1-5 low ventilation

The test series by Brandon et al. (2021), test 4 also highlights the effect of ventilation. Compared to the other tests, the duration of the fully developed phase much shorter. Moreover, it is observed that the high wind speeds at the time of testing result in ashes flying through the openings.

1.2.4 Influence of type of CLT

The type of CLT has large influence on the decay phase of the compartment fire, mainly relating to the effect of delamination. Delamination was observed in many of the large-scale compartment tests with exposed timber surfaces. It was observed that delamination during the fully developed phase can lead to sustained fire and that delamination in the decay phase can result in a secondary flashover. Unfortunately, all the tests for which delamination was witnessed which resulted in regrowth, were manually extinguished before a fully developed fire was observed.

Hadden et al. (2017) found that char layers on the ceilings were more prone to fall off compared to delamination of wall elements, which he concluded was due to gravity.

Janssens et al. (2017) did several compartment experiments to state the effect of delamination by comparing the fire dynamics for different types of adhesives. Test 1 was constructed by CLT with PU adhesive, test 2 was constructed with a MUF adhesive and test 3 with a fire-resistant PU adhesive. In all tests the ceiling was exposed and the walls non-combustible. From his tests followed that the test with PU adhesive showed delamination in the decay phase, which resulted in a secondary flashover. The MUF and the fire-resistant PU adhesives showed a decay without delamination and thus without secondary flashover. These results allowed for code change in Canada and America for the use of fire-resistant PU adhesives for large scale timber compartments.

However, the recent tests by Brandon et al. (2021) presented some problematic results for the compartment fire dynamics of "Tests 3" using the fire-resistant PU adhesive. In the decay phase of the test, when temperatures were below 300 degrees, suddenly HRR and temperature began to rise, and small flames behind the char were visible. Without delaminating the fire dynamics began to show signs of a secondary flashover. Unfortunately, the test was extinguished at this moment, and the influence of the flames not further examined. These results provide big concerns regarding the use of fire-resistant PU and further testing is needed. MUF adhesives have shown to provide the most certain prevention of delamination so far.

1.2.5 The influence of timber protection/encapsulation:

The influence on the efficiency of the timber protection has been the focus of many large-scale compartment tests. From the tests by Su et al. (2018) was observed that failing of the protection during the fully developed phase can result in prolonged fire exposure. Moreover, it was found that if gypsum fails during the decay phase, it can lead to a secondary flashover. From the tests by Su et al. (2018) follows that the exposed gypsum layer from the ceiling failed when the temperature behind the exposed gypsum board were between 300 and 500°C. From fully encapsulated experiments it was found that the gypsum boards on the ceiling are more prone to failure compared to gypsum boards on the walls.

1.2.6 Influence of sprinklers

For compartments with only one surface of exposed CLT, a decay is generally found to occur after some time. As only two tests considered the effect of sprinklers, only some conclusions can be drawn, although it clearly shows that the approach in the Eurocode is not an accurate for real fires.

Currently, only test 4 and 5 by Zelinka et al. (2018) considers the effect of sprinklers on the fire dynamics. Both compartments have fully exposed walls and ceiling and consists of an automatic sprinkler installation. Test 4 has an automatic sprinkler installation activated from the start of the fire and test 5 has a delayed sprinkler installation, which starts 20 minutes after the fire is detected. The results of the compartment temperatures is visible in the figures below.

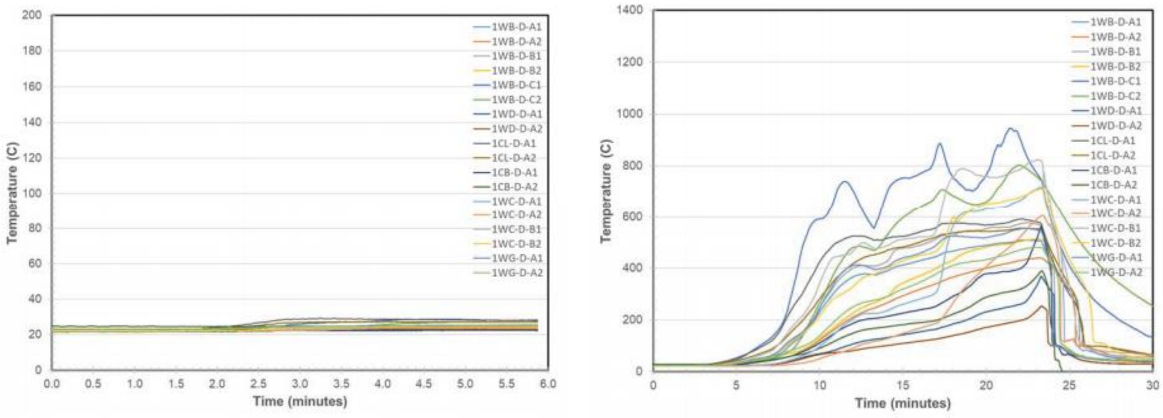


Figure 76: the effect of sprinklers on the fire dynamics, Zelinka et al. (2018); left: test 4; right: test 5

From the results of both tests follows that at the moment the sprinkler is activated, the fire will be extinguished, even if the CLT surfaces in the compartment are fully exposed.

2 PERFORMANCE BASED FIRE SAFETY DESIGN FOR MASS TIMBER BUILDINGS

This appendix focusses on performance-based fire safety design for mass timber buildings. First a short description regarding available methods and models for predicting compartment fires in general is presented. After this, models for predicting the fire dynamics in mass timber compartments is presented.

2.1 PERFORMANCE BASED FIRE SAFETY DESIGN

To predict the fire dynamics in a compartment, different types of models are available. The predictions of these models are based on mathematical formulas describing the physical and chemical behaviour in compartment fire of which include heat transfer, fluid dynamics and combustions. Although simple hand calculations have been used for this purpose in the past, the use of computer-based models has been leading since the 80s. There are two physics-based mathematical models which are commonly used, namely zone models and computational fluid dynamic models (CFD). Besides these, a simpler prediction method is the equation-based fire model, which uses analytical equations to predict the dynamics by parametric input. Each of these model types have different advantages and disadvantages, these which will be elaborated below. (Wade, 2019)

2.1.1 ZONE MODELS

The first zone model was built in 1970's with the aim to contribute to the study on compartment fires. A zone model solves equations for conservation of mass and energy for one or more control volumes. Normally, not more than 2 volumes per enclosure are considered: one volume for the hot upper layer of zone and one for the colder lower layer of the zone. The simplest approach is solving mass and energy conservation for the control volumes, as visible in Figure 77. (Wade, 2019)

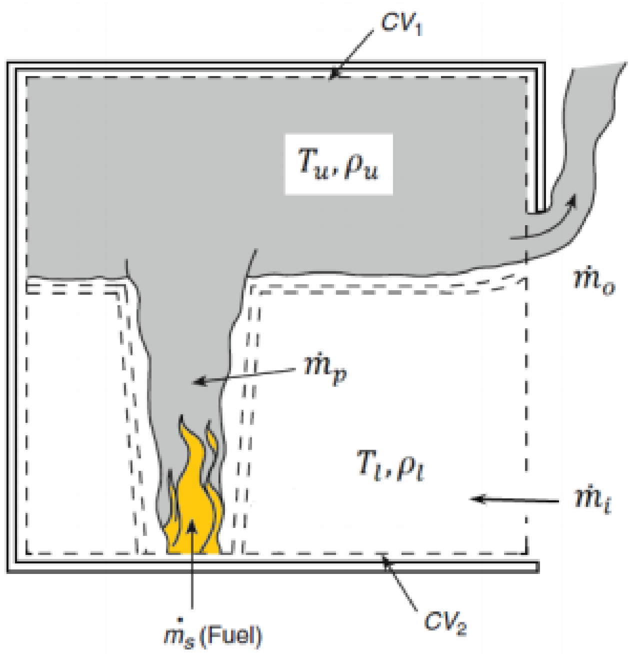


Figure 77: Zone model (Quintiere and Wade, 2015)

In the figure, CV1 and CV2 are the two compartment volumes. As visible, CV1 encloses the gasses in the upper layer and the gasses in the plume. CV2 encloses the remaining volume. The interface between the two layers can move up or down and this way the volumes change. This happens because the mass and energy released by the combustion of the fuel are transferred to the upper layer, which increases the volume of the upper layer and moves the interface more down. Moreover, volume from the upper layer is lost due to openings in this upper layer. By openings in the lower layer, cold air can flow into the zone and adds to the CV2. (Wade, 2019)

When using zone models, a lot of assumptions are made. For starters, the properties of the control volume are assumed to be uniform but can differ over time. Moreover, the gases which are transported in the plume are instantaneously distributed along the ceiling. Beside these general assumptions, Quintiere and Wade (2018) made a list of other commonly used assumptions. These will not be discussed in depth in this report.

Beside the general approach, many zone models include sub-models. These are used to quantify the mass and energy flows and are often based on imperial relationships. Moreover, sub-models can include specific advanced characteristics to increase purpose of the model, such as the contribution of timber to the fuel load (Wade, 2019).

Because of the many assumptions needed for the use of zone models, the application of the use of this model is limited to predict simpler fire scenarios. For more complex scenarios, as well as other type of fire modelling, CFD models provide a more advanced alternative.

2.1.2 CFD MODELS

Another type of fire dynamic prediction approach is the Computational fluid dynamics approach (CFD). CFD can be used for various type of problems related to fluids, of which including fire. In a CFD model, the compartment is divided into many (up to millions of) smaller volumes for which conservation of mass, momentum and energy are calculated by solving partial differential equations. Due to this, CFD is much more complex than the zone-model approach and a computer is generally required. (Wade, 2019)

2.1.3 EQUATION BASED MODELS

Equation based models are much simpler the CFD model and zone models. It uses parametric relationships based on analytical equations to predict the temperature in a fire compartment over time. Parameters required for the input are compartment dimensions, opening size, fuel load energy density, and thermal characteristics of the compartment linings. The National annax of NEN-EN 1991-1-2+C3 (2019) guidelines describe such a parametric method for the time-temperature curve for compartments up to 500m2 with a hight of maximum 4m.

Advantages of equation-based fire models is the user ease which provides the possibility of using simple spread sheets to calculate the fire compartment dynamics. However, the advantage is directly linking to the disadvantage considering the lack of possibilities to include mass and energy conservation equations. It is therefore an easy and accessible method however, yet not necessarily accurate.

2.2 FIRE MODELS FOR EXPOSED TIMBER COMPARTMENTS

In this section, performance-based fire safety design methods for mass timber buildings are presented.

NEN-EN 1991-1-2+C3 (2019) provides guidelines for performance-based fire design by the parametric temperature-time curve, which is an equation-based model. For non-combustible compartments, this method may provide a sufficient prediction of the fire dynamics, as the building materials themself don't contribute to the fuel or heat of the fire. For compartments with exposed timber surfaces, CLT may contribute to the fire and affect the characteristics.

Therefore new, improved engineering models have been developed in the last years, which consider the influence of the exposed timber on the fire dynamics in a compartment. In the next paragraphs, the models for which this method is considered is described more in depth.

2.2.1 HOPKIN ET AL. (2017)

Hopkin, Brandon and Anastova (2017) created a pragmatic zone model to predict the fire behaviour in exposed or partially exposed CLT compartments. The aim was to create a new design approach for fire safe, tall timber buildings.

The method is based on the use of effective thermal properties, which influence the mass burning rate (char) and the HRR. Here the char rate is based on the predictions of the fire and the timber temperature. The model considers the contribution of timber to the fuel load by determining the contribution on the HRR based on char rate calculations. The charring rate is estimated based on timber and fire temperature. With this the contribution of the HRR from the timber is calculated and added to the HRR from variable fire load to determine gas temperature. It is assumed that the gas temperature in the compartment is homogeneous throughout the compartment.

2.2.1.1 VALIDATION

The model is validated by comparing the predictions to test results from large scale fire tests series from McGregor (2013) and Medina Hevia (2014). From the comparison follows that the model prediction of the heating phase results in acceptable predicted temperatures for the walls until delamination occurred. For the compartments where no delamination occurred, the decay phase time was predicted accurately, however, the rate of temperature decrease in the decay phase was overestimated. They state that this could be improved by including the radiation between the surfaces in the model. During the fully developed stage, the model overestimated the HRR. Examples of the comparison of the prediction of the temperatures to the test results is visible in the figures below.

The final char depths calculated by this method do not result in conservative estimations when compared to the char depths found in the experiments. Hadden et al. (2017) state that this is because delamination was not to influence the char depth.

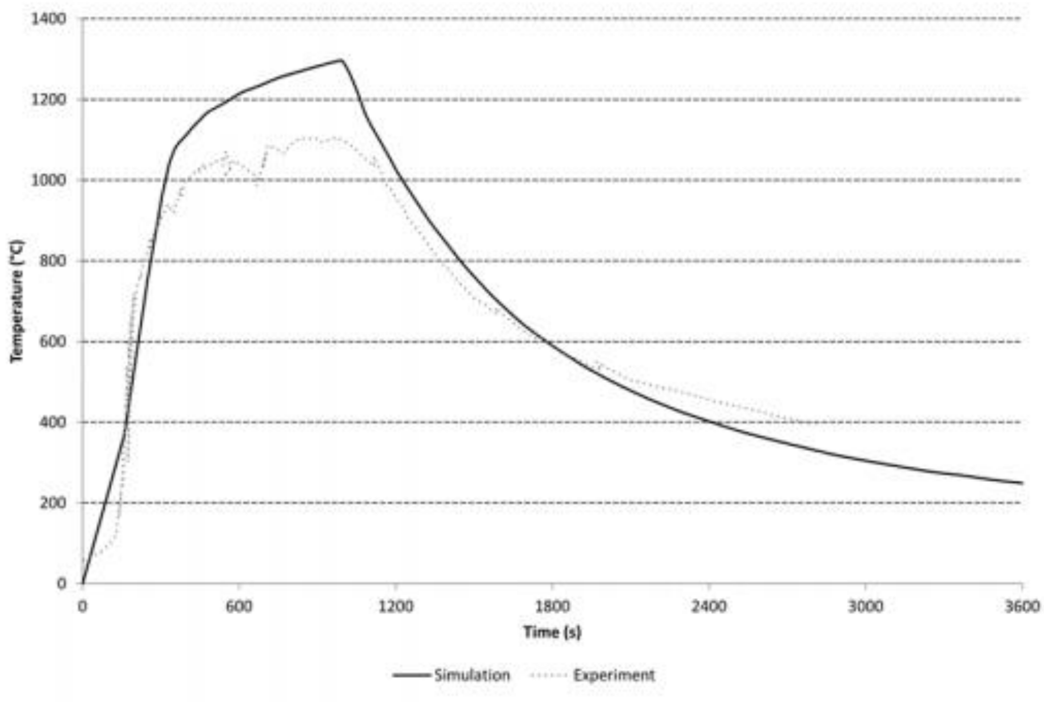


Figure 78: Comparison of temperature prediction and test result of test 3 by Medina Hevia (2014)

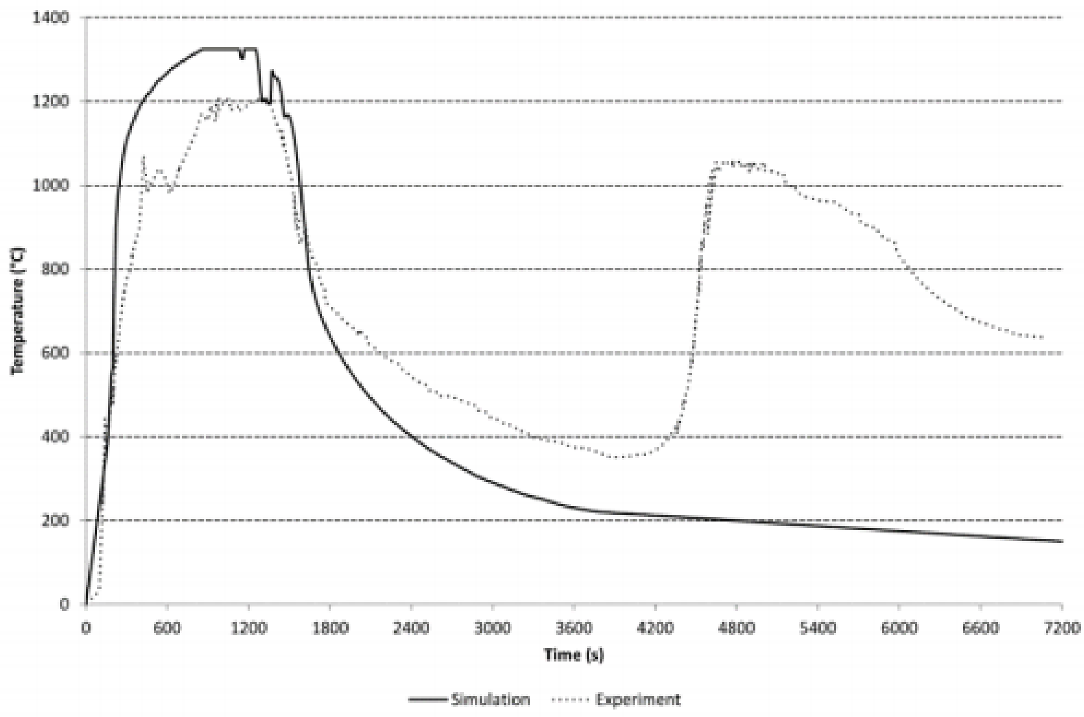


Figure 79: Comparison of temperature prediction and test result of test 1 by Medina Hevia (2014)

2.2.2 BRANDON (2018)

Brandon (2018) describes a method to predict the fire dynamics and the relating char depth based on the general parametric design fire from appendix A in the national Annex from NEN-EN 1991-1-2+C3 (2019). However, the method includes an iterative approach representing the additional fuel load from the exposed timber to the fire over time. The char depth is calculated based on the model from Hadvig (18981), who developed a method to predict the char depth based on parametric fires.

