Fire safety of vertical greenery systems

A decision-making framework for safely greening the building envelope

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Preface

This thesis was written as a graduation research for the MSc Architecture, Urbanism and Building Sciences at Tu Delft. When I was informed on the possibility of fire safety of green façades as a graduation topic, I was immediately interested. I had always been fascinated with fire safety related topics during my education, but found that it was always touched upon rather superficially. I had also worked with greenery systems in designs before, but had never really looked into the technical aspects of them. With this topic I got the opportunity to dive into two topics which were of interest to me and deepen my knowledge thoroughly on both.

I was warned beforehand that fire safety is not an easy topic, but I am very glad and proud that I took on the challenge. I want to thank both my supervisors, Ir. A.C. Bergsma and Dr. ir. M. Ottelé, for their guidance in this research. They guided my process, helped me to stay focused and could provide invaluable knowledge for the research. Furthermore I want to thank Ir. P.P.N. Hoondert and Ir. B.H.G. Peters from DGMR for their support. Without their knowledge and help on fire safety I am sure the current thesis would not have become what it is now. I also want to thank Bo Valkenburg, who graduated simultaneously on the topic of Fire Safety of Building-Integrated Photovoltaics. We worked rather closely during the research and could share useful work, discussions and ideas with on another. Lastly I want to thank all the other parties that were willing to speak to me and share their knowledge, views and experiences from the field.

Lastly I want to thank my partner, family and friends for supporting me during the graduation. Their encouragement and confidence in me gave me the strength to finish the research and overcome any obstacles during the process.

The goal of the research was to provide a better understanding of fire safety of vertical greenery systems, so I hope that this thesis can provide just that to anyone reading this. I wish you a pleasant read.

Carmen Guchelaar

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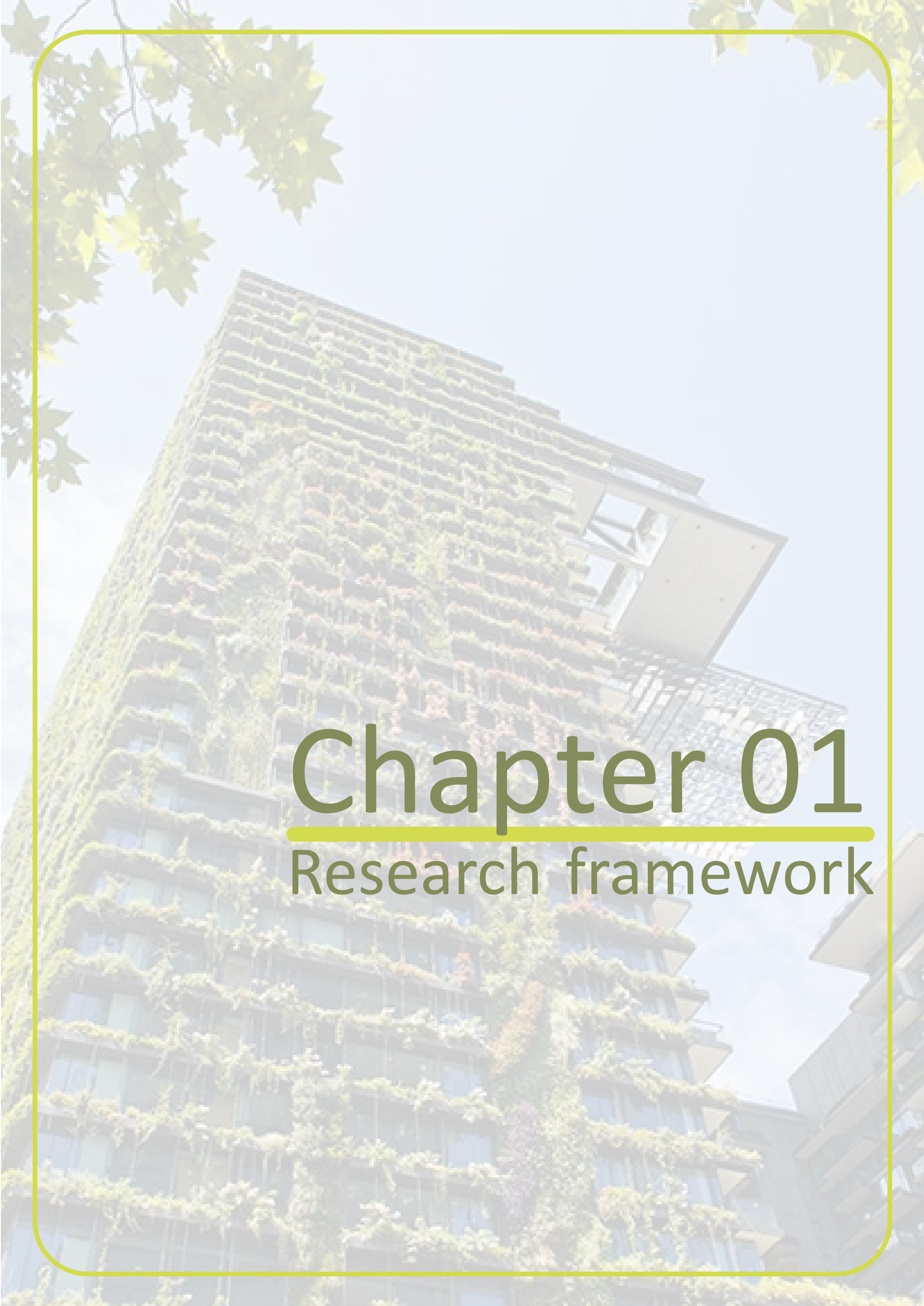
Abstract

Vertical Greenery Systems (VGS) show numerous advantages in terms of sustainability and a healthy living environment. Unfortunately it is found that current knowledge on the fire safety of these systems is lacking and can pose as a barrier for implementing the systems or can cause situations in which they are implemented which are unsafe. The current research aims to put a step forward into filling this knowledge gap. By literature research, interviews with different parties and a risk analysis on case-studies relevant parameters influencing the fire safety of VGS have been identified. A tool was developed which can analyse a façade design with VGS on its fire safety risks. The tool was tested on case-studies and evaluated by interviewees. The tool is to guide designers and raise awareness and understanding of what parameters in a design influence the risk. By raising the understanding on the topic of fire safety of designers, better informed and safer decisions can be made. During the research numerous mitigating measures have been found which can be used in a design to minimize the risk of using VGS. It was found that the type and amount of materials used in the system are of great influence of its fire safety performance, more so than the vegetation used. Furthermore the location of where on the façade the system is applied is of great impact on the risk the VGS causes. Concerns about fire safety of VGS are valid but there are plenty solutions and design considerations identified which help minimize the risks. A risk analysis tool can be helpful for designers to determine the fire risks of a design, increasing the understanding and awareness on the topic which empowers designers to make safe designs with VGS, thus enabling the safely greening of the building envelope.

Abbreviations

VGS	Vertical Greenery Systems
LWS	Living Wall Systems
GF s	Green façades
FMS	Fire Management Systems
UHI	Urban Heat Island
Bbl	The Environment Buildings Decree ('Besluit bouwwerken leefomgeving')
NEN	Dutch Norm ('NEderlandse Norm')
EN	European Standard (from German *Europäische Norm*)
NPR	Dutch Practice Guideline ('Nederlandse Praktijk Richtlijn')

Contents



Chapter 01
Research framework

1.1 Introduction

More than half of the world's population already live in towns or cities and it is predicted that urbanization will continue over the next decades (UNFPA, 2016). The need for healthy living in urbanised areas is thus increasingly important. The dense demographic of cities and lack of open green spaces cause many problems, including excessive heat, flash floods due to heavy rains, air pollution, noise hindrance, biodiversity loss and mental health issues. With the ever growing population of earth's cities, the need for healthy living in urbanised areas is incredibly important.

With the growing need to make the build environment sustainable, architects and engineers are looking for innovative solutions to create a future proof building landscape. Since space in cities is scarce, it is important to make smart use of the space that is available. Therefore making use of the vertical surfaces in cities, which are abundant, provides huge opportunities. An increasing development is the use of vertical greenery systems (hereinafter often referred to as VGS; Gunawardena & Steemers, 2020).

Even though vertical green is not something new in history, where people have been growing vines on façades for centuries (Ottelé, 2011), recent developments show an increase in different and much more complex systems. With the growing use and development of different systems, there is a wide spread range of systems currently available for use and most likely even more will be available in the future.

There is a lot of research discussing the positive effects vertical greenery systems can provide in terms of environment and health (Bustami et al., 2018). Positive aspects among others are mitigation of the heat island effect, stormwater management, providing shade to the building, having insulating properties, providing noise reduction, increase urban biodiversity and improving air quality. There is also much evidence that the presence of living green provides significant health benefits (Maast et al, 2006).

Still these systems are not common practice yet, because they also have downsides or insecurities in knowledge. One of these insecurities is the fire safety of vertical greenery systems (Alalouff, 2023; Dahanayake & Chow, 2018; Kotzen et al, 2023). The 'Netherlands Fire Service' and 'Association of Insurers' (Brandweer Nederland en Verbond van Verzekeraars) even released a 'position paper' where they voiced their concerns on the fire safety aspects of recent sustainability developments. They state that the recent developments are so rapid that the amount of manufacturers and systems is readily increasing, but regulations and legislation is falling behind (Brandweer Nederland en Verbond van Verzekeraars, 2021). The conclusion of a research done by The Dutch Institute for Public Safety (NIPV) is similar to these findings. They state that even though new sustainable developments have to comply with the Dutch Building Decree ('Bouwbesluit'; replaced as of January 1st 2024 by the Environment Buildings Decree ('Besluit Bouwwerken Leefomgeving' (Bbl))), the use of these systems do not always guarantee a save building. This is because the tests performed are not always appropriete for these systems and in general there is not much knowledge on the behaviour of fire in regards to VGS (van Liempd et al., 2022). The lack of knowledge and research into the fire safety of vertical greenery systems could work as a barrier for architects or building plan assessors to make use or approve of the systems (Kotzen et al, 2023). Which can cause city dwellers to miss out on the benefits that vertical greenery systems can provide in the urban landscape.

The current research focusses on identifying relevant fire safety risks when using vertical greenery systems in a design. Parameters which influence the fire safety risks are mapped out and a decision-making frame-work is developed which helps designers in their design process in making informed decisions to make sure vertical greenery systems can be implemented in the built environment in a responsible and safe manner in terms of fire safety.

1.2 Problem statement

As found in literature and news articles, there is a lot of doubt revolving around the fire safety of vertical greenery systems (Alalouff, 2023; Dahanayake & Chow, 2018). The lack of knowledge and wide spread research on this topic could pose as a barrier for the use of these systems in practice (Kotzen et al, 2023). Which would be a huge loss, as the systems can provide numerous environmental and health benefits to the urban landscape where horizontal space is scarce (Bustami et al., 2018). Designers could be discouraged to make use of vertical greenery systems as it would be easier to opt for more conventional façade systems with clearer standards and approved methods of use in terms of fire safety, but might not have the benefits vertical green can provide. Furthermore, building plan assessors, such as the fire department and the municipality, might not approve of plans with vertical greenery systems due to lack of knowledge and guidelines on the fire safety aspects of these systems.

Another problem arising from lack of knowledge and awareness on the fire risks of vertical greenery systems is that it could be that systems are being used which are not actually providing the necessary safety-level. Since the testing methods and regulations are found to not be properly assessed in their appropriateness for vertical greenery systems, it could be that systems are applied which comply to the according to the standards, but might not be performing according to what is desired and expected.

With an ever urbanizing world where space is scarce, the implementation of vertical greenery can provide health and environmental benefits other façade systems cannot. It is important that these systems can be implemented in a responsible and safe manner. Therefore it is necessary that a systematic approach is developed which takes the fire risks into account and provides adequate solutions in different safety levels (Kotzen et al, 2023). A clear design guide for designers could make the use of vertical greenery systems easier to implement and create safer situations.

1.3 Research Objective

The overarching research goal of this thesis is to create awareness and a better understanding of the fire safety aspects of vertical greenery systems and provide insight in what aspects and design parameters are of influence on the fire safety of these systems. This is to help designers gain a better understanding of how choices made during the design process influence the fire safety risk of a design.

To achieve this goal, the research begins with a comprehensive overview of fire safety aspects relevant to vertical greenery systems. The thesis explains the process of risk analysis to identify the key design parameters and their impact on fire safety. It is then explored how these parameters can be used as design solutions to mitigate risk and how additional measures can be implemented to further reduce the risk.

This information is translated into a decision-making framework, to help designers in making informed decisions when designing with vertical greenery systems. Advice is given on how to implement these systems with minimal risk, but also when it is necessary to pay extra attention.

With a better understanding of the relation between design options and their influence on fire safety, more informed and argumented decisions can be made, which ultimately lead to better and safer designs. With a better understanding of the fire safety aspects of vertical greenery systems it is anticipated that the use of these systems will be encouraged while ensuring the safety and well-being of occupants and communities.

1.4 Research question and sub-questions

The main research question the current thesis aims to answer is:

"How can a decision-making framework help guide the design process for outdoor vertical greenery systems which provides responsible fire risk management relevant to a building's characteristics?"

To be able to answer the main question, several sub-questions need to be answered. The sub-questions are organized by theme. The chapter in which the question will be discussed is mentioned after the question in the brackets.

The following sub-questions are to be answered to be able to answer the main research question:

Vertical greenery systems

"What are the different vertical greenery systems currently in use and how do they differ in configuration and materials?" (2.1)

"What are the advantages and disadvantages of vertical greenery systems?" (2.1)

Fire safety

"What are the current legislation and regulations on fire safety in buildings?" (2.2)

"What fire safety aspects are relevant to vertical greenery systems?" (2.3)

"What is the current approach of fire safety of vertical greenery systems in practice?" (2.3)

Risk assessment

"How can the fire risks of vertical greenery systems be assessed?" (3)

"What are the relevant and credible scenarios in terms of fire in vertical greenery systems?" (3)

"Which parameters influence the fire risk of using vertical greenery systems?" (3)

Design solutions

"Which design solutions can be utilised regarding the found risk scenarios?" (4)

"How can a decision-making framework be developed regarding the found parameters?" (5)

1.5 Methodology

The following methods are used during the research. A short description for each method is provided. The research framework is also visualized in Figure 1.1.

Literature research

To start the graduation research an extensive literature review is necessary to become familiar with the topic and find out what the current knowledge and lack of knowledge is. The literature review is used to gain knowledge about vertical greenery systems, fire safety in general, current knowledge on fire safety in VGS and the processes of risk assessment and decision-making frameworks. The knowledge gained from the literature research is used to ask appropriate questions in the interviews.

Interviews

Interviews are conducted with different parties involved with the fire safety of VGS, such as manufacturers, fire safety experts and insurance companies. Interviews are held early on in the research process to gain information about VGS and fire safety and what experience the different parties have herewith. The interviews can help with identifying risks and give first directions in possible design solutions. Later on in the research process, interviews are held to validate the found results with experts.

Risk analysis

With the knowledge gained in the literature review and the interviews, a risk analysis is conducted to get a clear overview of where the problems occur and what parameters have influence on the fire safety of a design. Also case-studies are used in a 'What-if' risk analysis to develop scenarios to help define the relevant parameters. When developing the solutions and design options, these are also evaluated on their influence on the fire safety risks. The risk analysis and the design research is an intertwined and iterative process.