Brandon accounts for the contribution of CLT to the fuel load by looking at the test results from Su et al. (2018). He recognizes that during the fully developed phase approximately 70% of the contribution of timber combusts outside (which is calculated based on the charring rate, and the heat release rate of 5,39 MJ/m2mm from Schmidt et al., 2016) contributes to the total heat release rate. The contribution of timber to the fuel load in the design method is by this iteratively accounted for. The aim of this method is not to accurately predict the fire dynamics, but to use this to calculate a more accurate structural fire behaviour by iteratively calculating the charring depth. The method is based on the following steps:

- Step 1: First iteration, calculation of the parameters for which the CLT does not contribute to the fuel, this results in the initial fire duration and final char depth for this iteration
- Step 2: Following iterations are needed to include the influence of the contribution of CLT to the fuel load. The iteration is stopped when the predicted char depths converge, at which the decay phase will start. In case the char depth does not converge, the fire is assumed to not decay
- Step 3: The maximum temperature found from the iteration at which char conversion is started can then be used to calculate the time-temperature curve

It is assumed that the method is only suitable for compartments up to 500 m2. The method describes a homogeneous temperature distribution throughout the compartment and assumes that the char depth on the exposed CLT is similar for every location. Moreover, the method does not account for the effect of delamination, or the effect of gypsum base board failure. Also charring behind the protection is not considered.

The prediction of the char depth is validated by 10 different tests from different test series where delamination did not occur or very late in the decay phase (Medina Hevia (2014) Hadden et al. (2017), Janssens (2017), Zelinka et al. (2018), Su et al. (2018)). From the comparison follows that the method results in conservative predictions of the damage (based on the charring depth) of the exposed CLT. For opening factors lower than 0,04m0,5, the predictions become even more conservative.

To ensure that the base-layer gypsum board does not fall off, Brandon (2018) presents a method to determine the time at which the gypsum-board fails. The number of times the gypsum board fails during the predicted compartment fire are the amount of gypsum boards (plus 1) needed to ensure that the base gypsum board ensures the required capacity. The method is based on the observation from the tests by Su et a. (2018), where the exposed gypsum layer from the ceiling fell-off when the temperatures behind the exposed gypsum board were between 300 and 500°C. With this, Brandon (2018), suggests that a temperature of 300°C on the unexposed side of the exposed gypsum layer could be used as a criterion for the failure/fall-off of the gypsum board protection. For this method, Brandon uses the computer model SAFIR (2007) to calculate the finite element temperatures in the gypsum boards. He uses the proposed temperature-time curve as input for the model. The method is presented in Figure 80

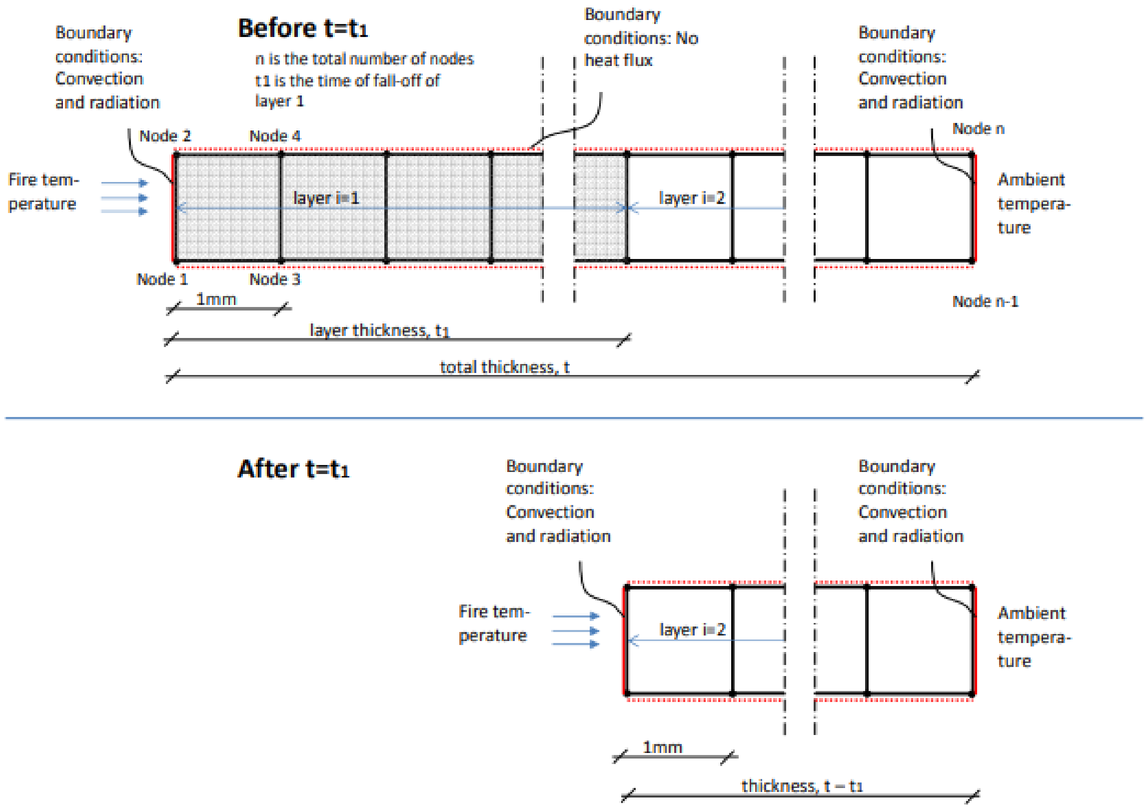


Figure 80: Schematic drawing a finite element model for calculations of temperatures behind gypsum boards (Brandon, 2021)

The gypsum board fall-off predictions are only validated for compartment tests where more than 1 gypsum layer was accounted for the encapsulation, to ensure that the base layer of the gypsum board did not fall-off. The comparison was done for 20 different tests from the test series from Frangi et al. (2008), McGregor et al. (2013), Medina Hevia (2014), Su and Lougheed, Hadden et al. (2017), Janssens (2017), Zelinka et al. (2018), Su et al. (2018) and more). From the comparison follows that the gypsum board fall-off predictions result in accurate or conservative predictions.

2.2.3 Barber et al (2018)

In 2018, Barber et al. (2018) presented a method based on a FSD model approach. The methodology uses Computational Fluid Dynamics (CFD) with a software package on Fire Dynamics Simulator (FSD), utilizing the pyrolysis model within the FSD, to account for the influence of exposed timber on the HRR based on the charring rate. The HRR is determined and calibrated against cone calorimeter test data. By this, the methodology quantifies the response of the exposed timber and gives the overall char depth which presents the FRL based on the compartment characteristics.

Although the model presents opportunities regarding the more accurate prediction of structural fire resistance, it is concluded that for design purposes the model may not be sufficient as computational time is too long for design purpose.

2.2.4 WADE (2019/2020)

Wade (2019) proposes two sub-models for the fire compartment model B-risk and evaluates their accuracy based on results from experimental large-scale compartment fires. The two models are based on pyrolysis characteristics and are the following:

- SMA: the equivalence ratio wood pyrolysis sub-model
- SMC: Kinetic wood pyrolysis sub-model

B-RISK is a two-zone model which has been developed by the University of New Zealand. Originally, the model only calculated the fire dynamics for non-combustible compartments. With the sub-models by Wade (2019) the dynamic contribution of timber surfaces (without iteration) is determined based on wood combustion and fuel load, including the char depth. The models also include the influence of delamination on the fire dynamics. Both models are used to predict the enclosure gas temperatures and the char depth.

The two sub-models describe two different approaches. The SMA describes the contribution of the mass and energy due to the timber based on the assumed 300 degrees isotherm for which char forming is considered to occur. The rate at which pyrolysis gases burn is a user specified input parameter, based on the excess fuel factor or the global equivalent ratio.

The SMC model includes the contribution of the exposed timber on the mass and energy to the fire "*based on Arrhenius equation for temperature-dependent reaction rate that describes the thermal de-composition of the wood*". It considers a consistent global equivalent ratio between 1,3 and 2,0 and provides an estimate of HRR inside and external to the compartment. The model allows for inclusion of delamination.

The models were evaluated based on recent compartment fire tests done by Su et al. (2018). It was concluded that in general, the SMA sub-model with a GE ratio of 1,3 may be adequate sufficient in many cases. The kinetic sub-model allows proportion of burning inside and external to compartment and gives more accurate prediction. The fuel response sub-model may provide better prediction of the rate of temperature decay. The char depth predictions were in these cases good, although not always conservative.

2.2.5 BARBER (2016-2020)

In 2016, Barber (2016) presented a calculation method on how to predict the structural capacity of a CLT element. The test was described as a twostep approach and based on the results from the small-scale compartment experiments from Crielaart (2015). The method is considered to be suitable for the prediction of the fire dynamics for compartments with two exposed surfaces following 2 steps:

- Step 1: Determination of the critical lamella thickness for outer layer to reduce possibility of delamination. This is based on the charring depth from EC1 and parametric fires
- Step 2: Check configuration of self-extinguishment

With the basics from the method in 2016, Barber, has now further developed the method to allow a similar approach as the method by Brandon (2018). The method is based on the parametric time-temperature curve from EN-1991-1-2, but with some alterations and an iterative approach to account for the additional fuel due to exposed timber.

The current approach does not account for the effect of delamination or protection failure. Moreover, charring behind the protection is not considered. The char depth only considered the 300-degree isotherm, and thus therefore not account for the additional strength loss due to pyrolysis below this layer. The char depth predictions are validated based on test results from McGregor (2013), Medina Hevia (2014), Su et al. (2018), and Zelinka et al. (2018). It is concluded that the method does not predict the duration of the growth and decay of the fire well, however temperatures are rather accurate. For well-ventilated fires, the prediction is better, which also results in better predictions regarding the char depth. It is concluded that the method tends to over-estimate the char depth for lower ventilated compartments as the fire peak occurs much later although it sometimes also underestimates the char depths as the decay phase prediction is generally not long enough.

2.2.6 ZEFUSS AND HOSSER (2007)

Rackauskaite et al., (2020) recognized that the parametric curve from Zefuss and Hosser (2007) presented in the building codes in Germany, predicts a more accurate fire decay phase compared to the parametric curve from the Eurocode. From recent research by McNamee et al. (2020) was found that the method by Zefuss and Hosser (2007) predicts the decay phase of compartment fires with exposed timber even better than the iterative methods by Brandon (2018) and Barber (2016). However, the method does yet not include prediction of char the depth. The iterative method by Barber is therefore currently altered to be useable in the parametric curve by the German parametric curve. The figure below shows the different prediction methods by Zefuss and Hosser (2007), Brandon (2018) and Barber (2016) representing compartment Test 2 by Zelinka et al. (2018).

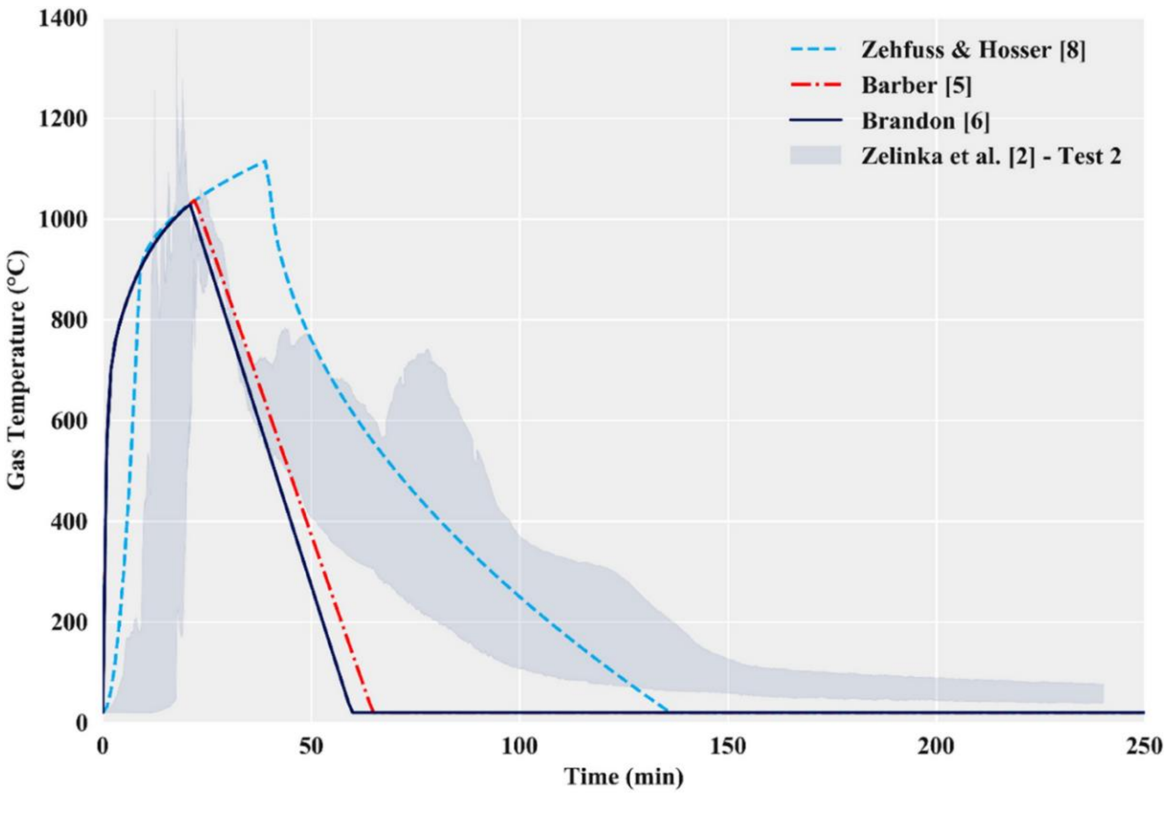


Figure 81: Comparison between fire experiment results from test 2 by Zelinka et al. (2018) and performance based design fires (Figure gained from (Rackauskaite et al., 2020)

3 DATA INVENTORY FOR BUILDING ELEMENTS

In this appendix, the inventory for the material related input data needed for the design tool calculations is presented. This is based on literature review and product data. First, the inventory for CLT is presented, after which the inventory for encapsulation and sprinkler installations follows.

3.1 Cross Laminated Timber CLT

In this section a short description is presented regarding data analysis of the CLT. The section first starts with a description of the fire safety element, after which the material quantities, and circular characteristics of the element is presented.

3.1.1 Description of CLT

Untreated CLT mainly consists of 2 main materials, timber, and glue. In the Netherlands, the type of timber used in CLT products is typically spruce and is usually imported from Scandinavia, the Baltics or mid-Europe. (Swedish Wood, 2019) As has been observed in chapter 4, the type of adhesive highly affects the burning behaviour of a CLT element. Three different types were recognized, namely MUF, PU and fire-resistant PU. From these three, PU adhesive has been observed to be sensitive to delamination, whereas MUF and fire-resistant adhesive have been observed to be less prone to delamination.

For the CLT elements used in this research the data from the EPD document by Mayr-Melnhof Holz (2018-2021) in Austria is used, which considers a CLT element with MUF adhesive (and some additional PU adhesive). An overview of the characteristics is presented in Table 26.

Table 26: Material data CLT

Element	Material	Quantity	Unit
CLT	Total	469,94	Kg/m3
	Spruce	87,5	%
	Water	10,5	%
	PUR adhesives	0,6	%
	MUF adhesive	1,5	%
	EPI adhesive	0,1	%

3.1.1.1 Economic cost

According to CBI (2017) the typical market price for 1 cubic meter of CLT in Europe is €500. Because the material quantity is calculated in total kg/year the economic value must be expressed in €/kg. This is done by dividing the cost with the density of the material. This results in a cost of 500/470 = €1,06/kg.

3.1.1.2 Environmental cost

The environmental cost of the CLT is gained from the EPD data provided by Mayr-Melnhoff Holz (2018-2021). The LCI data is based on a declared unit of 1 m^3. In the research, a declared unit of 1 kg is considered. Therefore, the data is re-calculated and presented as value per kg. Based on this, one kg of CLT results in an environmental cost of €0,02. An overview of the data for A1-A3 is presented in Table 27.