Case-studies

Fuelling the 'What-if' scenarios, case-studies are used. Design assignments are developed for different cases, ranging from simple to complex. During these assignments, problems are encountered. These problems help with creating the 'What-if' scenarios. The 'What-if' scenarios help with defining the relevant parameters which influence the fire risk of a design.

Case-studies are aslo used to evaluate and test the decision-making framework. The case-studies serve as a practical application of the framework and an evaluation of the outcomes of the framework.

Research by design

As mentioned before, case-studies are used to define the relevant parameters. By trying out different designs in different cases, information and knowledge is gained on what problems might occur in terms of fire safety in different designs. Also by evaluating the design options for the solutions a research by design aproach is used.

Evaluation

During the research process, steps need to be evaluated to check if the outcomes are in line with the preceded information. As mentioned earlier, case-studies and interviews with experts are used as evaluation methods.

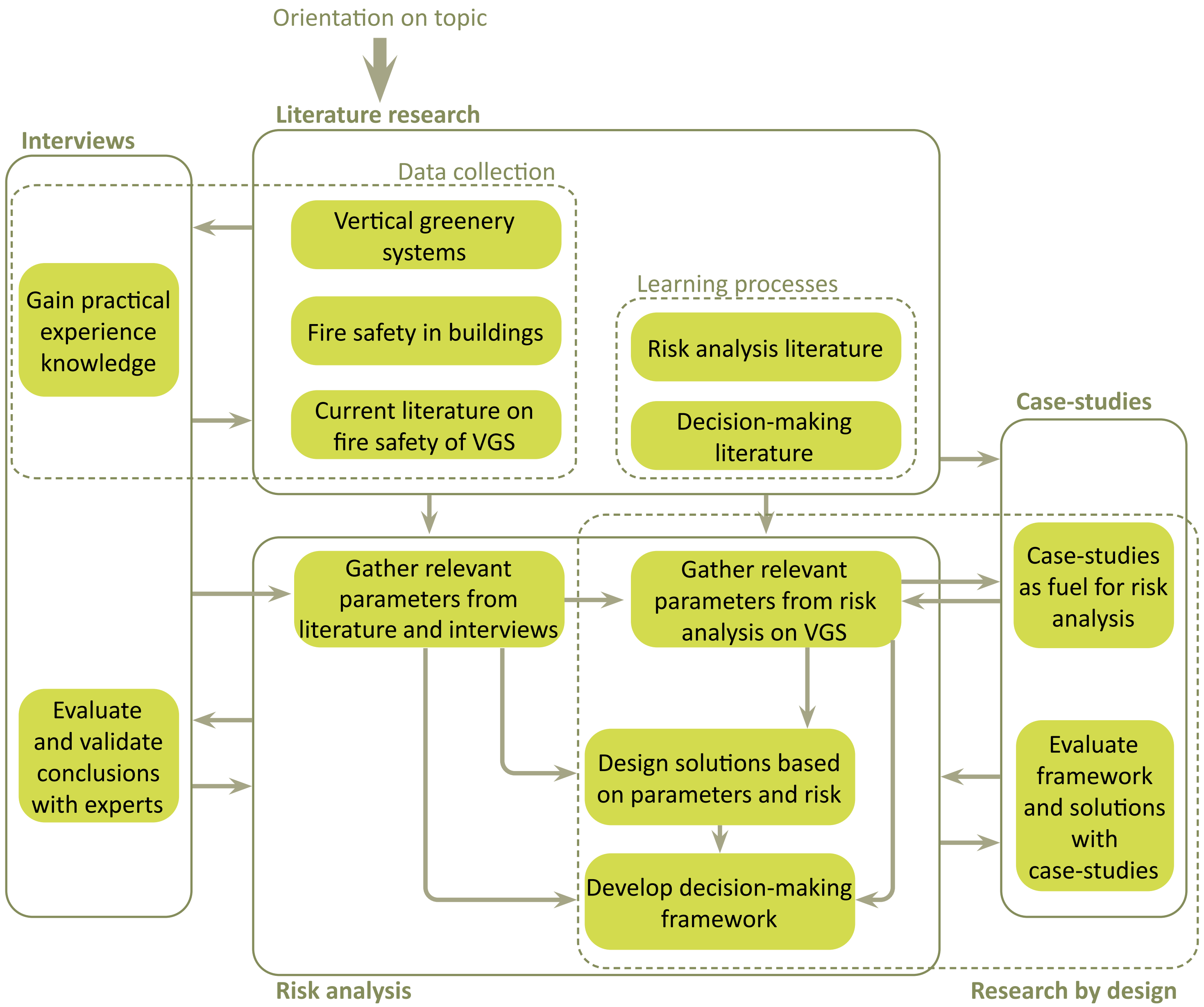


Figure 1.1: Research framework (own work)

1.6 Boundery conditions

To frame the research, certain boundary conditions are set. One boundary condition is that the focus in regulations and legislations will be the Dutch and European ones, since this thesis is written in the Netherlands. Legislation differs per country and it is outside of the scope of this thesis to map out all the differences. The focus of this thesis is providing a better understanding for safe implementation of vertical greenery systems, the exact legislation of different countries should not make a huge difference, as all legislation aims to provide safe situations. Mentions of practices in other countries will be made, as literature found was in most cases not from the Netherlands.

Furthermore the focus of the current thesis will be on outdoor vertical greenery systems which are organic. Vertical greenery systems can also be applied indoors, but that will not be the focus of this thesis. There are also 'green façades' with artificial plants, but these will also not be taken into account for the current thesis.

As vertical greenery systems can have the greatest impact in hardened areas and are most relevant to use in dense demographics with scarce ground space, the focus of the thesis will be an urban setting. Furthermore shall the focus be on buildings were people reside, so for example not on warehouses. Regardless, the found solutions and mitigating measures in this thesis can also work in fire management in those situations as well.

1.7 Thesis structure and workflow

The structure of the thesis roughly follows how the research process went. Since research is an iterative and not a linear process, steps back and forth were made during the research, but generally the information from the early chapters was used to work on the steps made in the later chapters. Every chapter starts with an introduction where an explanation of the function of the chapter is given. At the end of every chapter a short overview of the key aspects found in the chapter is given.

Chapter 2 discusses the literature research, where the relevant information necessary for the research is gathered. In part 2.1, an overview is shown of the different vertical greenery systems that are currently used and what the differences are in their build-up and materiality. Here also the advantages and disadvantages of the systems are explained. In part 2.2 an overview is presented on fire safety in general and how fire is treated in legislation and management. In part 2.3 the focus is on fire safety of vertical greenery system. An overview of which aspects are important according to literature and interviews and found VGS fire cases is made.

Chapter 3 shows the process of a fire risk assessment. First a brief overview of different risk assessment methods is discussed and why the chosen method was chosen. Then the used method and developed scenarios using case-studies are explained. The found parameters are discussed and their impact explained. Different design options per parameter are given. Lastly it is explained how the weight of the different parameters is developed.

In chapter 4 the developed decision-making framework is explained. First the goal of the framework and tool and how they can be used in a design process is explained. Thereafter it is shown how quick wins can be identified and an example of a design in a relative complex setting is given.

In chapter 5 the research is discussed and recommendations are made for future research. An overview of the found conclusions is given and it is explained what the relevance of the research is. Lastly a reflection is described on the process of the research.

In the appendix supporting information for understanding the research is set out. Here a summary of the interviews held is documented and an overview of the case-studies used is shown. Images from the tools and the infographic are also shown here.

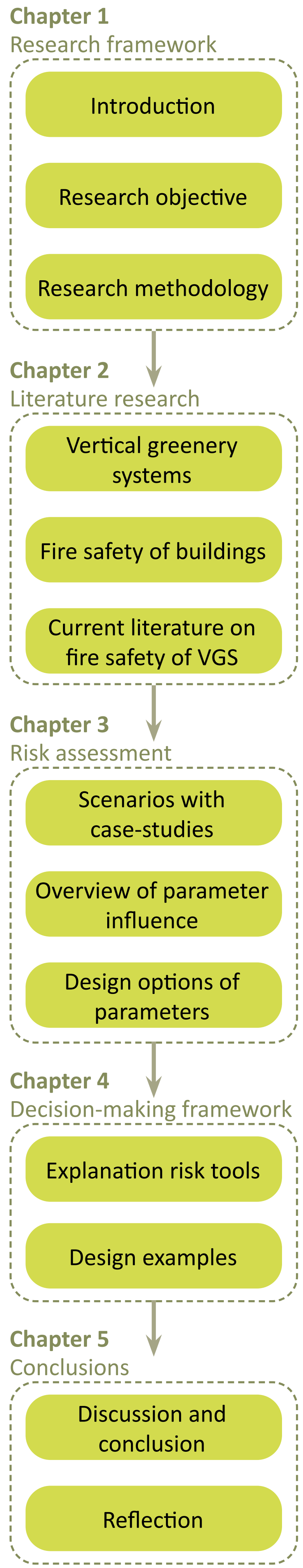
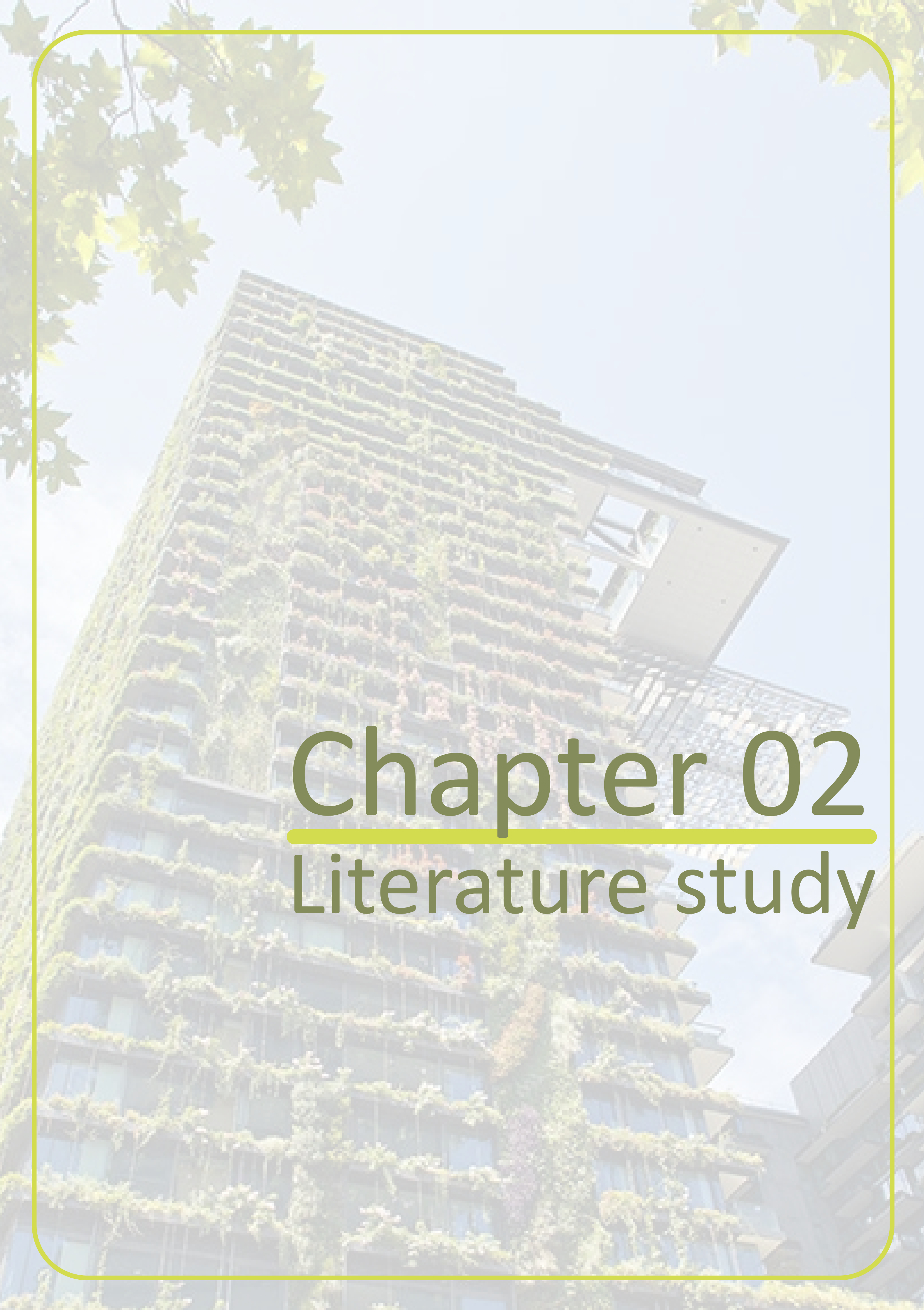


Figure 1.2: Thesis structure (own work)



Chapter 02
Literature study

2.1 Vertical greenery systems (VGS)

This chapter gives on overview of existing vertical greenery system and their classification. An overview of the differences between systems in their materiality and build-up is discussed. Futermore the advantages and the disadvantages of using these systems is presented.

2.1.1 Introduction of vertical greenery systems (VGS)

Vertical greenery has been used by humans for centuries. The first archaeological evidence dating back to the Roman empire, where climbing plants would grow on colonnades, walls and trellis screens to provide shade in the hot Mediterranean sun (Bowe, 2004, p. 46). During the Renaissance period fruit walls were extremely popular, and from the 17th century North American growing plants were introduced in Europe and used to be grown on façades (Ottelé, 2011).

These first mentions of greening vertical surfaces mainly involved the growth of climbing plants on the surfaces. Stanley Hart White, professor and landscape architect, was the first to propose a different method of greening vertical surfaces. In 1938 he patented his invention the ‘botanical brick’, which is seen as the first living wall system (Pritchard & Pritchard, 2023). Unfortunately his invention didn’t take much root in his own time. It took 50 years before another visionary took a step further into the world of living wall systems. In 1988 Patric Blanc created a system which could be placed on top of a load-bearing wall. It existed of a metal frame holding PVC panels on which fabric was stapled. The irrigation system made use of a hydroponic system (Kotzen et al, 2023). In the past few decades the interest and application of vertical greenery has notably increased. With this increase in popularity, the development of different systems and manufacturers has taken a flight.

This can also be seen in research. According to a research by Bustami et al. the amount of research on VGS has significantly increased in the last years (Bustami et al., 2018). This is visualised in Figure 2.1.