Table 27: LCI-data CLT

Environmental impact category	Unit	Total (A1-A3)
GWP	[kg CO2-Ee]	3,12E-01
ODP	[kg CFC11-Eq]	1,56E-09
AP	[kg SO2-Eq]	1,17E-03
EP	[kg(PO4)^3-Eq]	2,64E-04
POCP	[Kg ethene-Eq]	2,08E-04
ADPE	[kg SB-eq]	1,36E-06
ADPF	[kg SB-eq]	4,09E+00

3.1.2 SERVICE LIFE

The fire safety measure for timber, belongs to the structural element. Therefore, the element can be categorized into Brand's "structure" building layer. This presents a functional service life between 30 and 300 years. It is expected that the functional service life of mass timber is at least 100 years.

In the data from Mayr Melnhof Holz (2018-2021) the technical service life is considered to be over 100 years, if used as designated.

3.1.3 END OF LIFE SCENARIO

CLT has high potentials regarding end-of-life value as re-use and recycling. Re-using CLT elements is possible in case the remaining technical characteristics comply with the technical requirements for new purpose. In case re-use is not possible, CLT can be recycled into new engineered timber products such as OSB by shredding the CLT into small wood chips. (Swedish Wood, 2019)

The normative values regarding end-of-life scenario for timber presented by Nationale Milieudatabase (2020) state end-of-life values as 5% for reuse, and 10% for recycling. By this, the potential end-of-life residual value regarding reuse and recycling are not considered. In the research therefore the theoretical value is considered, following 100% reuse and recycling potential. (Swedish Wood, 2019)

3.1.4 DETACHABILITY

It is expected that the CLT elements are connected by screws, bolts and other type of mechanical fasteners. Based on the methods presented in the document DGBC (2019), this results in a detachability factor of 0,8.

3.1.5 RECYCLABILITY

CLT has the potential to be recycled into new engineered timber elements such as OSB panels. Though there are a significant amount of alternative engineered timber elements, the research focuses on recyclability to OSB panels. For this, some characteristics of OSB panels are required. This data is gained by EPD data from (Fritz Egger GMbH & Co OG Holzwerkstoffe, 2018–2023). An overview of the characteristics of OSB is presented in

Table 28. Based on this, it is observed that 85-92% of OSB is typically dry spruce. It is therefore considered that 85% of OSB can be replaced by used CLT.

Table 28: Characteristics of OSB

Element	Material	Quantity	Unit
OSB	Total	607	Kg/m3
	Dry Spruce	85-92	%
	Water	4-6	%
	MUF adhesive	>8	%
	Ammonium sulphate	1	

3.2 Inventory for Encapsulation

In this section the analysis of the data needed for the calculation of the encapsulating elements is presented. Firstly, a short description of the encapsulation is presented after which the specific values and quantities for the calculations is presented.

3.2.1 Description of encapsulation

Gypsum board encapsulation is used to protect the structural timber from the temperatures of a fire by encapsulating and this way insulating the timber and preventing burning. The insulating capacity of the encapsulation depends on the type of encapsulation, the thickness of the encapsulation, and the numbers of layers. It is expected that the encapsulation board is applied directly to the timber by screws (Figure 82), as this method was used most frequently in the large-scale compartment fire tests.

Figure 82: Fastening of encapsulation

From conclusions of chapter 4 follows that the fire performance of gypsum board protection is an essential part of the fire safety of a mass CLT building. From many large-scale fire tests of which the tests by Su et al. (2018), Zelinka et al. (2018) and Brandon et al. (2021), it was recognized that type X gypsum board (fibre reinforced encapsulation), applied directly on the CLT has high potential in protecting the timber sufficiently without significant failing and can even lead to complete protection against charring in case enough gypsum layers were applied (in general 3 layers).

Therefore, this research the product data is based on type X, fibre-reinforced encapsulation called “Promatect -100” produced by Promat presented in the EPD datasheet (Promat, 2015-2021). On overview of the characteristics is presented in

Table 29: Material data encapsulation

Element	Material	Quantity	Unit
Promatect - 100	Total	890	Kg/m3
	Sand	5-20	%
	Lime	2-15	%
	Calcium silicate	2-15	%
	Gypsum	>50	%
	Fibres	<3	%

3.2.1.1 Economic cost

Only material cost is considered and is based on market price for 875 kg/m^3 based on *Bouwmaterialen - Bouwbestel.nl ® - Bouwmateriaal Online*, (n.d). With this the elements cost the following:

Table 30: Economic cost Encapsulation

Type	Specifics	Excl. BTW	Per kg
Promatect - 100	250cm X 120cm Thickness: 10mm	€54,62	€2,08
	250cm X 120cm Thickness: 12mm	€60,85	€2,31
	250cm X 120cm Thickness: 15mm	€80,73	€2,05

From this calculation follows that the price varies per kg, it is considered that the price per kg for encapsulation is 2,15€. It should be noted that the cost may be lower if bought in bulk for a large building. If the costs are known, these can easily be adjusted in the tool.

3.2.1.2 Environmental cost

The environmental cost of the CLT is gained from the EPD data provided by Promat (2015-2021). An overview of the data is presented in Table 27. As the declared unit in the research is similar to the unit presented by Promat (2015-2021) (1kg), the data does not have to be converted.

Table 31: LCI-data encapsulation

Environmental impact category	Unit	Total (A1-A3)
GWP	[kg CO2-Ee]	5.18E+2
ODP	[kg CFC11-Eq]	8.60E-7
AP	[kg SO2-Eq]	1.02E+0
EP	[kg(PO4)^3-Eq]	1.64E-1
POCP	[Kg ethene-Eq]	4.43E-2
ADPE	[kg SB-eq]	2.11E-3
ADPF	[kg SB-eq]	8.65E+3

3.2.2 Service life

Gypsum board protection can be considered as a space-plan aspect in the layers by Brand, which indicated that the service life is somewhere between 3 and 30 years (Brand, 1994). For the research an expected functional service life of 25 years is considered.

The document by Promat (2015-2021) defines an expected service life of 25 years.

3.2.3 End of life scenario

According to the document by Promat (2015-2021), the gypsum boards have potential to be reused or recycled. The document describes that the products can be reused if the boards are removed non-destructively. If the boards are not contaminated with other materials, the boards can be recycled by the manufacturer.

The normative values regarding end-of-life scenario for gypsum presented by Nationale Milieu Database (NMD, 2020) state end-of-life values as 0% for reuse, and 5% for recycling. By this, the potential end-of-life residual value regarding reuse and recycling are not considered.

According to the EPD datasheet from Promat (2015-2021), recycling of the encapsulation is possible in case the material is not contaminated with other building materials. However, it is not likely that the outer layer of encapsulation is uncontaminated, due to the wish for paint or other plaster inside a residential compartment. It is therefore considered that the outer layer of encapsulation cannot be recycled. In case there is more than one later of encapsulation available, it is considered that the inner layers can be recycled. Though the recyclability of the elements is described, the potential methods are not explained in the document. It is assumed that 100% of the uncontaminated.

In the research it is therefore considered that both for re-use and recycling the outer encapsulation layer cannot be reused or recycled due to contamination with other products due to user preference (e.g., paint). The inner encapsulations are considered to be 100% reuse-or recyclable.

3.2.4 DETACHABILITY

As the gypsum boards are attached to the timber by screws (as visible in Figure 82), the gypsum boards themselves are easily detached from the structure. Based on the methods presented in the document DGBC (2019) this results in a detachability factor of 0,8.

3.2.5 RECYCLABILITY

According to Promat (2015-2021) closed loop recycling is possible, which indicates that the waste can be used to make the same product again. This means that typically gypsum is 100% recyclable. However, approximately 6% of the functional unit in the EPD datasheet is related to paper. This means that for the functional unit, 94% is recyclable.

3.3 INVENTORY PARAMETERS SPRINKLER

In this appendix, the analysis of the data needed for the calculation of the sprinkler elements is presented. Firstly, a short description of sprinkler pipes is presented after which the specific values and quantities for the calculations is presented.

3.3.1 DESCRIPTION OF SPRINKLER SYSTEM

Applying a sprinkler in a mass timber building can quickly control and even extinguish a fire, as observed from large scale compartment test series by Zelinka et al. (2018). There are different types of sprinklers, which can be either a dry or wet system. In general, a simple sprinkler consists of water supply pipes and heads. Besides this, a water source for water supply is required and pumps to provide sufficient pressure. The pumps and relating aspects ca be defined as the "central unit". (Breunese & Maljaars, 2015)

Similarly, to the CLT and encapsulation data, the sprinkler data was gained from EPD data. However, specific EPD data on sprinklers was not found. Therefore, the calculation of the environmental impact calculation is based on sprinkler pipes only based on EPD data from alternative elements with similar materials.

In the calculations, the sprinkler pipe material is based on CPVC plastic sprinkler pipes. The EPD data was gained by Vinidex (2016-2021). An overview of the characteristics is presented in Table 26.

Table 32: Material data CLT

Element	Material	Quantity	Unit
PVC sprinkler pipe	Total	1420-1480	Kg/m3
	PVC resin	82	%
	Filler	14	%
	Calcium based stabilizer	2,2	%
	Titanium white	0,83	%
	Chlorinated polyethylene	0,39	%
	Oxidized polyethylene wax	0,22	%
	Polyethylene wax	0,19	%
	Azodicarbonamide	0,11	%
	Pigments	<0,5	%
	Methyl methacrylate	<0,1	%
	Calcium Stearate	<0,1	%

3.3.1.1 ECONOMIC COST

Based on the article by Dukers & Latten (2000), the average cost of a sprinkler installation per m2 is around €35 per m2. This does not present the costs of the pipe only, but also the costs of sprinkler heads. Moreover, the document presents a cost of around approximately €150,000 per central unit, for which it is expected that a central unit is needed for every 10.000 m2 GFA. (Dukers & Latten, 2000)

3.3.1.2 ENVIRONMENTAL COST

The environmental cost of the sprinkler pipes is gained from the EPD data provided by Vinidex (2016-2021). As the data is already presented per kg, conversion of the data was not needed. An overview of the data is presented in Table 27.

Table 33: LCI-data sprinkler pipe

Parameter	Unit	A1-A3
GWP	[kg CO2-Ee]	3,608
ODP	[kg CFC11-Eq]	7,628E-08
AP	[kg SO2-Eq]	0,00898
EP	[kg(PO4)^{3}-Eq]	0,002237
POCP	[Kg ethene-Eq]	0,0005364
ADPE	[kg SB-eq]	4,27E-06
ADPF	[kg SB-eq]	31,36

To account for the central unit in the environmental impact calculations, a total value for 1 unit is chosen as €2000 per unit. This is based on the relative relation between economic cost for encapsulation and CLT compared to one central unit of sprinkler, such that it represents similar contribution as for the economic impact.

3.3.2 Service life

A sprinkler system can be considered as “services” in the layers by Brand (1994), which means that the expected service life should be within 7-15 years. A functional service life of a 15 years is considered.

According to Vinidex (2016-2021), the technical service life of PVC pipes is 100 years.

For the central unit, a functional and technical service life of 100 years is considered.

3.3.3 End of life scenario

According to Vinidex (2016-2017): Full post-use reuse and recycling of PVC pipes is possible. Therefore, it is considered that 100% of the sprinkler pipes can be reused.

Note, the end-of-life benefit of the central unit is left out of the scope.

3.3.4 Detachability

It is expected that the sprinkler pipes are connected by dry connections. Based on the methods presented in the document DGBC (2019) this results in a detachability factor of 0,8.

3.3.5 Recyclability

PPFA - Plastic Pipe and Fittings Association (2012) present a code standard for pipes with more than 90% recyclates from old CPVC pipes. It is therefore considered that 100% of the pipe can be recycled into 90% of the content for a new pipe.

4 OVERVIEW OF INPUT PARAMETERS DESIGN TOOL

In this appendix, the overview of the parameters that are used for the calculations of the design tool is presented. This overview provides clarity and transparency regarding the choices and will enhance potential improvement of the design tool by allowing easy adjustment of the values if research is elaborated.

4.1 MATERIAL RELATED PARAMETERS

In this section an overview of the values needed to calculate the material use of the fire safety materials, which consists of three main parts: (1) monetary cost per material unit, (2) parameters for material input and (3) parameters for end-of-life circularity value.

4.1.1 MONETARY COST

The monetary cost of the fire safety elements is presented for both economic as environmental cost. The economic cost is presented in Table 34.

Table 34: Economic monetary cost of building elements

Parameter	CLT	Encapsulation	Sprinkler pipe	Central unit	Unit
Cost per unit	1,06	2,15	-		[€/kg]
Cost per unit			35		[€/m2]
Cost per unit				150000	[€/unit]

The environmental costs are based on EPD data. The cost is calculated by the LCI data, converted by an impact factor. Table 35 presents the overview of the used LCI data

Table 35: Overview of LCI data

Parameter	CLT	Encapsulation	Sprinkler pipe	Central unit	Unit
GWP	3,12E-01	5,18E-01	3,61E+00	2000 in total	[€/kg]
ODP	1,56E-09	8,60E-10	7,63E-08		[€/kg]
AC	1,17E-03	1,02E-03	8,98E-03		[€/kg]
EP	2,64E-04	1,64E-04	2,24E-03		[€/kg]
POD	2,08E-04	4,43E-05	5,36E-04		[€/kg]
ADPE	1,36E-06	2,11E-06	4,27E-06		[€/kg]
ADPF	4,09E+00	8,65E+00	3,14E+01		[€/kg]

4.1.2 MATERIAL INPUT PARAMETERS

The material input calculation is done based on material quantity, and functional service life of the considered elements. Table 36 presents an overview of the considered parameters.

Table 36: Overview of material input parameters

Parameter	CLT	Encapsulation	Sprinkler	Central unit	Unit
Quantity per unit	470	890	1480	1 unit/building	Kg/m3
Dimensions	User defined	User defined	D-50 [mm] t-2 [mm]		[mm]
Functional service life	100	25	15	100 years	Years

4.1.3 End-of-life circularity value parameters

The end-of-life value calculations are based on different parameter related to the considered fire safety elements.

4.1.3.1 End of life scenario

Although Platform CB'23 (2019) defines that the fixed values should be used as stated by Nationale Milieudatabase (2020) these values have been concluded to be very negatively assessed if compared by research and manufacture data. The values considered and presented is Table 37.

Table 37: End-of-life scenario parameters

Parameter	CLT	Encapsulation	Sprinkler	Unit
Reuse	100	n-1/n	100	%
Recycle	100	n-1/n	100	%

4.1.3.2 End of life value parameters

The factors used in the calculations for the design tool are presented in Table 38.

Table 38: End-of-life-value parameters

Parameter	CLT	Encapsulation	Sprinkler	Unit
Technical service life	100	25	100	[years]
Detachability factor	0,8	0,8	0,8	[-]
Recycle content 1	87,5	94	100	[%]
Content in component 2	85	94	90	[%]

4.2 FIRE RISK RELATED PARAMETERS

In this section an overview of the values needed to calculate the fire risk of the fire safety design is presented. To calculate the risk, building value, probability parameters and damage quantity are required as well as fire dynamic and fire resistance calculation parameters.

4.2.1 MONETARY BUILDING VALUE

The monetary building value is expressed in economic and environmental value. The economic building value is determined by determining the average purchase cost of the building HAUT in Amsterdam per m2. This resulted in a value of €8000 per meter squared. (HAUT, 2018)

The environmental building value is defined by the MPG of the building, in this case defined as the maximum allowed MPG of 0,8.

4.2.2 PROBABILITY VALUES

The values for the probability calculations are determined by literature review and methods presented in the main report. An overview of the values is presented in the following sections.

4.2.2.1 F(A)

To calculate F(A) the expected frequency of a fire is needed. A value of $5*10^{-7}$/m2*year is assumed in accordance to (Lecture slide CIE4281. Parwani, 2019, Slide 4

4.2.2.2 P1

The values used to calculate P1 are described in the main text. An overview is presented in Table 39.

Table 39: Values for P1 calculations

Parameter	Description	Value	Unit
P1.1	Probability of sprinkler working	98	[%]
P1.2	Probability of FF extinguishing	100	[%]

4.2.2.3 P2

The probability of natural decay is determined by dividing characteristics of large-scale compartment fire tests into three categories, depending on number of exposed surfaces. In the tool, rather than considering number of exposed surfaces, a distinction is made between percentage of exposed CLT. An overview is presented in

Table 40: P2.1: Probability of natural decay

Design variant	Description	PU adhesive	MUF adhesive	Unit
1	>30% exposed	14	75	[%]
2	<30% exposed	43	100	[%]
3	0% exposed	100	100	[%]

Additional risk relates to whether encapsulation base layer failure can occur, which is dependent on the type of encapsulation. The risk-factors are presented in Table 41.

Table 41: R2.1: Risk factor for encapsulation failure

Aspect	Description	Value	Unit
Type of encapsulation	Normal	0,8	[-]
	Fire rated	1,0	[-]

The probability of moment of natural decay is divided in similar design variants as P2.1. AN overview of the values is presented in Table 42.