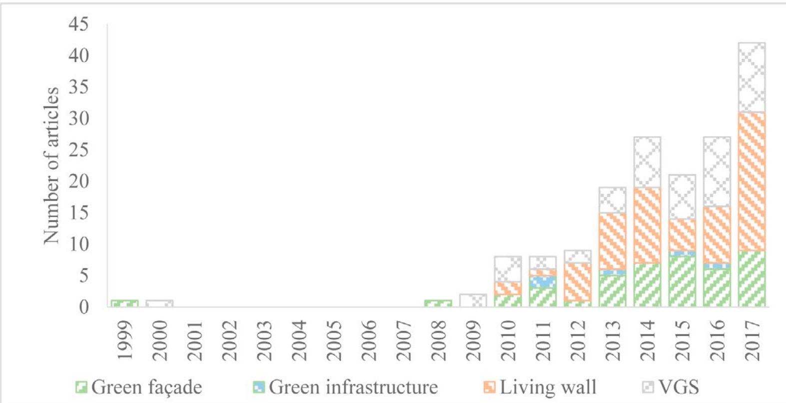


Figure 2.1: Number of VGS papers published by year (Bustami et al., 2018)

2.1.2 Classification of different systems

Both in academic literature and in practice of manufacturers, terminology is not used in a very systematic way. Terms as green façades, green walls, living walls and vertical gardens are used interchangeably in some cases (Radic et al, 2019). To prevent misconceptions in this research the terminology and classification as shown in Figure 2.2 will be used throughout the current thesis. The overarching term used for all systems is Vertical Greenery System (VGS).

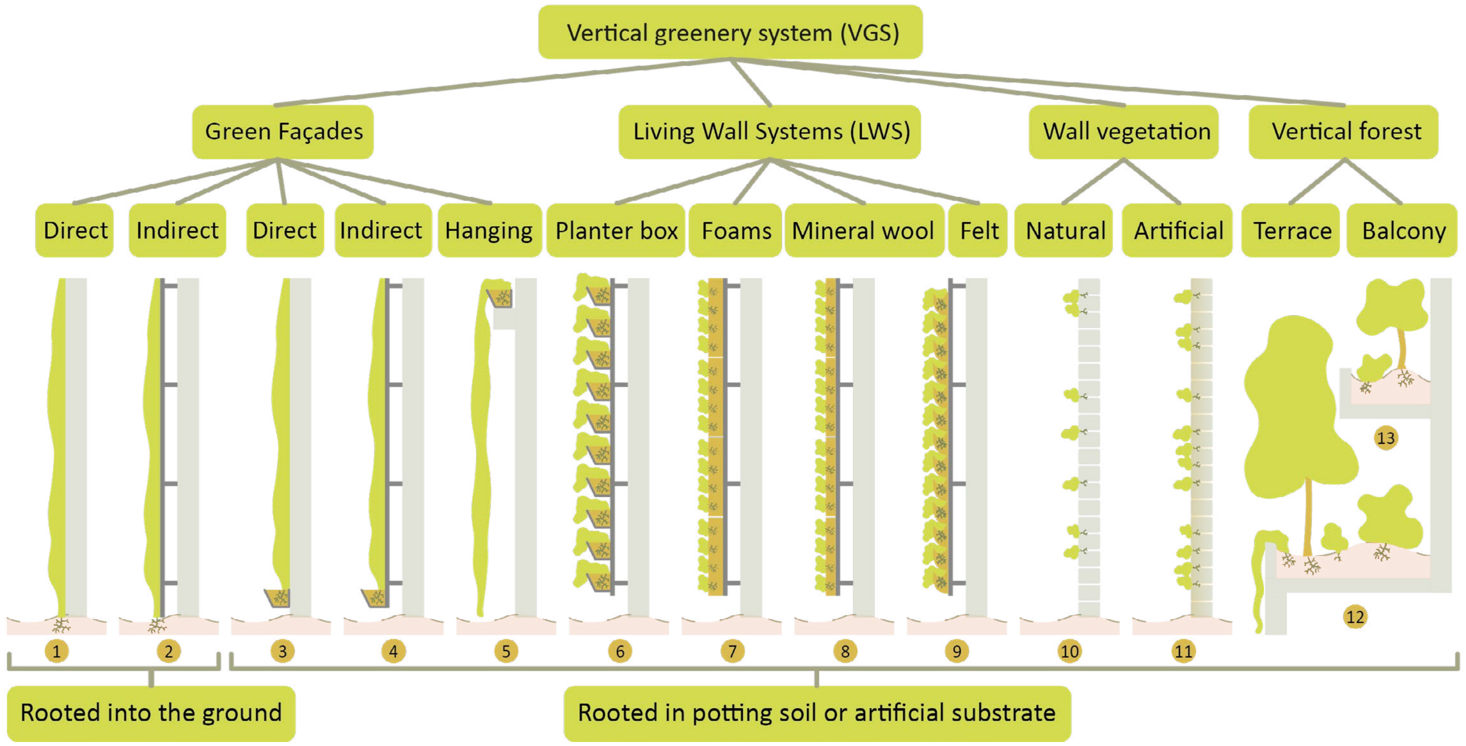


Figure 2.2: Classification of vertical greenery systems (own work)

A definition given by Ottelé is as follows (Ottelé, 2011):

> *"Vertical green is the result of greening surfaces with plants, either rooted into the ground, in the wall material itself or in planter boxes attached to the wall in order to cover buildings in vegetation."*

In accordance with this definition, in literature most differentiations are made based on growing method and supporting structure. A main distinction can be made between vertical green rooted into the ground (systems 1-2) and vertical green rooted in potting soil or artificial substrates (not rooted into the ground; systems 3-13).

A definition given by Radic et al for living wall systems is (Radic et al, 2019):

> *"Livings walls are self-sufficient living walls that are attached to the exterior or interior of a building. They differ from green façades (e.g., ivy walls) in that the plants root in a structural support which is fastened to the wall itself. The plants receive water and nutrients from within the vertical support instead of from the ground."*

Even though according to these definitions, one would assume system 3-5 to be considered LWS, as they are not rooted into the ground or the wall itself, in literature these systems are mostly referred to as green façades. To be consistent with existing literature, the same will be done in the current thesis.

Furthermore there are 5 main components of VGS: vegetation, growing media (substrate), support structure, irrigation system and drainage (Manso & Castro-Gomes, 2015). The systems which are not rooted into the ground will need an irrigation and drainage system. This can be done manually, in which case no extra materials are used in the VGS itself. This can also be done automatically, in which case an irrigation installation needs to be added in the VGS, which uses additional materialseee and adds complexity to the system.

Green façades (GF)

Green façades are façades where climbing plants are rooted at the base of the façade and grow along the façade. The most basic systems are rooted into the ground soil (system 1-2) and therefore do not need an irrigation and nutrient system. There is a distinction between direct and indirect systems. With direct green façades the plants grow directly onto the main façade without an extra supporting structure (system 1). With indirect green façades the plants grow on a supporting structure attached to the façade (system 2).

As mentioned before, in literature climbing plants which are potted at the base of the wall (system 3-4), or hanging from a roof or balcony (system 5), are also considered green façades instead of living wall systems. Because these systems are not rooted into the ground, they will need additional irrigation and nutrient supply.

The materials involved in green façades are the support structure (in the indirect systems 2 & 4), the growing media (in the systems not rooted into the ground 3-5) and the vegetation. The systems not rooted into the ground can be implemented with an automatic irrigation and drainage system.

Figure 2.3: Direct green façade rooted into ground soil (system 1) (Zioandsons, 2015)

Figure 2.4: Indirect green façade rooted into ground soil (system 2) (Own work)

Figure 2.5: Indirect green façade rooted into concrete planter boxes at base of façade using a plastic trellis support structure (system 4) (Geoplast, 2019)

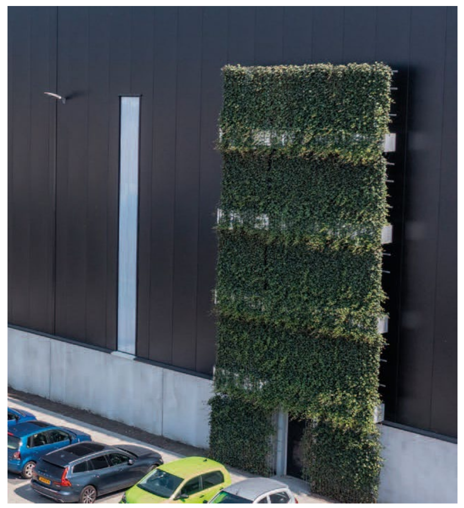


Figure 2.6: Indirect green façade rooted into aluminium planter boxes at several heights of the façade using a steal trellis support structure (system 4) (Mobilane, n.d.b)

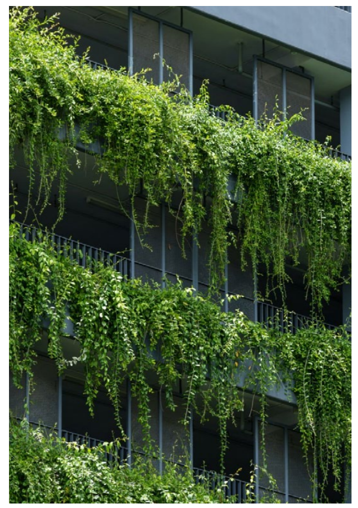


Figure 2.7: Hanging green façade rooted into pots (system 5) (Paison, 2022)

Living wall systems (LWS)

As mentioned before, living wall systems are systems where the plants are not rooted into the ground but in structural supports which are connected to the façade. Because the vegetation can be rooted all along the façade, a wider range of plants can be used than in green façades, as the vegetation does not necessarily need to be climbing plants. Due to how the systems are build up and connected to the façade, LWS are always indirect systems. Four main systems can be identified:

- LWS based on planter boxes, trays, vessels, modular boxes/holders (system 6);
- LWS based on foams (system 7);
- LWS based on mineral wool (system 8).
- LWS based on layers of felt sheets (system 9);

The main distinction between these systems is between the typology and the used materials for the support structure and the growing media. All these systems need an irrigation and drainage system, mostly found to be automatic. It is also possible to use automatic monitoring systems which monitor the moisture content of

Figure 2.8: LWS based on planter boxes, trays, vessels, modular boxes/holders (system 6) (Biotecture, n.d.a)

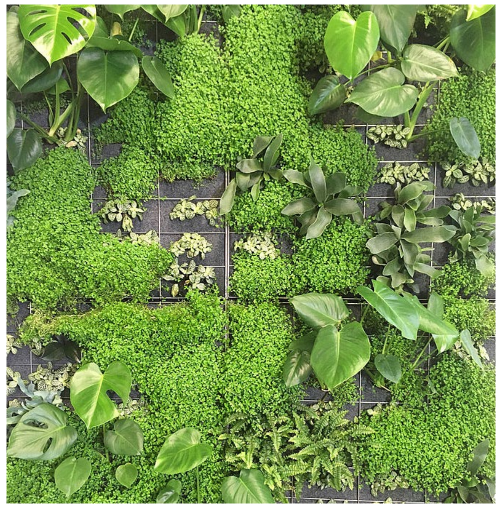


Figure 2.9: LWS based on foams (system 7) (Carpenter, n.d.)

Figure 2.10: LWS based on layers of felt sheets (system 8) (Notcot, 2011)

Figure 2.11: LWS based on mineral wool (system 9) (Lawn & Garden, n.d.)

the substrate with sensors.

Wall vegetation

Another form of vertical green is wall vegetation. With wall vegetation the plants are rooted directly into the wall itself. The plants can grow naturally without human intervention (system 10) or artificial where plant growth is stimulated (system 11). An example of artifical wall vegetation is Delft Quay Wall Garden (Utanner, 2023) as shown in Figure 2.13. The materials involved in wall vegetation are the wall itself and the vegetation. These two systems will not be further discussed in the current thesis as they are vastly different in terms of application and use from the other systems.

Figure 2.12: Natural wall vegetation (system 10) (VIDOK, 2019)

Figure 2.13: Artificial wall vegetation (system 11) (Own work)

Vertical forests

Lastly there are systems which can create vertical forests, allowing for trees and other vegetation to grow along the façade of a building. This can be achieved by using terraces (system 12) and balconies (system 13) as big planter boxes. In this system the vertical green is not part of the façade system itself, as can be seen in Figure 2.14, but are placed in large protrusions (balconies) or on stepped façades (terraces) in front of the façade, and thus still creating vertical green along the height of a building. In these systems often a wide variety of trees, bushes and plants is used, where the trees can even stretch along multiple floors, as can be seen in Figure 2.15. It is not necessary to use trees in these systems, but to be consistent with existing literature the overarching term for these systems used is Vertical Forests. An irrigation and drainage system can be added or the system can work with water retention.

Figure 2.14: Green balcony from eye level. Can be seen it is not part of the façade itself (van Onna, n.d.)

Figure 2.15: Green balconies along the façade of a high rise building (COIMA, 2020)

Positioning in façade

Another distinction which can be made is in which way the system is part of the façade. This is mostly relevant for systems 1-9. The VGS system can be used as the cladding of the façade, be against a façade or be placed at a certain distance from the façade working as a second skin. For the façade integrated position, the LWS are most suitable, as the Green Façades do not have a proper water retaining layer. Al systems work by placing it against the façade. Green Façades are most suitable for placing at a distance from the façade, due to functionality, as this way of placing is mostly done when there is a walkable area between the VGS and the façade. The LWS would block most of the sunlight to the space behind it, which would not be desirable. When in front of a closed façade without windows or walkable space behind it, this would not be much of a problem. Green Façades allow for daylight to penetrate through the system, creating a pleasant and natural environment behind the system.

Figure 2.16: Three ways of attaching to the building (Own work)

For system 12 and 13, the distance from the façade at which the trees, bushes and plants grow is mostly relevant.

2.1.3 Main components of VGS

As mentioned before, there are 5 main components of VGS: vegetation, growing media (substrate), support structure, irrigation system and drainage (Manso & Castro-Gomes, 2015).

Vegetation

The vegetation consists of the types of plant species which are suitable for the different systems. These can be climbing plants, hanging plants, succulents, shrubs, grasses, perennials and more. It differs per climate, orientation, amount of shade and type of system which plants are suitable for a project. Furthermore some plants change with the seasons. Perennials or deciduous plants go into dormancy during winter. These plants therefore have different influence on fire behaviour in different seasons. Evergreens keep their leaves all year round and are therefore more consistent throughout the seasons in their influence on fire behaviour.

Growing media (substrate)

The growing media (or substrate) can either be soil based or hydroponic based with (in)organic substrates. The function of the growing media is to provide water, nutrients and oxygen to the roots and work as an anchor point for the roots to hold on to (Jiffy group, n.d.). Organic substrates include sphagnum peat moss, bark, coconut coir and rice hulls (PT Horticulture, 2016). Inorganic substrates include sand, gravel, perlite, vermiculite, mineral wool, clay pebbles and expanded polystyrene balls or flakes (Oak Leaf Gardening, n.d.). Also a microfibre cloth, foam or mineral wool can be used for the growing media.

Support structure

The support structure is the structure that assists in holding up the vegetation. There are several different parts in the support structure as shown in Figure 2.17. Firstly there is the support for climbing plants which help guide the plants to grow along. These can be metal, wooden or plastic. Secondly there are the elements which hold the place where the plants are rooted into, these can be filled with a growing media if necessary. These are usually plastic, metal or made of fabric. In some cases they can also be stony or wooden. Thirdly there is usually a framework connected to the wall of the façade to connect the VGS to the building. This is often done with aluminum or steel profiles. Lastly in some systems a waterproof layer is placed at the back of the system to protect the rear façade from water damage (Kotzen et al, 2023).