Table 42: P2.2: Probability of moment of natural decay

Design variant	<30 min	<60 min	<90 min	<120 min	<180min	<240 min	Unit
1: >30 exposed	0	0	25	50	100	100	[%]
2: <30% exposed	0	17	17	83	83	100	[%]
3: 0% exposed	0	17	50	83	100	100	[%]

Because of the definition of natural decay rather than self-extinguishing, it is expected that post-fire fire fighter extinguishing is needed for extinguishing. This is dependent on the fire fighter accessibility. An overview of the expected risk regarding fire-fighter accessibility is presented in Table 43.

Table 43: Risk factor for post-fire fire fighter extinguishing

Aspect	Description	Value	Unit
Building height	<28m	1,0	[-]
	>28m	0,5	[-]

4.2.3 Rehabilitation quantity

The impact of the fire is expressed as the required quantity compartment or building that should be replaced after a fire. This results in the total quantity of replacement for the four different scenarios as presented in Table 44, representing as a percentage of the building.

Table 44: Percentage of building that is expected to be lost for specific fire scenario

Scenario	Description of damage	Value	Unit
Scenario 0	No damage	0	[%]
Scenario 1	Water and smoke damage in one compartment	$0{,}05/n_{storeys}$	[%]
Scenario 2	Loss of one compartment	$1/n_{storeys}$	[%]
Scenario 3	Loss of multiple compartments	$n_{lost}/n_{storeys}$	[%]
Scenario 4	Total loss of building	100	[%]

4.2.4 Fire dynamic parameters

To be able to predict the fire dynamics in the compartment, and determine the required resistance, some design related input is required. In Table 45 only the fixed parameters (independent from design) are presented.

Table 45: Values for fire dynamic calculation

Scenario	Description of damage	Value	Unit
Fuel load density	In the design tool a value is used that represents similar values as used for the large-scale compartment fire tests.	560	[MJ/m^2]
CLT characteristics	This is the combination of density, specific heat and thermal conductivity. The value is based on similar assumptions as Brando (2018)	770	[J/m^{2}s^{0,5}]
Char rate	The expected nominal charring rate is defined as 0,7, which is in accordance with the results from Barlett et al. (2019)	0,7	[mm/min]
Alpha	Heat release rate of 5,39 MJ/m2mm from Schmidt et al., 2016	5,39	[-]

tlim	This is the rate of development which can be either fast, medium or slow (00:15; 00:20; 00:25). In NEN-EN-1991-1-2+C3 (2019), this is dependent on compartment function.	00:15	[h]

4.2.5 THERMAL MODEL CALCULATIONS

The thermal model calculation presents the calculations for charring depth and zero strength layer over time. For this calculation a set of parameters is required, this is presented in Table 46, together with the assumed values from the design tool.

Table 46: Values for thermal model calculations

Parameter	Description	Value	Unit
Encapsulation thickness	The thickness is determined based on product data from Promat, presenting eighter 10 or 12 mm	10 12	mm
Insulation time encapsulation	The insulating time of the encapsulation is determined by product data from Promat. The insulation time of the encapsulation with a thickness of 10 mm is 30 min, and 60 min for 12 mm.	30 60	min

4.2.6 FIRE RESISTANCE CALCULATIONS

For the structural calculation, a number of parameters are needed, presented in Table 47.

Table 47: Values used in the structural fire resistance calculations

Parameter	Description	Value	Unit
Load parameters			
Weight related aspects for cement screed loads	It is assumed that there is a cement screed on the floor, resulting in additional floor loads.	1638	[kg/m^3]
Cement thickness		0,03	[m]
Variable floor load	The variable floor load is determined by NEN-EN 1991-1-1	1,75	[kN/m2]
Strength parameters			
CLT panel width	It is assumed that all panels have a width of 1 meter.	1,0	m
CLT strength class	A strength class of C24 has been considered.	C24	-
E0xmean	For strength class C24 defined as presented by Swedish Wood (2019)	11000	MPa
fmxlay,k		24,00	MPa
fc0x		21,00	MPa
Gamma M	As defined by NEN-EN 1995-1-1	1,25	-
Kmod	Considering long term load combination	0,7	-

5 ELABORATED DESIGN EXAMPLE

In this appendix, the total calculation and quantification method performed by the design tool is presented based on the example from section 9.1 in the report. This example allows increased understanding of the calculation steps in the design tool.

5.1 DESCRIPTION OF THE DESIGN

The example considers a design of a compartment GFA of 140 m2, for 25 storeys. The dimensions are presented in Figure 83. The structural floor and wall elements are constructed by 5 lamellas with a thickness of 35 mm per lamella. The additional fire safety measures consist of a sprinkler and 70% encapsulation for both wall and ceiling consisting of a 2-layer fire rated encapsulation with a thickness of 12mm per layer. In Figure 83, the total overview of the input parameters in the design tool is presented.

Design parameters

In this sheet, the user defines the design specific parameters. By changing the fire safety design measures, it is possible to see how this affects the results on the balnace between material use and fire risk.

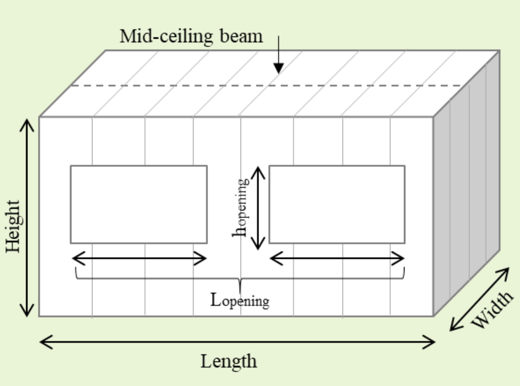
Building dimensions and characteristics

Building characteristics

Parameters	Value	Unit
Number of storeys	25	[-]
Service life	100	[years]

Compartment characteristics

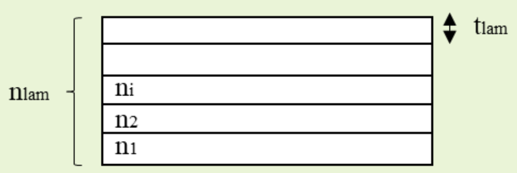
Parameters	Value	Unit
Storey height	2,73	[m]
Width	7	[m]
Length	20	[m]
Mid ceiling-beam	Yes	[-]
Opening height	1,78	[m]
Total opening length	11,5	[m]
Percentage open	100	[%]



Fire safety design relating measures

CLT characteristics

Parameters	Value	Unit
Adhesive type	MUF	[-]
Floor lamellas	5	[-]
Wall lamellas	5	[-]
Thickness floor lam.	35	[mm]
Thickness wall lam.	35	[mm]



Sprinkler availability

Parameter	Value	Unit
Sprinkler availability	Yes	[-]

Encapsulation characteristics

Parameters	Value	Unit
Percentage	70,00	[%]
Location	Ceiling & walls	[-]
Type	Fibre reinforced	[-]
Number of layers	2	[-]
Thickness	12	[mm]

Figure 83: Input parameters design tool. Extended example

5.2 MATERIAL USE CALCULATIONS

In this section, the calculations for the material use of the fire safety measures is calculated based on cost and end-of-life benefit.

$$Material\ use = C - B$$

5.2.1 MATERIAL COST CALCULATIONS

The material cost calculation is calculated by using the following formula:

$$C = \sum €_i \times M_{In,i}$$
$$M_{In,i} = m_i \times f_{production,i} \times f_{use,i}$$

5.2.1.1 QUANTITY OF MATERIAL PER ELEMENT (M_I)

CLT

The quantity of CLT is calculated using the following formula, expressed as the total amount of kg for the total building.

$$m_{CLT,building} = \rho_{CLT} * ((A_{walls} - A_{Opening}) * t_{walls} + GFA * t_{floor}) * n_{storeys}$$
$$m_{CLT,building} = 470 * \left((147{,}42 - 20{,}47) * 0{,}175 + 140 * 0{,}175\right) * 25$$
$$m_{CLT,building} = 549{,}0 * 10^3 \quad \text{[kg]}$$

Encapsulation

The quantity of encapsulation is calculated using the following formula, expressed as the total amount of kg for the total building.

$$m_{Enc,building} = \rho_{Enc} * A_{Enc} * t_{Enc,lay} * n_{Enc,lay} * n_{Storeys}$$
$$m_{Enc,building} = 890 * 326{,}87 * 0{,}012 * 2 * 25$$
$$m_{Enc,building} = 174{,}6 * 10^3 \quad \text{[kg]}$$

Sprinkler

The quantity of sprinkler material consists of the sprinkler pipes and a central unit. For the economic impact calculations, the material quantity is based on the GFA. Therefore:

$$m_{spr,pipe,building,EC} = GFA_{comp} * n_{storeys}$$
$$m_{spr,pipe,building,EC} = 140 * 25$$
$$m_{spr,pipe,building,EC} = 3500{,}0 \quad \text{[m}^2\text{]}$$

The material quantity for the sprinkler pipes on which the environmental impact is calculated is based on the material quantity of the pipes, calculated using the following formula, expressed as the total amount of kg for the sprinkler pipes in the total building.

$$m_{spr,pipe,building,Env} = \rho_{spr,pipe} * A_{spr,pipe} * n_{spr,pipe/m2} * GFA_{comp} * n_{storeys}$$
$$m_{spr,pipe,building,Env} = 1480 * (0{,}25 * (0{,}05 - 0{,}048)^2) * 0{,}25 * 140 * 25$$

$$m_{spr,pipe,building,Env} = 406{,}8 \qquad [kg]$$

Beside the sprinkler pipes, the central system is accounted for. It is assumed that the system can be expresses as one unit per 100.000m2.

5.2.1.2 PRODUCTION PHASE FACTOR ($F_{PRODUCTION,I}$)

It is assumed that the material factor for the production phase is consistent with the amount of material calculated for 1 building.

$$f_{Production,i} = 1 \qquad [-]$$

5.2.1.3 USE PHASE FACTOR ($F_{USE,I}$)

For the use-phase, the technical and functional service life of the elements determine the frequency of replacement. This is calculated by the following formula.

$$f_{use,i} = (\frac{t_{sl,b}}{t_{fsl,i}} - 1) \qquad [-]$$

CLT

The frequency of replacement for CLT is calculated in the following way:

$$f_{use,CLT} = (\frac{t_{sl,b}}{t_{fsl,CLT}} - 1)$$
$$f_{use,CLT} = (\frac{100}{100} - 1)$$
$$f_{use,CLT} = 0 \qquad [-]$$

Encapsulation

The frequency of replacement for the encapsulation is calculated in the following way:

$$f_{use,Enc} = (\frac{t_{sl,b}}{t_{fsl,Enc}} - 1)$$
$$f_{use,Enc} = (\frac{100}{25} - 1)$$
$$f_{use,Enc} = 3 \qquad [-]$$

Sprinkler

The frequency of replacement for sprinkler pipes is calculated in the following way:

$$f_{use,Spr-pipe} = (\frac{t_{sl,b}}{t_{fsl,Spr-pipe}} - 1)$$
$$f_{use,Spr-pipe} = (\frac{100}{15} - 1)$$
$$f_{use,Spr-pipe} = 6$$

The frequency of replacement for the central sprinkler unit is calculated by:

$$f_{use,Spr-CS} = (\frac{t_{sl,b}}{t_{fsl,CS}} - 1)$$
$$f_{use,Spr-CS} = (\frac{100}{100} - 1)$$
$$f_{use,Spr-CS} = 0 \quad [-]$$

5.2.1.4 Total material input (cost) results per element

The total results of the calculations are done for both environmental and economic impact.

CLT

For the CLT, the total amount of material is calculated as:

$$M_{In,CLT} = m_{CLT} \times (f_{production,CLT} + f_{use,CLT})$$
$$M_{In,CLT} = 549{,}0 \times 10^3 \times (1{,}0 + 0{,}0)$$
$$M_{In,CLT} = 549{,}0 \times 10^3 \quad [kg]$$

This results in a total economic cost of:

$$C_{Ec,CLT} = €_{EC,CLT} \times M_{In,CLT}$$
$$C_{Ec,CLT} = 1{,}06 \times 549{,}0 \times 10^3$$
$$C_{Ec,CLT} = 583{,}9 \times 10^3 \quad [€]$$

And a total environmental cost of:

$$C_{Env,CLT} = €_{Env,CLT} \times M_{In,CLT}$$
$$C_{Env,CLT} = 0{,}02 \times 549{,}0 \times 10^3$$
$$C_{Env,CLT} = 12{,}8 \times 10^3 \quad [€]$$

Encapsulation

For the encapsulation, the total amount of material is calculated as:

$$M_{In,Enc} = m_{Enc} \times (f_{production,Enc} + f_{use,Enc})$$
$$M_{In,Enc} = 174{,}6 \times 10^3 \times (1{,}0 + 3{,}0)$$
$$M_{In,Enc} = 698{,}2 \times 10^3 \quad [kg]$$

This results in a total economic cost of:

$$C_{Ec,Enc} = €_{EC,Enc} \times M_{In,Enc}$$
$$C_{Ec,Enc} = 2{,}15 \times 698{,}2 \times 10^3$$
$$C_{Ec,Enc} = 1501 \times 10^3 \qquad [€]$$

And a total environmental cost of:

$$C_{Env,Enc} = €_{Env,Enc} \times M_{In,Enc}$$
$$C_{Env,Enc} = 0{,}03 \times 698{,}2 \times 10^3$$
$$C_{Env,Enc} = 22{,}5 \times 10^3 \qquad [€]$$

Sprinkler

For the sprinkler pipes, the total amount of material is calculated in two ways for either the economic or environmental impact calculations. The total amount of material for the economic impact calculations are calculated as follows:

$$M_{In,Spr-pipe,EC} = m_{Spr-pipe,EC} \times (f_{production,Spr-pipe} + f_{use,Spr-pipe})$$
$$M_{In,Spr-pipe,EC} = 3{,}5 \times 10^3 \times (1{,}0 + 6{,}0)$$
$$M_{In,Spr-pipe-EC} = 24{,}5 \times 10^3 \qquad [m^2]$$

For the environmental impact calculations, the total amount of material is calculated as follows:

$$M_{In,Spr-pipe,Env} = m_{Spr-pipe,Env} \times (f_{production,Spr-pipe} + f_{use,Spr-pipe})$$
$$M_{In,Spr-pipe,Env} = 113{,}9 \times (1{,}0 + 6{,}0)$$
$$M_{In,Spr-pipe-Env} = 2{,}9 \times 10^3 \qquad [kg]$$

Besides the pipes, a central unit is considered for the sprinkler system. The amount of material is calculated as:

$$M_{In,Spr-CS} = m_{Spr-CS} \times (f_{production,Spr-pipe} + f_{use,Spr-pipe})$$
$$M_{In,Spr-CS} = 1 \times (1{,}0 + 0)$$
$$M_{In,Spr-CS} = 1 \qquad [unit]$$

This results in a total economic cost of the total sprinkler system of:

$$C_{Ec,Spr} = €_{EC,Spr-pipe} \times M_{In,Spr-Pipe,EC} + €_{EC,Spr-CS} \times M_{In,Spr-CS}$$
$$C_{Ec,Enc} = 35 \times 24{,}5 \times 10^3 + 150 \times 10^3 \times 1$$
$$C_{Ec,Enc} = 1007{,}5 \times 10^3 \qquad [€]$$

And a total environmental cost of:

$$C_{Env,Enc} = €_{Env,Spr-pipe} \times M_{In,Spr-pipe,env} + €_{Env,Spr-CS} \times M_{In,Spr-CS}$$

$$C_{Env,Enc} = 0{,}24 \times 2{,}9 \times 10^3 + 2{,}0 \times 10^3 \times 1$$

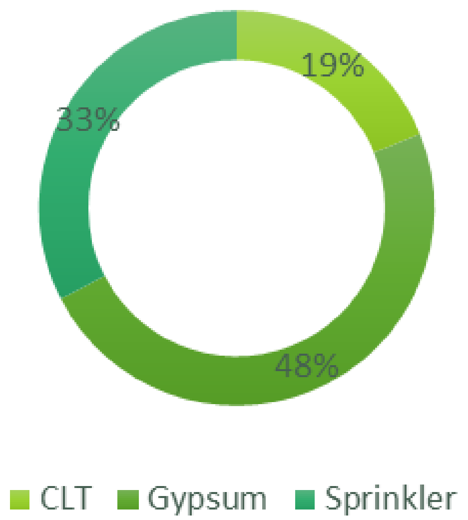
$$C_{Env,Enc} = 2{,}68 \times 10^3 \quad [€]$$

5.2.1.5 Overview of the total material cost

Based on this, the user interface of the design tool provides an overview of the total material cost calculations. These are presented in Table 48 and visualized in Figure 86.

Table 48: Results cost for example

Design aspect	Economic impact [€]	Environmental impact [€]
CLT	€ 583.953,13	€ 12.816,06
Encapsulation	€ 1.501.094,83	€ 22.488,96
Sprinkler	€ 1.007.500,00	€ 2.683,32
Total	€ 1.600.344,78	€ 37.988,34



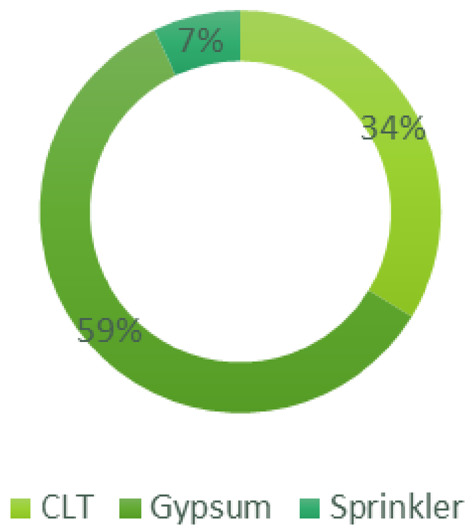


Figure 84: Results material cost. Left: Economic impact, Right: Environmental impact

5.2.2 End of life-value calculations

The benefit of the building elements is based on end-of-life circularity value. This is calculated by the following formulas:

$$B_{Design} = \sum €_{Ec/Env,i} \times V_i$$

$$V_i = M_{Out,i} \times MAX(V_{reuse,i}; V_{recycle,i})$$

5.2.2.1 Material output flows ($M_{OUT,I}$)

The material output is determined by the similar number of materials that is calculated by the material input. This way, the total material output is the following:

$$M_{Out,i} = M_{In,i}$$

$$M_{Out,CLT} = M_{In,CLT} = 549{,}0 \times 10^3 \quad \text{[kg]}$$

$$M_{Out,Enc} = M_{In,Enc} = 728{,}8 \times 10^3 \quad \text{[kg]}$$

$$M_{Out,Spr-Pipe,EC} = M_{In,Spr-Pipe,EC} = 24{,}5 \times 10^3 \quad [\text{m}^2]$$

$$M_{Out,Spr-Pipe,Env} = M_{In,Spr-Pipe,Env} = 2{,}9 \times 10^3 \quad \text{[kg]}$$

$$M_{Out,Spr-CS} = M_{In,Spr-CS} = 1 \quad \text{[unit]}$$

5.2.2.2 Reusability value

The reusability value is calculated by the following formulas:

$$V_{reuse,i} = \%_{reuse,i} * f_{detachability,i} * v_{reuse,i}$$

$$v_{reuse,i} = \frac{t_{tsl,i} - t_{fsl,i}}{t_{fsl,i}}$$

CLT

The reusability value of the CLT elements is with this calculated in the following way:

$$V_{reuse,CLT} = \%_{reuse,CLT} * f_{detachability,CLT} * \frac{t_{tsl,CLT} - t_{fsl,CLT}}{t_{fsl,CLT}}$$

$$V_{reuse,CLT} = 100\% \times 0{,}8 * \frac{100 - 100}{100}$$

$$V_{reuse,CLT} = 0\% \quad [\%]$$

From the calculation follows that the end-of-life reusability value of the CLT is 0. This is because the assumed functional and technical service life are both 100 years, and which this thus no remaining value for reuse.

Encapsulation

The reusability value of the encapsulation is calculated in the following way:

$$V_{reuse,Enc} = \%_{reuse,Enc} * f_{detachability,Enc} * \frac{t_{tsl,Enc} - t_{fsl,Enc}}{t_{fsl,Enc}}$$

$$V_{reuse,Enc} = 50\% \times 0{,}8 * \frac{25-25}{25}$$
$$V_{reuse,Enc} = 0\% \qquad [\%]$$

Similar to the results of the reusability value of the CLT, the encapsulation reusability value is calculated to be 0, as yet again the technical and functional service life of the elements is expected to be the same.

Sprinkler

The reusability value of the sprinkler pipes is calculated in the following way:

$$V_{reuse,Enc} = \%_{reuse,Enc} * f_{detachability,Enc} * \frac{t_{tsl,Enc} - t_{fsl,Enc}}{t_{fsl,Enc}}$$
$$V_{reuse,Enc} = 100\% \times 0{,}8 * \frac{100-25}{100}$$
$$V_{reuse,Enc} = 85\% \qquad [\%]$$

The end-of-life value of the central sprinkler system installation is left out of the scope for the end-of-life benefit calculations.

The reusability value is calculated to be 85%, this value is high and may be explained by the expected long technical service life of 100 years, based on manufacture data, compared to the assumed functional service life for services as expressed by the layers from Brand.

5.2.2.3 Recyclability value

The recyclability value is calculated by the following formulas:

$$V_{recyclability,i} = \%_{Recyclel,i} * v_{Recycle,i}$$
$$v_{recycle,i} = \%_{Recycle,1,i} * \%_{Recycle,2,i}$$

CLT

The recyclability value of the CLT elements is calculated in the following way:

$$V_{recyclability,CLT} = \%_{Recyclel,CLT} * \%_{Recycle,1,CLT} * \%_{Recycle,2,OSB}$$
$$V_{recyclability,CLT} = 100\% * 87{,}5\% * 85\%$$
$$V_{recyclability,CLT} = 74{,}4\%$$

Encapsulation

The recyclability value of the encapsulation is calculated in the following way:

$$V_{recyclability,Enc} = \%_{Recyclel,Enc} * \%_{Recycle,1,Enc} * \%_{Recycle,2,Enc}$$
$$V_{recyclability,Enc} = 50\% * 94\% * 94\%$$
$$V_{recyclability,Enc} = 44\%$$

Sprinklers
The recyclability value of the encapsulation is calculated in the following way:

$$V_{recyclability,Spr-pipe} = \%_{Recyclel,Spr-pipe} * \%_{Recycle,1,Spr-pipe} * \%_{Recycle,2,Spr-pipe}$$
$$V_{recyclability,Spr-Pipe} = 100\% * 100\% * 90\%$$
$$V_{recyclability,Spr-Pipe} = 90\%$$

5.2.2.4 Total end-of-life benefit results per element

Based on this, the total end-of-life benefits of the elements can be calculated and expressed in economic and environmental monetary value.

CLT
For the CLT, the total end of life value is calculated as:

$$V_{CLT} = M_{Out,CLT} \times MAX(V_{reuse,CLT}; V_{recycle,CLT})$$
$$V_{CLT} = 549{,}0 \times 10^3 \times MAX(0; 74{,}4\%)$$
$$V_{CLT} = 408{,}3 \times 10^3 \quad [kg]$$

This results in a total economic cost of:

$$B_{Ec,CLT} = €_{EC,CLT} \times V_{CLT}$$
$$B_{Ec,CLT} = 1{,}06 \times 408{,}3 \times 10^3$$
$$B_{Ec,CLT} = 434{,}3 \times 10^3 \quad [€]$$

And a total environmental cost of:

$$B_{Env,CLT} = €_{Env,CLT} \times M_{In,CLT}$$
$$B_{Env,CLT} = 0{,}02 \times 408{,}3 \times 10^3$$
$$B_{Env,CLT} = 8{,}6 \times 10^3 \quad [€]$$

Encapsulation
For the encapsulation, the total end of life value is calculated as:

$$V_{Enc} = M_{Out,Enc} \times MAX(V_{reuse,Enc}; V_{recycle,Enc})$$
$$V_{Enc} = 698{,}2 \times 10^3 \times MAX(0; 44)$$
$$V_{Enc} = 154{,}2 \times 10^3 \quad [kg]$$

This results in a total economic cost of:

$$B_{Ec,Enc} = €_{EC,Enc} \times V_{Enc}$$

$$B_{Ec,Enc} = 2{,}15 \times 154{,}2 \times 10^3$$
$$B_{Ec,Enc} = 331{,}6 \times 10^3 \qquad [€]$$

And a total environmental cost of:

$$B_{Env,Enc} = €_{Env,Enc} \times M_{In,Enc}$$
$$B_{Env,Enc} = 0{,}03 \times 154{,}2 \times 10^3$$
$$B_{Env,Enc} = 4{,}6 \times 10^3 \qquad [€]$$

Sprinkler

For the sprinkler pipes, the total amount of material output is calculated in two ways for either the economic or environmental impact calculations, which affects the end-of-life circularity value. The end-of-life circularity value for the economic impact calculations are calculated as follows:

$$V_{Spr-Pipe,EC} = M_{Out,Spr-pipe,EC} \times MAX(V_{reuse,Spr-Pipe}; V_{recycle,Spr-Pipe})$$
$$V_{Spr-Pipe,EC} = 24{,}5 \times 10^3 \times MAX(85\%; 90\%)$$
$$V_{Enc} = 22{,}1 \times 10^3 \qquad [m^2]$$

For the environmental impact calculations, the total amount of material is calculated as follows:

$$V_{Spr-Pipe,Env} = M_{Out,Spr-pipe,Env} \times MAX(V_{reuse,Spr-Pipe}; V_{recycle,Spr-Pipe})$$
$$V_{Spr-Pipe,Env} = 2{,}9 \times 10^3 \times MAX(85\%; 90\%)$$
$$V_{Enc} = 2{,}6 \times 10^3 \qquad [kg]$$

The central unit of the sprinkler system is left out of the scope for the benefit calculation.

This results in a total economic benefit for the sprinkler pipes of:

$$B_{Ec,Spr} = €_{EC,Spr-pipe} \times M_{In,Spr-Pipe,EC}$$
$$B_{Ec,Enc} = 35 \times 22{,}1 \times 10^3$$
$$B_{Ec,Enc} = 771{,}8 \times 10^3 \qquad [€]$$

And a total environmental benefit of:

$$B_{Env,Spr} = €_{Env,Spr-pipe} \times M_{In,Spr-pipe,env}$$
$$B_{Env,Spr} = 0{,}24 \times 2{,}9 \times 10^3$$
$$B_{Env,Spr} = 0{,}6 \times 10^3 \qquad [€]$$

5.2.2.5 Overview of the total material benefit

The total material benefit calculation is calculated by the following formula:

$$B_{Design} = \sum €_{Ec/Env,i} \times V_i$$

$$B_{Design} = B_{CLT} + B_{Enc} + B_{Spr}$$

Based on this, the user interface of the design tool provides an overview of the total element benefit calculations. These are summarized in Table 49 and visualized in Figure 85.

Table 49: Results of benefit calculation

Design aspect	Economic impact [€]	Environmental impact [€]
CLT	€ -434.315,14	€ -8.637,52
Encapsulation	€ -331.591,85	€ -4.574,54
Sprinkler	€ -771.750,00	€ -549,91
Total	€ -1.537.656,98	€ -13.761,97

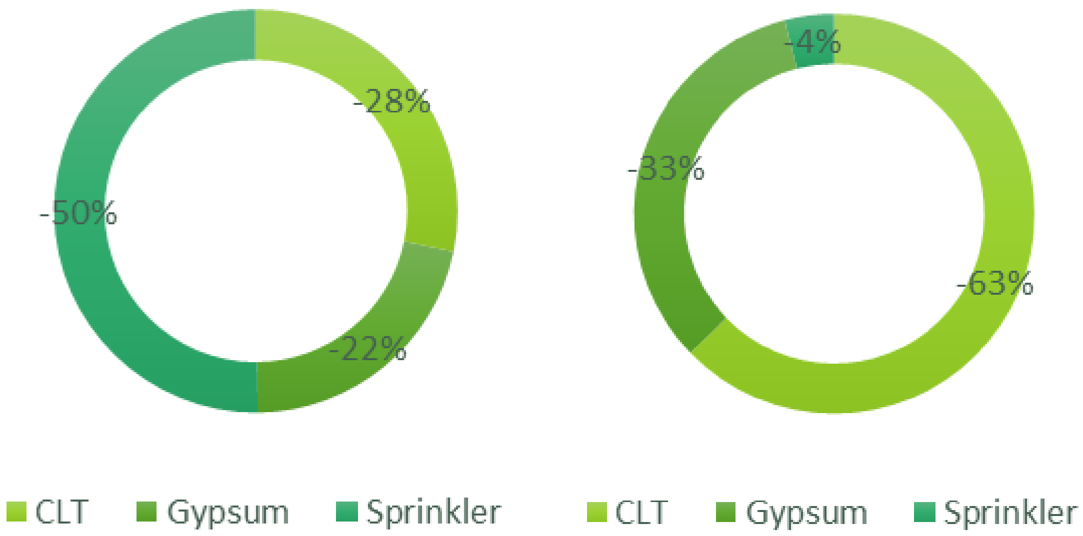


Figure 85: Results of benefit calculation. Left: Economic impact. Right: Environmental impact

5.2.3 Total material use

With the calculated material cost and benefits, it is now possible to calculate the total material use of the elements. The results are presented in Table 50 and visualized in Figure 86.

Table 50: Total material use example

Design aspect	Economic impact [€]	Environmental impact [€]
CLT	€149638	€4179
Encapsulation	€1169503	€17914
Sprinkler	€235750	€2113
Total	€1554819	€24226

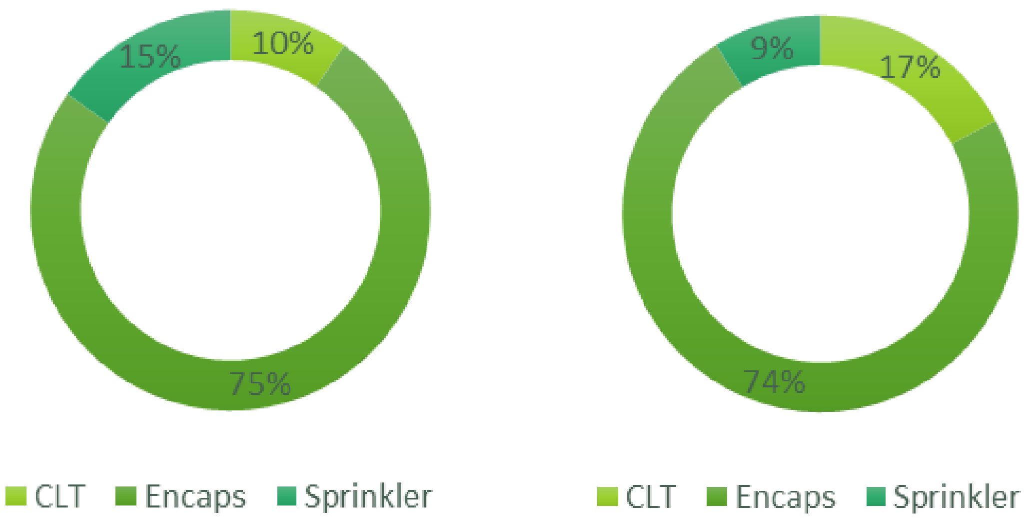


Figure 86: Total result of material use: Left: Economic impact; Right: Environmental impact

5.3 RISK CALCULATIONS

The fire risk calculations is calculated by the following formula:

$$R_{Design} = VB_{Ec/Env} \times \sum P_i \times D_i$$

5.3.1 PROBABILITY CALCULATIONS

The probability per fire scenario is calculated as presented in the fault-tree in Figure 24. The formulas are further summarized below.

$$P_{Scenario,0} = 100\% - F(A)$$

$$P_{Scenario,1} = F(A) \times P1$$

$$P_{Scenario,2} = F(A) \times (100\% - P1) \times P2$$

$$P_{Scenario,0} = F(A) \times (100\% - P1) \times (100\% - P2) \times P3$$

$$P_{Scenario,0} = F(A) \times (100\% - P1) \times (100\% - P2) \times (100\% - P3)$$

5.3.1.1 DETERMINE F(A)

F(A) is calculated by the following formula:

$$F(A) = 5 \times 10^{-7} \times GFA_C \times n_{storeys} \times t_{SL,B}$$

$$F(A) = 5 \times 10^{-7} \times 140 \times 25 \times 100$$

$$F(A) = 17{,}5\%$$

5.3.1.2 DETERMINE P1

P1 is the probability that the fire is extinguished before flashover by the presence of a sprinkler installation. This is calculated by the following formula:

$$P_1 = P_{1,1} \times P_{1,2}$$

In this formula P1.1 relates to the probability of the sprinkler functioning. This is considered to be 0 if no sprinkler is available and 98% is a sprinkler is available. P1.2 relates to the expected post-sprinkler extinguishing if fire fighters. It is expected that this is 100%. Based on this, P1 is calculated as:

$$P_1 = P_{1,1} \times P_{1,2}$$

$$P_1 = 98\% \times 100\%$$

$$P_1 = 98\%$$

5.3.1.3 DETERMINE P2,

P2 is the probability that the fire is extinguished before the structure fails, either floor or wall elements. The calculation of P2 is very extensive and consists of several parts. The main formulas used for the calculation are the following:

$P_2 = P_{2,ext}$	*if:*	$t_{fail} > t_{ext,calc}$
$P_2 = 0\%$	*if:*	$t_{fail} \leq t_{ext,calc}$

The calculation consists of four main steps:

- Step 1: Calculate the expected moment of extinguishing
- Step 2: Calculate the expected moment of structural failure
- Step 3: Determine the probability of the moment of extinguishing
- Step 4: Determine P2

<u>Step 1: Calculate the expected moment of extinguishing (tcalc,ext)</u>

The calculated moment of extinguishing is based on methods presented by Brandon (2018), which is integrated onto the design tool. Based on the calculations, the design tool calculates the fire dynamics and with this the expected moment of extinguishing.