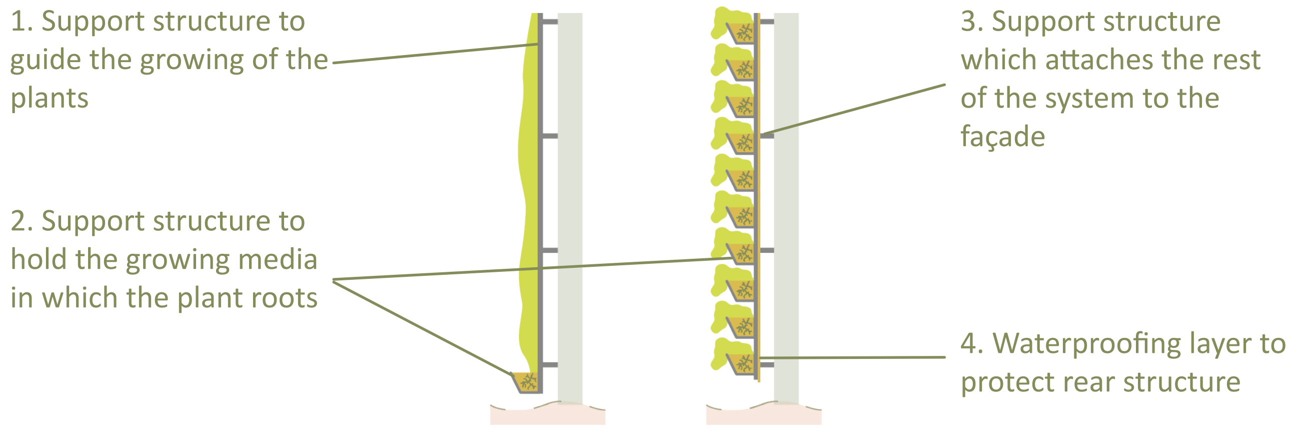


Figure 2.17: Support structure different parts (Own work)

Irrigation

The irrigation is the system which provides the water supply for the plants. This can be done manually, in which case no additional material is added in the VGS itself. But in many cases the irrigation is implemented within the system. In incorporated irrigation systems PVC, EVA or PE pipe lines are placed throughout the VGS which provide the necessary hydration. Connectors of the pipes also include rubber and silicone. Common systems used are drip or sprinkler systems (Manso & Castro-Gomes, 2015).

The lines can differ in density per system as shown in Figure 2.18. They can run only on the top of the wall, or on top of every module or on top of every row of plants. Density influences the proper distribution of water but can also be necessary if different plants in the system have different needs in terms of water supply.

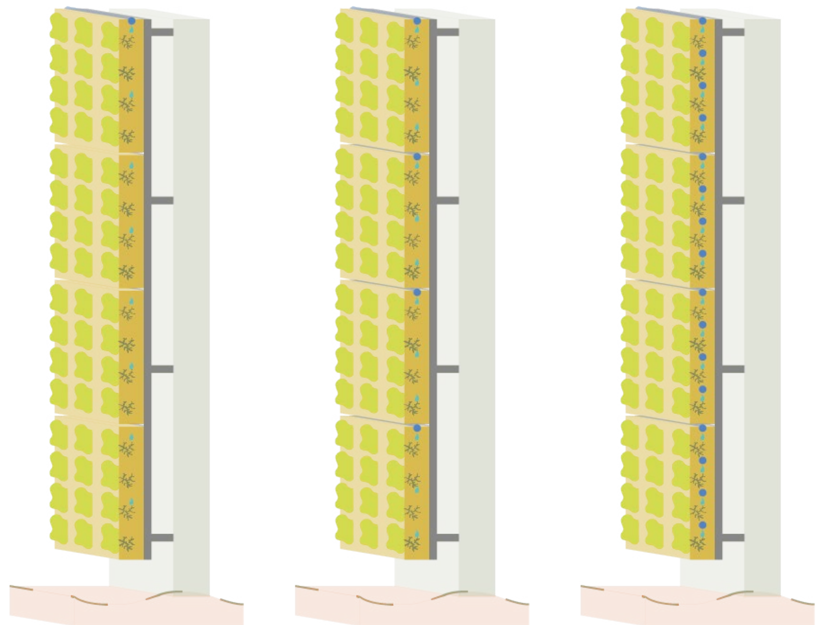


Figure 2.18: Density differences of irrigation. From left to right, low to high density. (Own work)

Furthermore the use of capillary action is sometimes used. With this a microfibre textile is placed verticaly at the back of the system. With the capillary action, water that is brought to the system is then distributed along the textile.

Drainage

The drainage consists of the elements needed for getting rid of the excess water. Drainage takes place by gravity. The excess water can either simply be collected at the bottom through holes in the container elements or be guided per module towards a rear drainage layer that guides the excess water to the bottom. The water can then either be flown into the underneath ground or the sewer, or it can be collected and reused in the system.

2.1.4 Materiality of the different systems

In the following section the present components per system and the materials used for the different components is discussed.

System 1. Direct GF rooted into the ground soil

In this system the vegetation is the only component used, since the plants are rooted into the ground soil and there is no support structure other than the external wall of the building.

The vegetation used for this system consists of self-clinging climbing plants, either with areal roots or suckers (Ottelé, 2011).

System 2. Indirect GF rooted into the ground soil

The second system uses an additional support structure for the plants that are rooted into the ground soil to grow along. So the components used in this system are vegetation and support structure.

Since a support structure is present, a wider variety of climbing plants can be used for this system such as twining climbers or tendril climbers (Ottelé, 2011). For the support structure several materials can be used either in cable, rope, trellis or mesh form. Materials used are steel, aluminium, HDPE (or other plastics) and wood .

System 3. Direct GF not rooted into the ground soil

The third system consists of climbing plants that are rooted into a planter box which grow along the external wall of the building without additional support for the plants to grown onto. The components used in these systems include thus the vegetation, growing medium and the support structure of where the plants root into the growing medium. Since the plants are not rooted into the ground, an additional irrigation and drainage system is needed.

The vegetation used in this system includes the same type of plants as in system 1, self-clinging climbers (Ottelé, 2011). The growing media can be either organic or inorganic. The support structure consists of the planter boxes or pots which hold the growing media where the plants are rooted into. These planter boxes or pots can be made of different materials. When they are placed on the ground they can be made of more heavy material, such as ceramics or concrete, as shown in Figure 2.5. When attached to the wall they are made of lighter material, such as wood, HDPE (or other plastics), aluminium sheets or steel sheets (Manso & Castro-Gomes, 2015). The irrigation system can be manual or automatic. In case of a manual system, no additional materials are added to the system. In case of an automatic system, pipes bring water to the growing medium in the support structure. At the bottom, a drainage system will be necessary to prevent the overflow of the planter boxes. This can be done through holes or with a hose system. With a hose system the water can be reused.

System 4. Indirect GF not rooted into the ground soil

The fourth system consists of vegetation that is rooted into planter boxes and is guided to grow along a support structure in front of the external façade of the building. The components used in these systems are vegetation, growing media, support structure, an irrigation system and a drainage system.

The same type of plants as system 2 can be used for this system and the same type of growing medium, irrigation system and drainage system as system 3 can be used. For the support structure, the same type of planter boxes as system 3 can be used. Additionally the support structure of system 2 is also used. This system is basically a combination of system 2 and system 3.

System 5. Hanging GF

In the hanging system vegetation, growing media, support structure, irrigation and drainage is used, because the hanging system consists of hanging plants grown somewhere at a height of the façade and flow down the façade.

The vegetation used for system 5 are trailing plants. These are plants that cascade along the ground or out of pots but do not root at nodes along the stem. Which gives them the ability to 'dangle' from a balcony or pot along the façade. For the growing media either organic or inorganic substrate can be used. The support structure consists of a planter box which can sit on top or in of a balcony, at a protruding part of the façade or at the roof or be hung onto the façade with an additional support structure to attach it to the façade. Since the plants are not rooted into the ground soil, an irrigation and drainage system will be needed.