Table 51: Results of calculation steps

Step	Parameter	Equation	Unit
1	Opening factor	$O = \left(\frac{A_v}{A_t}\right)\sqrt{h_v}$	[$m^{1/2}$]
		$O = \left(\frac{100\% \times 20{,}5}{427{,}4}\right)\sqrt{1{,}78} = 0{,}067$	
2	Heating rate/time factor	$\Gamma = \left(O/\sqrt{\rho c\lambda}\right)^2/(0{,}04/1160)^2$	[-]
		$\Gamma = \left(O/\sqrt{770}\right)^2/(0{,}04/1160)^2 = 6{,}39$	
3	Start time of decay	$t^1_{max} = \max\left[\left(0{,}2 * 10^-3 * q_{t,d}/O\right); t_{lim}\right]$	[hour]
		$t^1_{max} = \max[(0{,}2 * 10^-3 * 192{,}65/O); 00; 15]$	
		$t^1_{max} = 0{,}57$	

The total char depth is calculated as:

Table 52: Results of iteration steps

Step	Parameter	Equation	Unit
1	Initial charring rate	$\beta_{par} = 1{,}5\beta_0 * \frac{0{,}2\sqrt{\Gamma} - 0{,}04}{0{,}16\sqrt{\Gamma} + 0{,}08}$	[mm/min]
		$\beta_{par} = 1{,}5\beta_0 * \frac{0{,}2\sqrt{\Gamma} - 0{,}04}{0{,}16\sqrt{\Gamma} + 0{,}08}$	
		$\beta_{par} = 1{,}01$	
2	Time at which char rate reduces	$t^1_0 = 0{,}009\frac{q_{t,d}}{O}$	[min]
		$t^1_0 = 0{,}009\frac{192{,}65}{0{,}067} = 25{,}85$	
3	Final char depth	$d^1_{char} = 2\beta_{par}t_0$	[mm]
		$d^1_{char} = 2 * 1{,}01 * 25{,}85 = 52{,}14$	

After which the iterative steps are calculated to include the contribution of exposed CLT to the fuel load by:

Table 53: Results of calculation steps

Step	Parameter	Equation	Unit
1	Total fuel load divided by the surface area of compartment bound	$q_{td}^{i+1} = q_{fml} + \frac{A_{CLT} * \alpha_1 * (d_{char}^{i} - 0{,}7\beta_{par} * t_{max}^{1})}{A_c}$	[$m^{1/2}$]
		$= 192{,}65 + \frac{80{,}09 * 5{,}39 * (d_{char}^{i} - 0{,}7 * 1{,}01 * 0{,}57)}{326{,}87}$	
2	Start time of decay	$\mathrm{t}_{\mathrm{max}}^{\mathrm{i+1}} = \max[(0{,}2 * 10^{-}3 * q_{t,d}^{i+1}/O); \mathrm{t}_{\mathrm{lim}}]$	[hour]
		$\mathrm{t}_{\mathrm{max}}^{\mathrm{i+1}} = \max[(0{,}2 * 10^{-}3 * q_{t,d}^{i+1}/O); 00; 15]$	
3	Time at which char rathe reduces	$t_0^{i+1} = 0{,}009\frac{q_{t,d}^{i+1}}{O}$	[min]
		$t_0^{i+1} = 0{,}009\frac{q_{t,d}^{i+1}}{0{,}067}$	
4	Final char depth	$d_{char}^{i+1} = 2\beta_{par}t_0^{i+1}$	[mm]

The iteration of the contribution of CLT to the fuel load continues until the difference in fuel load contribution 0,01 compared to the previous calculation. The iteration is done 30 times. An overview of the results of the iteration is presented in Table 54, only considering 10 iterations as for this example it is observed that after the 8th iteration the difference becomes smaller then 0,01.

Table 54: Results of iteration of CLT contribution to fire load steps

Iteration	q_{td}^{i+1}	Difference	$\mathrm{t}_{\mathrm{max}}^{\mathrm{i+1}}$	t_0^{i+1}	d_{char}^{i+1}
0	192,65		0,57	25,84	52,14
1	247,53	54,87	0,74	33,20	66,99
2	263,28	15,75	0,78	35,31	71,25
3	267,80	4,52	0,80	35,91	72,48
4	269,10	1,30	0,80	36,09	72,83
5	269,47	0,37	0,80	36,14	72,93
6	269,58	0,11	0,80	36,15	72,96
7	269,61	0,03	0,80	36,16	72,97
8	269,62	0,01	0,80	36,16	72,97
9	269,62	0,00	0,80	36,16	72,97
10	269,62	0,00	0,80	36,16	72,97

With this, the temperature-time calculations can be done, which are calculated based on the following formula for the heat face:

$$\Theta = 20 + 1325(1 - 0{,}324e^{(-0.2t*\Gamma)} - 0{,}204e^{(-1.7t*\Gamma)} - 0{,}472e^{(-19t*\Gamma)})$$

$$\Theta = 20 + 1325(1 - 0{,}324e^{(-0.2t*6{,}39)} - 0{,}204e^{(-1.7t*6{,}39)} - 0{,}472e^{(-19t*6{,}39)})$$

And the following formula for the decay phase, as tmax*Γ = 4,77 >2

$$\Theta = \Theta_{max} - 250(t * \Gamma - \Gamma * t_{max}^{i+1} * x)$$

$$\Theta = 914{,}4 - 250(t * 6{,}39 - 6{,}39 * 0{,}80 * 1)$$

Based on this, the compartment temperature is calculated over time. The results are plotted in Figure 87 on the next page. The figure shows both the parametric fire curve without additional fuel due to exposed timber as presented by the methods from NEN-EN 1991-1-2+C3 (2019), and the fire curve as follows from Brandon (2018). From the result follows that the CLT exposed compartment extinguishes after 82 min.

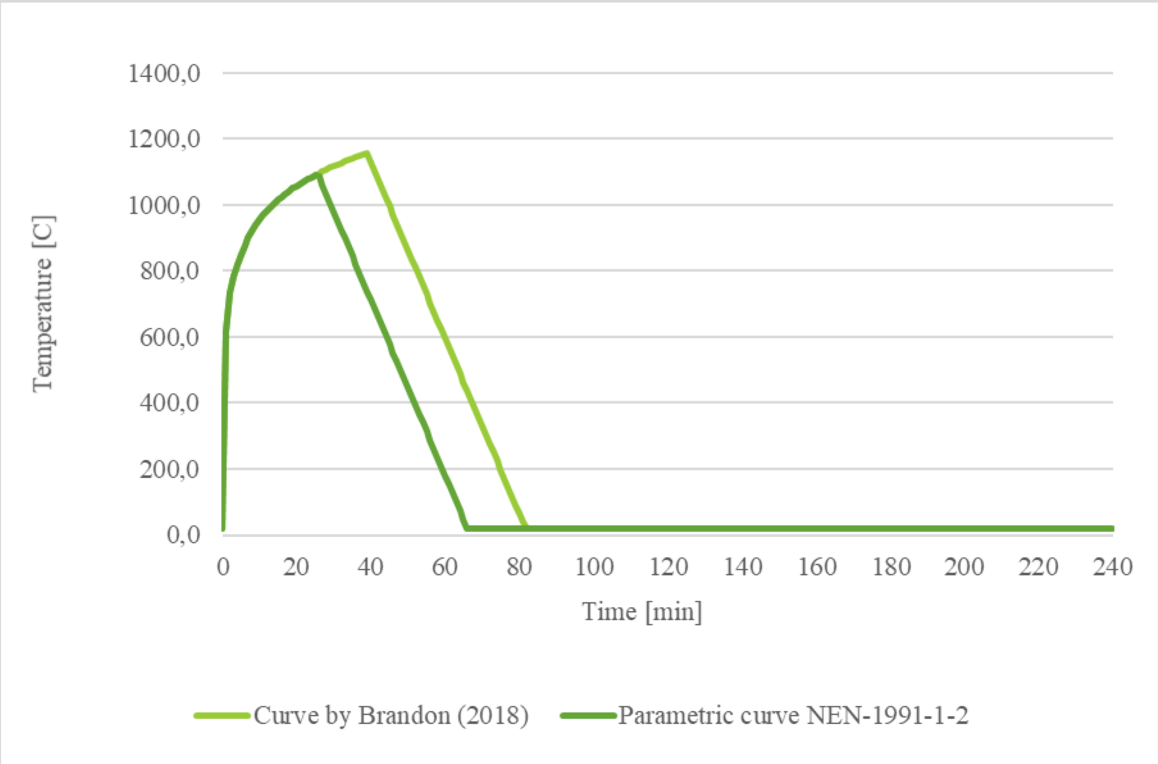


Figure 87: Results fire dynamics of elaborated example

<u>Step 2: Calculate the expected moment of structural failure (t_{fail})</u>

The tool calculates the structural behaviour for a floor and wall element over time as it is exposed to compartment fire. With this, the t_{fail} is calculated as:

$$t_{fail} = MIN(t_{fail,floor}; t_{fail,wall})$$

The calculation consists of two main steps:

- Step 2.1: Calculation of effective cross-section over time
- Step 2.2: Calculation of stress over time

<u>Step 2.1: Calculation of the effective cross-section</u>

The calculation of the effective cross-section is dependent on thickness and number of timber lamellas, type of timber adhesive and the encapsulation. In this example, walls and floors are constructed from 5 lamellas oof each 35mm, with MUF adhesive. The encapsulation consists of 2 layers of 12mm thick fire rated encapsulation. However, as only 70 % of ceiling and walls are encapsulated, 30% is not. This means that the most vulnerable elements are the elements without encapsulation, on which the calculation is based. The total

$$d_{ef} = d_{char} + d_0$$

The formulas and their result for the considered example are presented in Table 55. As the composition of floor and wall members are similar, the char depth calculations are the same. The additional non-loadbearing layer however deviates.

Note, MUF adhesive is considered, and the element is therefore not considered to delaminate. Moreover, as ceiling and walls are not fully encapsulated, it is considered that the most dominant elements are non-encapsulated elements.

Table 55: Thermal gradient calculations

Parameter	Formula	Result	Unit
Char depth	$d_{char} = \beta_0 * t$	$d_{char,0} = 0{,}7 * t$	[mm]
Zero strength layer floor slab	$d_{0,floor} = \frac{h_{CLT}}{100} + 10$	$d_{0,floor} = \frac{h_{CLT}}{100} + 10$	[mm]
Zero strength layer walls	$d_{0,floor} = \frac{h_{CLT}}{15} + 10{,}5$	$d_{0,floor} = \frac{h_{CLT}}{15} + 10{,}5$	[mm]

The tool automatically calculates the char depth over time, for three different alternatives for wall and floor based on adhesive type ad protection. The result of the calculation is presented in Figure 88. As explained, for this specific design MUF-floor and MUF-wall are dominant for the zero strength layer depth calculations (def), which represent exposed CLT elements with MUF adhesive.

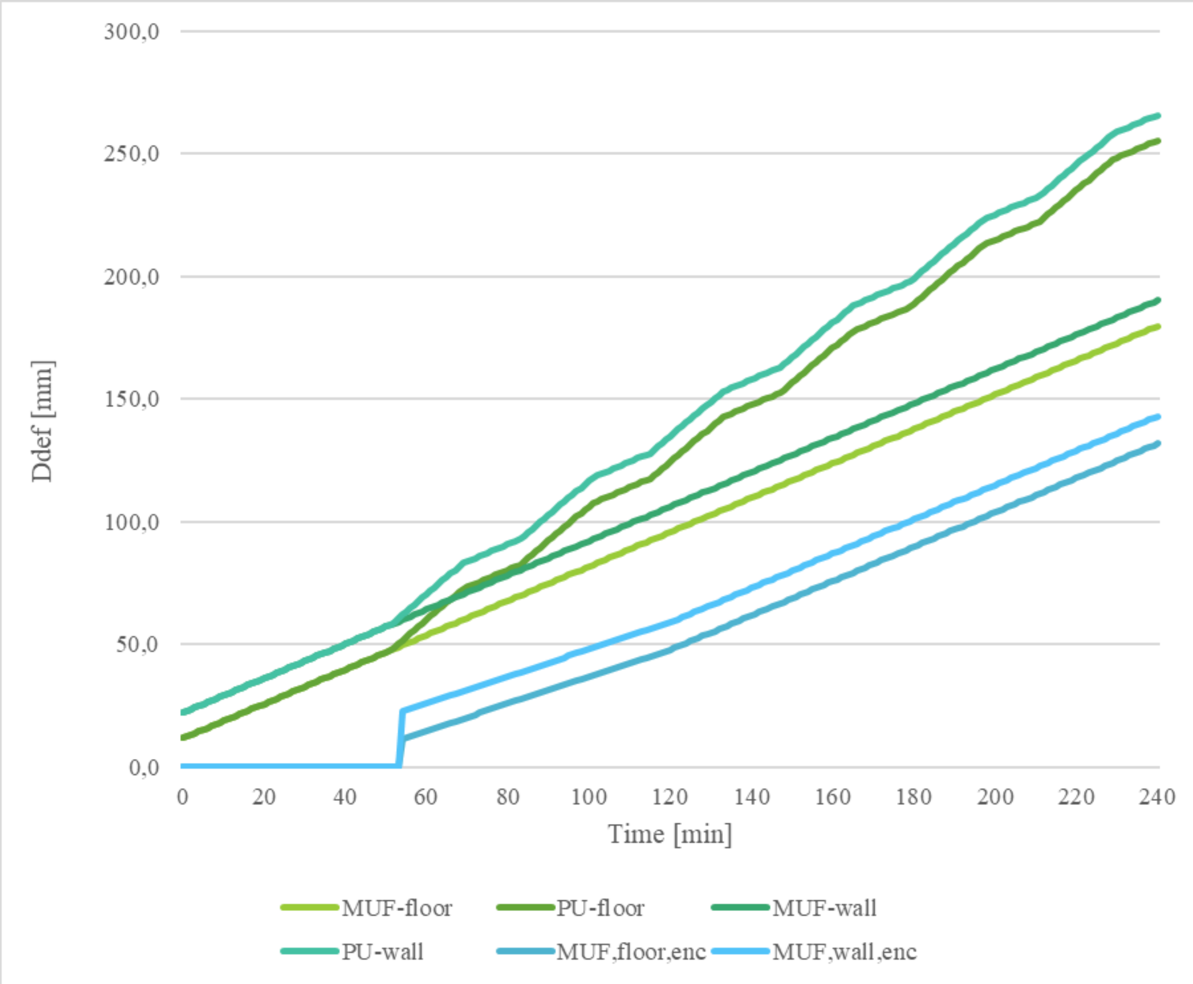


Figure 88: Thermal gradient results

Based on this, the effective cross-section over time is calculated for the different elements. This influences the cross-section properties over time. The effect is further described below.

<u>Step 2.1: Calculation of the fire resistance over time</u>
The calculation of the effective cross-section is dependent on thickness and number of timber lamellas, type of timber adhesive and the encapsulation. In this example, walls and floors are constructed from 5 lamellas of each 35mm, with MUF adhesive.

It is expected that for all floors that structural behaviour of the floor elements is similar, as loads are considered to be similar. For the wall elements, the most loaded wall element is considered, which is determined to be an element of the wall on the ground floor compartment. It is noted that this assumption does not present a perfect condition for the tool, as the location of the fire affects the moment of wall-failure. For future improvements this aspect should be accounted for. Table 56 presents a summary of the most dominant factors used in the calculations.

Table 56: Load and resistance calculations

Parameter	Floor element	Wall element
Max load	6,4 [kNm]	12,8 [kN/m]
Max allowed stress	14,8 [MPa]	11,8 [MPa]

From the calculations follows that the floor fails at 133 min and the wall fails at 84 min. The stress line over time is visualized in Figure 89.

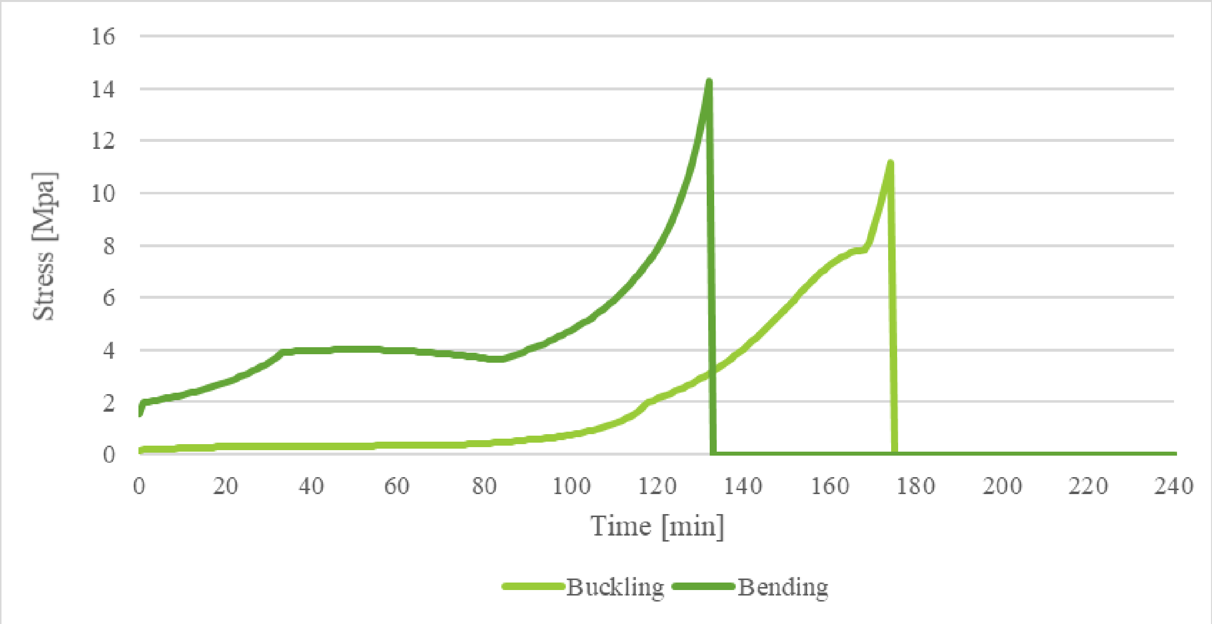


Figure 89: Stress calculations

Step 3: Determine the probability of moment of extinguishing ($P_{2,ext}$)

It is observed that the calculations by Brandon (2018) do not provide a perfect representation of the expected moment of extinguishing. Therefore, the moment of failure and moment of calculated extinguishing must be compared to the expected moment of extinguishing based on the results of large-scale compartment fire tests. The probability of moment of extinguishing is calculated by the following formula:

$$P_{2,Ext} = P_{2,1} * P_{2,2} * P_{2,3}$$

To determine this, this part is further sub-divided to four steps:

- Step 3.1. Determine probability of natural extinguishing
- Step 3.2. Determine probability of moment of extinguishing
- Step 3.3. Determine probability of post-fire fire fighter extinguishing
- Step 3.4. Calculate $P_{2,ext}$

Step 3.1: Determine probability of natural decay ($P_{2.1}$)
The probability of natural extinguishing is determined by the following formula:

$$P_{2,1} = P_{2,1,1} * R_{2,1,enc}$$

$P_{2.1.1}$ is the probability of natural decay based on the number of exposed CLT surfaces and the type of adhesive and can be determined from Table 57. In the example, 30% of the CLT is exposed and MUF adhesive is used. This results in a probability of natural decay of 100%.

Table 57: Probability of natural decay

Design type	Description	PU adhesive	MUF adhesive	Unit
1	>30% exposed	14	75	[%]
2	<30% exposed	43	100	[%]
3	0% exposed	100	100	[%]

$R_{2,1,Enc}$ is the additional risk factor relating to the type of encapsulation used that is, representing the risk of base-layer encapsulation failure. In the example fire rated encapsulation is used, which results in a risk factor of 1.0.

With this, the probability of natura decay $P_{2.1}$ can be calculated:

$$P_{2,1} = P_{2,1,1} * R_{2,1,enc}$$

$$P_{2,1} = 100\% * 1{,}0$$

$$P_{2,1} = 100\%$$

Step 3.2: Determine probability of moment of natural decay ($P_{2.2}$)

The probability of moment of natural decay is based on the number of exposed CLT surfaces and related to the moment of structural failure. $P_{2.2}$ can be determined from Table 58. In the example, 30% of the CLT is exposed, and the moment of failure (t_{fail}) is 152 min (see step 1). This results in a probability of moment of extinguishing before failure of 83%.

Table 58: Overview of values for probability of moment of extinguishing

Percentage exposed	Number of tests	<30 min	<60 min	<90 min	<120 min	<180min	<240 min
>30%	4	0%	0%	25%	50%	100%	100%
<=30%	6	0%	17%	17%	83%	83%	100%
0%	6	0%	17%	50%	83%	100%	100%

Step 3.3: Determine probability of post-fire fire fighter extinguishing ($P_{2.3}$)

The probability of post-fire fire fighter extinguishing is depending on the fire fighter accessibility and calculated by:

$$P_{2,3} = P_{2,3,1} \times R_{2.3.1} + P_{2,3,2} \times R_{2.3.2}$$

Where $P_{2.3.1}$ is the probability that that a fire occurs at a floor below 28 meter, and $P_{2.3.2}$ is the probability that a fire occurs at a compartment above 28 meter. This way, $P_{2.3.1}$ is calculated as:

$$P_{2,3.1} = \frac{n_{storeys,<28m}}{n_{storeys,total}}$$

$$P_{2,3.1} = \frac{10}{25}$$

$$P_{2,3.1} = 40\%$$

And with this:

$$P_{2,3.2} = 100\% - 40\% = 60\%$$

$R_{2.3.1}$ and $R_{2.3.1}$ relate to risk factor regarding post-fire extinguishing based on the type of intervention. It is assumed that below 28 meter the fire can be extinguished from outside due to the height of the fire fighter ladder. Above this height, offensive intervention is needed to extinguish the decayed fire, which increases the risk. It is assumed that $R_{2.3.1.}$ is 1,0 and that $R_{2.3.1.}$ is 0,5.

With this, $P_{2.3}$ is calculated as:

$$P_{2,3} = P_{2,3,1} \times R_{2.3.1} + P_{2,3,2} \times R_{2.3.2}$$

$$P_{2,3} = 40\% \times 1{,}0 + 60\% \times 0{,}5$$

$$P_{2,3} = 70\%$$

Step 3.4: Calculate the probability of moment of extinguishing ($P_{2.ext}$)

From the results from the previous steps, the probability of moment of extinguishing is calculated by:

$$P_{2,Ext} = P_{2,1} * P_{2,2} * P_{2,3}$$
$$P_{2,Ext} = 100\% * 83\% * 70\%$$
$$P_{2,Ext} = 58{,}1\%$$

For visualization, the decision tree for determining $P_{2,ext}$ is presented in Figure 90.

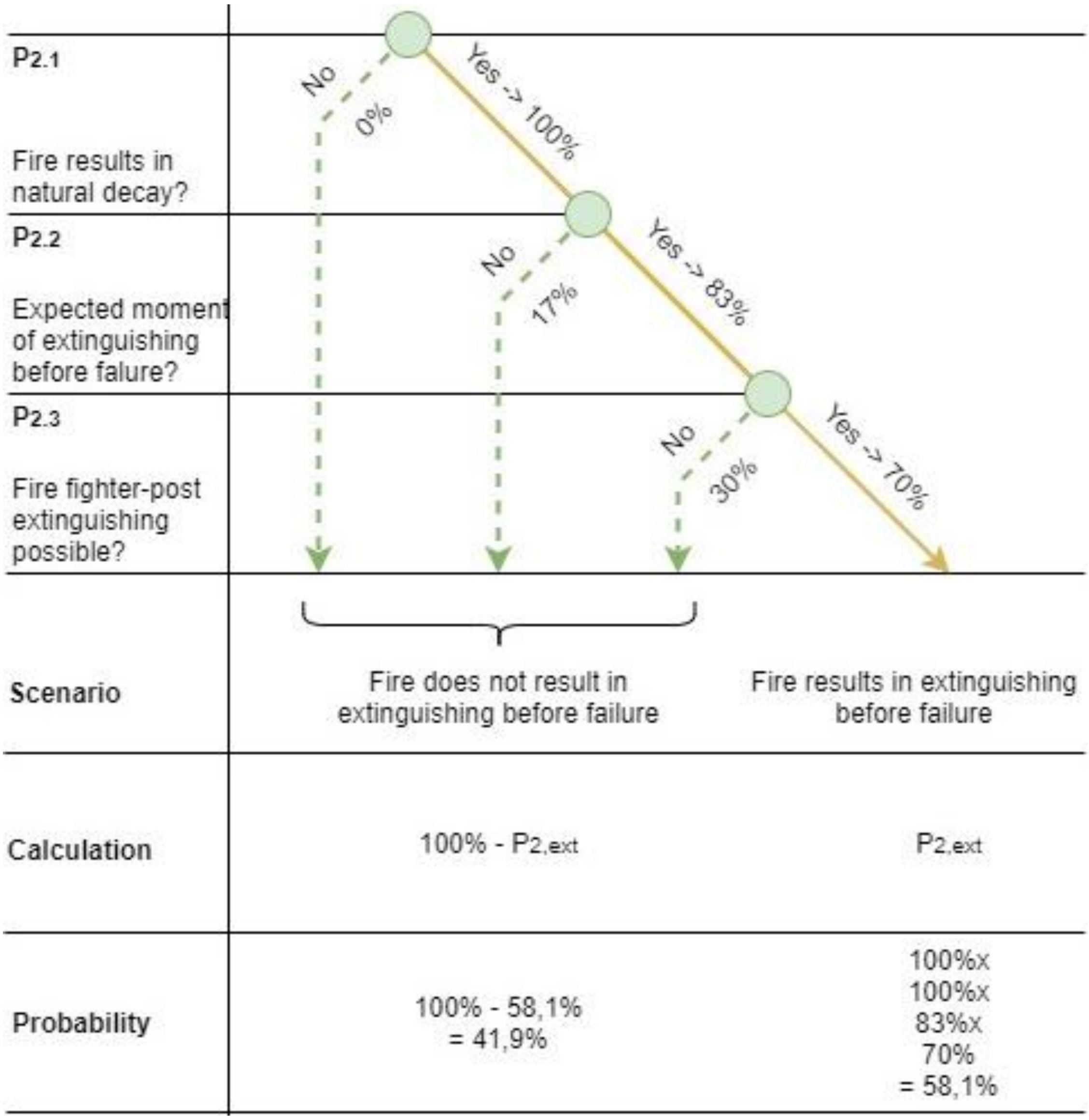


Figure 90: Results fault-tree example P2,ext

Step 4: Determine P2

With the results presented in step 1, 2 and 3, it is now possible to determine P2 by the following formula:

$P_2 = P_{2,ext}$	*if:*	$t_{fail} > t_{ext,calc}$
$P_2 = 0\%$	*if:*	$t_{fail} \leq t_{ext,calc}$

Based on the results, it follows that t_{fail} is 152 min and $t_{ext,calc}$ is 87 min. This means that $t_{fail} > t_{ext,calc}$ and therefore P2 = $P_{2,ext}$. This means that P2 = 58,1%.

5.3.1.4 Determine P3

P3 is the probability that if there is a fire and the structure fails, this does not lead to progressive collapse. This is dependent on the location of the fire and the structural capacity of the elements below the location of the fire. For this, structural calculations are done determining the additional load for each storey. P3 is calculated by the following formula:

$$P_3 = 100\% - \frac{n_{storey,collapse} + 1}{n_{storey,total}}$$

In this formula, $n_{storey,collapse}$ maximum storey number at which either floor or wall elements cannot withstand the additional loads from the structure. $n_{storey,collapse}$ is calculated as:

$$n_{storey,collapse} = MAX(n_{Storey,collapse,floor} ; n_{Storey,collapse,wall})$$

The results per storey are summarized in Table 59. The tool compares the floor and wall strength to the storey stress and defines the storey at which the stress exceeds the strength. At this storey, the location of collapse is determined. From the results of this example, it is observed that the location of collapse for the floor stress is at storey 17, as at this floor the additional stress becomes higher than the maximum allowed stress of 14,8 MPa. The wall stress is not exceeded for any storey. Based on this, $n_{storey,collapse}$ is 17.

Table 59: Results of additional load on strcture due to structural failure - per building storey

Storey	Load if collapse Floor [kNm]	Floor stress [MPa]	Load if collapse Wall [kN]	Wall stress [MPa]
0	192,22	47,55	439,37	4,18
1	184,53	45,65	421,79	4,02
2	176,85	43,75	404,22	3,85
3	169,16	41,84	386,64	3,68
4	161,47	39,94	369,07	3,51
5	153,78	38,04	351,50	3,35
6	146,09	36,14	333,92	3,18
7	138,40	34,24	316,35	3,01
8	130,71	32,33	298,77	2,85
9	123,02	30,43	281,20	2,68
10	115,33	28,53	263,62	2,51

11	107,65	26,63	246,05	2,34
12	99,96	24,73	228,47	2,18
13	92,27	22,82	210,90	2,01
14	84,58	20,92	193,32	1,84
15	76,89	19,02	175,75	1,67
16	69,20	17,12	158,17	1,51
17	61,51	15,22	140,60	1,34
18	53,82	13,31	123,02	1,17
19	46,13	11,41	105,45	1,00
20	38,44	9,51	87,87	0,84
21	30,76	7,61	70,30	0,67
22	23,07	5,71	52,72	0,50
23	15,38	3,80	35,15	0,33
24	7,69	1,90	17,57	0,17
25	0,00	0,00	0,00	0,00

With this, P3 can be calculated as:

$$P_3 = 100\% - \frac{n_{storey,collapse} + 1}{n_{storey,total}}$$

$$P_3 = 100\% - \frac{17 + 1}{25}$$

$$P_3 = 28\%$$

5.3.1.5 Total failure-tree

Based on the above presented presentations, the failure tree is calculated for each scenario.

$$\boldsymbol{P_{Scenario,0} = 100\% - F(A)}$$

$$P_{Scenario,0} = 100\% - 17{,}5\% \qquad = 82{,}50\%$$

$$\boldsymbol{P_{Scenario,1} = F(A) \times P1}$$

$$P_{Scenario,1} = 17{,}5\% \times 98\% \qquad = 17{,}15\%$$

$$\boldsymbol{P_{Scenario,2} = F(A) \times (100\% - P1) \times P2}$$

$$P_{Scenario,2} = 17{,}5\% \times (100\% - 98\%) \times 58{,}1\% \qquad = 0{,}20\%$$

$$\boldsymbol{P_{Scenario,3} = F(A) \times (100\% - P1) \times (100\% - P2) \times P3}$$

$$P_{Scenario,3} = 17{,}5\% \times (100\% - 98\%) \times (100\% - 58{,}1\%) \times 28\% \qquad = 0{,}04\%$$

$$\boldsymbol{P_{Scenario,4} = F(A) \times (100\% - P1) \times (100\% - P2) \times (100\% - P3)}$$

$$P_{Scenario,4} = 17{,}5\% \times (100\% - 98\%) \times (100\% - 58{,}1\%) \times (100\% - 28\%) \qquad = 0{,}11\%$$

5.3.2 DAMAGE CALCULATIONS

For each fire scenario, the impact of the fire differs. This is calculated expressed as lost building value due to the specific fire scenario. With this, for the different fire scenarios, the monetary impact, either economic or environmental, is calculated where, $VB_{EC/Env}$ is the building value, and D_i is the expected damage for a specific fire scenario.

$$I_i = VB_{Ec/Env} \times D_i$$

5.3.2.1 SCENARIO 0

Scenario 0 describes the scenario that no fire is present. Therefore, no damage is expected.

5.3.2.2 SCENARIO 1

Scenario 1 describes the scenario for which a local fire is extinguished before flashover is reached, due to sprinkler activation. Only smoke and water damage of 1 compartment is expected, defined to be 5% of the value of the compartment. This results in a percentage lost due to scenario 1 by:

$$D_1 = \frac{5\%}{n_{storeys}}$$
$$D_1 = \frac{5\%}{25}$$
$$D_1 = 0{,}2\%$$

5.3.2.3 SCENARIO 2

Scenario 2 describes the scenario for which a compartment fire does not result in structural collapse, and therefore can withstand a burnout. It is assumed that one compartment is lost. With this, the percentage of the total building value that is lost by scenario 2 is calculated as:

$$D_2 = \frac{1}{n_{storeys}}$$
$$D_2 = \frac{1}{25}$$
$$D_2 = 4\%$$

5.3.2.4 SCENARIO 3

Scenario 3 is the scenario that part of the building is lost, which is defined as the number of compartments at which structural collapse will not occur. The calculation for the location of structural collapse was presented in Table 59. Based on this, the expected damage of scenario 3 is calculated as:

$$D_3 = \frac{n_{storeys,building} - (n_{storey,collapse} + 1)}{n_{storey,total}}$$
$$D_3 = \frac{25 - (17 + 1)}{25}$$
$$D_3 = 28\%$$

5.3.2.5 SCENARIO 4

Scenario 4 is the scenario that describes total building loss, which is 100% of the building.

5.3.3 REHABILITATION COST

VB_{EC} is the economic value of the building, which is determined by the purchase price per m^2, which is chosen to be €8000 and the total GFA. With this, VB_{EC} is calculated as:

$$VB_{Ec} = GFA \times €_{VB,EC}$$

$$VB_{Ec} = 3500 \times 8000$$

$$VB_{Ec} = 28 \times 10^6 \qquad [€]$$

VB_{Env} is the environmental value of the building, which is determined by the MPG per m^2 per year, which is chosen to be 0,8 based on the current building restrictions regarding the maximum allowed MGP. With this, VB_{Env} is calculated as:

$$VB_{Env} = GFA \times €_{VB,Env}$$

$$VB_{Env} = 3500 \times 0{,}8$$

$$VB_{Env} = 280 \times 10^3 \qquad [€]$$

The calculation of the damage is presented for each scenario in the following paragraphs, defined as percentage of the building value that is lost due to a specific fire scenario.

5.3.4 TOTAL IMPACT RESULTS

The design tool presents values for the total impact per fire scenario by multiplying the economic and environmental building value, and the percentage of the building lost per scenario, the total impact per scenario can be calculated by:

$$I_i = VB_{Ec/Env} \times D_i$$

The results are summarized in Table 60.

Table 60: Overview of calculated economic impact

Scenario	Economic impact	Environmental impact
0	$I_{0,EC} = 28 \times 10^6 \times 0 = €0$	$I_{0,EC} = 280 \times 10^3 \times 0 = €0$
1	$I_{0,EC} = 28 \times 10^6 \times 0{,}2\% = €56 \times 10^3$	$I_{0,EC} = 280 \times 10^3 \times 0{,}2\% = €560$
2	$I_{0,EC} = 28 \times 10^6 \times 4\% = €1{,}1 \times 10^6$	$I_{0,EC} = 280 \times 10^3 \times 4\% = €11{,}2 \times 10^3$
3	$I_{0,EC} = 28 \times 10^6 \times 28\% = €78{,}4 \times 10^6$	$I_{0,EC} = 280 \times 10^3 \times 28\% = €78{,}4 \times 10^3$
4	$I_{0,EC} = 28 \times 10^6 \times 100\% = €28 \times 10^6$	$I_{0,EC} = 280 \times 10^3 \times 100\% = €280 \times 10^3$

5.3.5 TOTAL RISK CALCULATIONS

The total risk of the design is calculated by a summation of the risk results of all fire scenarios. With this, the total risk of the design is calculated as:

$$R_{Design} = \sum P_i \times I_i$$

Note: This presents a similar calculation as the calculation as stated in the formula below though already the impact is defined in monetary value.

$$R_{Design} = VB_{Ec/Env} \times \sum P_i \times D_i$$

5.3.5.1 ECONOMIC RISK RESULTS

For the economic risk this results in the following risk per scenario and in total, summarized in Table 61.

Table 61: Total economic risk results

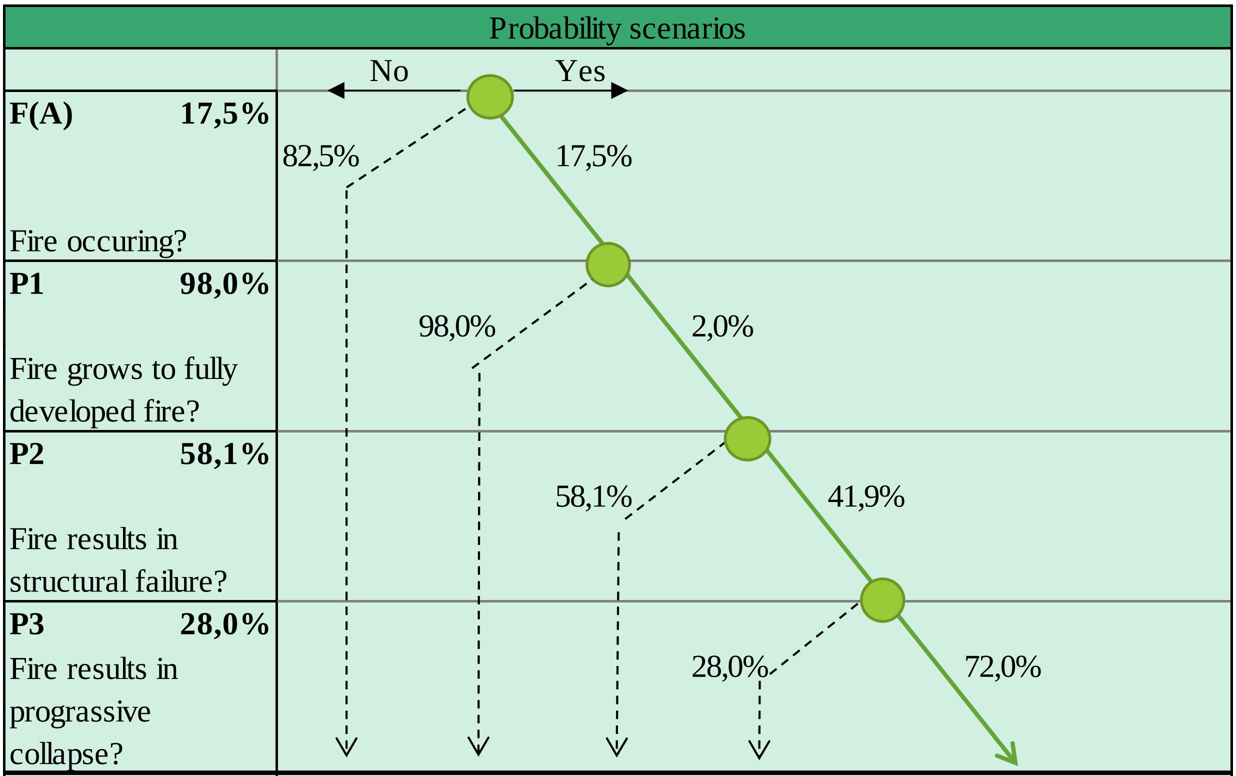
Scenario	Formula	Result [€]
0	$R_{0,EC} = 82{,}50\% \times €0$	$= €0$
1	$R_{1,EC} = 17{,}15\% \times €56 \times 10^3$	$= €9604{,}0$
2	$R_{2,EC} = 0{,}20\% \times €1{,}1 \times 10^6$	$= €2277{,}5$
3	$R_{3,EC} = 0{,}04\% \times €7{,}8 \times 10^6$	$= €3219{,}26$
4	$R_{4,EC} = 0{,}11\% \times €28 \times 10^6$	$= €29564.64$
Total	$R_{Total,EC} = R_{0,EC} + R_{1,EC} + R_{2,EC} + R_{3,EC} + R_{4,EC}$	$= €44665{,}42$

For the environmental risk calculations this results in the following risk per scenario and in total, summarized in Table 62:

Table 62: Economic risk results

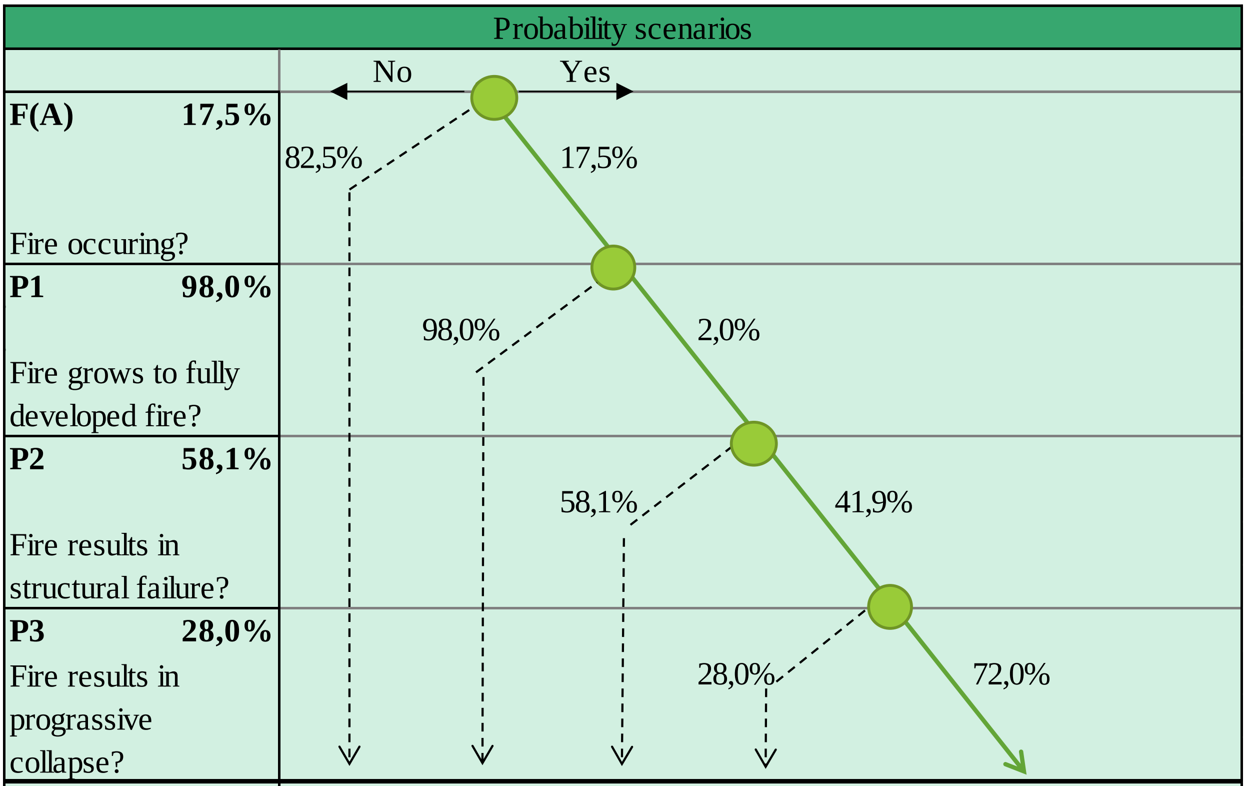
Scenario	Formula	Result [€]
0	$R_{0,EC} = 82{,}50\% \times €0$	$= €0$
1	$R_{1,EC} = 17{,}15\% \times €560$	$= €96{,}0$
2	$R_{2,EC} = 0{,}20\% \times €11{,}2 \times 10^3$	$= €22{,}8$
3	$R_{3,EC} = 0{,}04\% \times €78{,}4 \times 10^3$	$= €32{,}19$
4	$R_{4,EC} = 0{,}11\% \times €280{,}0 \times 10^3$	$= €295{,}65$
Total	$R_{Total,EC} = R_{0,EC} + R_{1,EC} + R_{2,EC} + R_{3,EC} + R_{4,EC}$	$= €446{,}65$

The design tool summarizes the most important results of the risk-calculation in a fault-tree. The economic fault-tree is presented in Figure 91, the environmental fault-tree is presented in Figure 92.



Scenario (i)	0	1	2	3	4
Frequency (Fi)	82,50%	17,15%	0,20%	0,04%	0,11%
Damage (Di)	€ -	€ 56.000	€ 1.120.000	€ 7.840.000	€ 28.000.000
Risk (Ri)	€ -	€ 9.604,00	€ 2.277,52	€ 3.219,26	€ 29.564,64

Figure 91: Overview of elaborated risk result presented by design tool



Scenario	0	1	2	3	4
Frequency	82,50%	17,15%	0,20%	0,04%	0,11%
Damage	€ -	€ 560	€ 11.200	€ 78.400	€ 280.000
Risk	€ -	€ 96,04	€ 22,78	€ 32,19	€ 295,65

Figure 92: Overview of total environmental risk results presented by the design tool

5.4 TOTAL RESULTS.

Based on the previous calculations, the total balance between material use and fire risk can be calculated by the “circular fire safety impact value”:

$$Cirular\ fire\ safety\ impact = Material\ use + Fire\ risk$$

$$Cirular\ fire\ safety\ impact = (Cost - Benefit) + Fire\ risk$$

This results in a total economic circular fire safety impact of:

$$Cirular\ fire\ safety\ impact = (3092547{,}95 - 1537656{,}98) + 44665{,}42$$

$$Cirular\ fire\ safety\ impact = 1599556{,}38$$

For the environmental impact this results in:

$$Cirular\ fire\ safety\ impact = (37988{,}34 - 13761{,}97) + 446{,}65$$

$$Cirular\ fire\ safety\ impact = 24673{,}02$$

In Figure 93 and Figure 94, an overview of the results by the design tool is presented.

Total impact

Impact:		**Economic**
Costs	€	3.092.547,95
Benefits	€	-1.537.656,98
Risk	€	44.665,42
Total	**€**	**1.599.556,39**

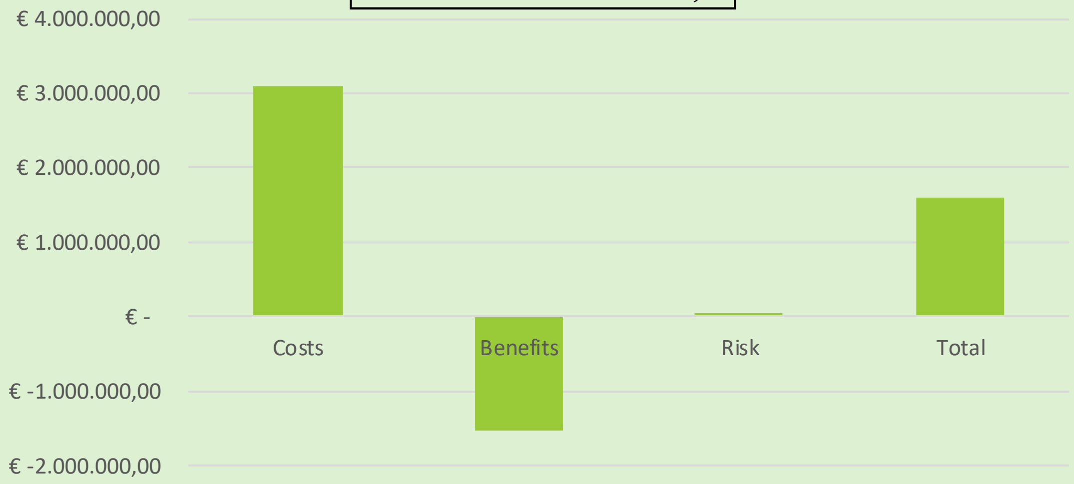


Figure 93: Results for economic impact presenting the balance between material use and fire risk

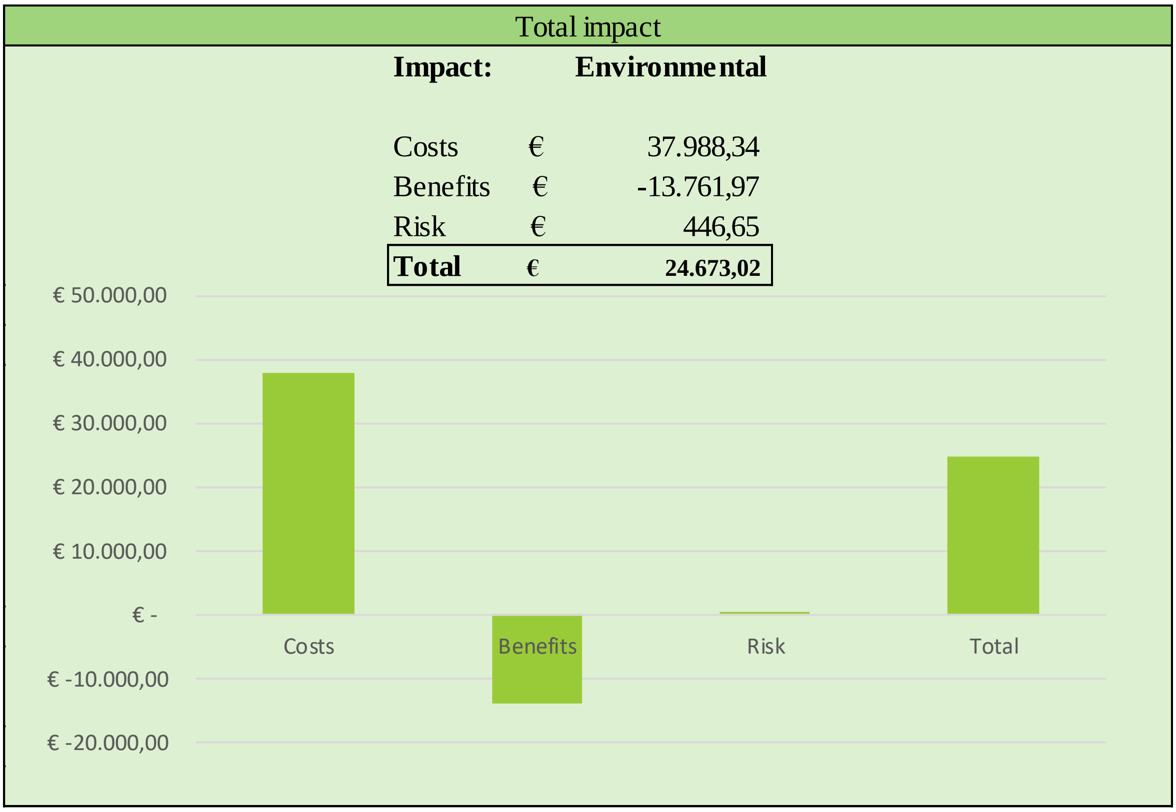


Figure 94: Results for environmental impact presenting the balance between material use and fire risk