System 6. LWS based on planter boxes, trays, vessels, modular boxes/holders

In this system vegetation is rooted into a growing medium which is hold up by a support structure along the façade. The system is often attached to the façade with an additional support structure. Since the vegetation is not rooted into the ground an irrigation and drainage system is necessary.

Since the vegetation used in this system does not need to be able to climb, a wider variety of species can be used than in systems 1-5. Types of vegetation found in the system often consists of shrubs, succulents, grasses and perannials. The support structure can be made up of a lot of different materials and in different shapes and sizes. Most used materials are HDPE, EPP, aluminium and steel. The additional support structure is usually made of aluminium or steel. The growing media can be either organic or inorganic. It is also found that support of microfibre cloth with capillary function, to provide even distribution of the water and nutrients. For the irrigation tubes can be placed in different densities in the system. Drainage works with gravity and the water is collected at the bottom of the system.

System 7. LWS based on foams

This system is based on vegetation rooting into foam. The foam works both as the support structure and the growing medium. The foam can absorb the water necesarry for the plants to grow. So in this system the materials used are usually kept moist. Irrigation and drainage is necessary for this system.

The vegetation used needs to be able to root into the foam. The foam used is 'Oasis'. The foam works both as the growing media and the support structure. An additional support structure is necessary for attaching to the façade. A water retention layer can be placed between the foam and the rear façade. Irrigation is done through piping and making use of the capillary ability of the foam. Drainage works with gravity and the water is collected at the bottom of the system.

Figure 2.19: Example of a VGS with modular plant holders made of EPP and a steel additional support structure (System 6) (Mobilane, n.d.a)

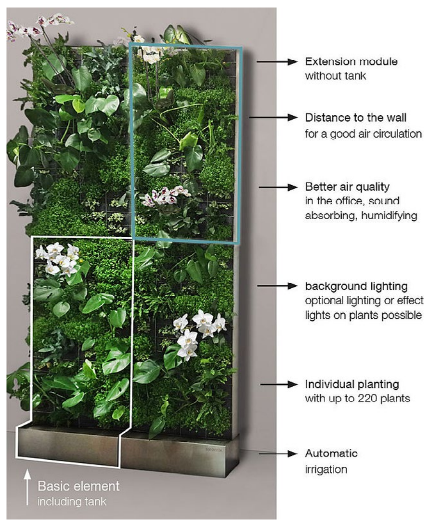


Figure 2.20: Example of a VGS based on foam (System 7) (Carpenter, n.d.)

System 8. LWS based on mineral wool

In this system the vegetation is placed in mineral wool which is the growing media. The mineral wool is usualy held in place by a support structure and it needs to be attached to the façade with an additional support structure. To prevent the rear façade from moisture a waterproofing layer needs to be placed behind the mineral wool. The system needs irrigation and drainage.

The vegetation used in this system is the same as in system 5. The growing media is the mineral wool. The mineral wool is held in place with a plastic box or felt and attached to the façade with an aluminium or steel support structure. The waterproofing layer can be made of a cementbased panel. The system will need an irrigation system which can be implemented in different densities. Drainage can work with a rear drainage layer made of geotextile guiding the water down where the water is collected at the bottom of the system.

System 9. LWS based on layers of felt sheets

In this system the vegatation is placed inside pockets of fabric which are stapled on a support structure. In the pockets a growing media can be placed which can either be a substrate or mineral wool or geotextile is used as a hydroponic system. There needs to be a waterproofing layer at the back of the system to protect the rear façade. The system is hung on the façade with an additonals support structure. Irrigation and drainage is necessary for this system.

The vegetation used in this system is the same as in system 5. The growing media can be of (in)organic substrate or mineral wool or geotextiles. The support structure consists of layers of fabric stapled on a support structure. The fabric can be made of (recycled) plastic. Instead of staples, a metal mesh can be used to hold the fabric against the backboard. The backboard can be made of various types of plastic, aluminium, cement fibre and more. The system will need an irrigation system which can be implemented in different densities. Drainage can work with a rear drainage layer made of geotextile guiding the water down where the water is collected at the bottom of the system.

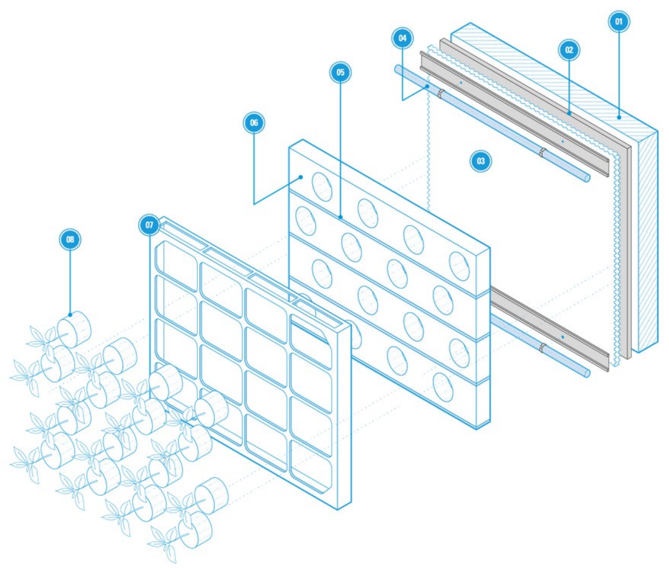


Figure 2.21: Example of a VGS with mineral wool and a PP support structure and aluminium additional support structure (System 8) (Biotecture, n.d.b)

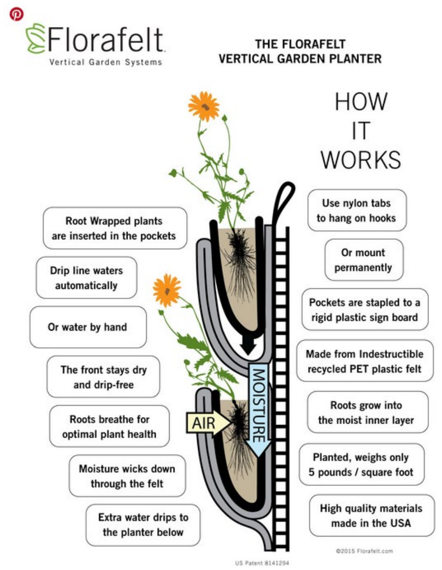


Figure 2.22: Example of a VGS with felt support structure and a plastic backboard (System 9) (Florafelt, 2015)

System 12. Vertical forest in terraces

In this system plants grow in large areas on parts of the building where the geometry of the building jumps back, leaving spaces which can be utilised. This system can be implemented as an intensive green roof system with growing media and support structure. The system will need irrigation and drainage.

Since the plants in this system have access to a rather large amount of growing medium, a wide variety of plants can be used. Even shrubs and trees can be used in this system. The growing medium is usually soil. The support structure consists of the roof of the building on which the waterproofing layer, root barrier layer and the drainage are placed. Irrigation is done with piping or water retention is used.

System 13. Vertical forest in balconies

In this system plants grow in large protruding parts of the façade. The balconies function as large planter boxes. This system can be implemented as an intensive green roof system with growing media and support structure. The system will need irrigation and drainage.

Since the plants in this system have access to a rather large amount of growin media, a wide variety of plants can be used. Even shrubs and trees can be used in this system. The growing medium is usually soil. The support structure consists of the balcony protruding from the building structure in which the waterproofing layer, root barrier layer and the drainage are placed. Irrigation is done with piping or water retention is used. .

Figure 2.23: Example of a vertical forest using terraces (System 12) (Vero Digital, n.d.)

Figure 2.24: Example of a vertical forest using balconies (System 13) (Vero Digital, n.d.)

In both system 12 and 13 the support structure is very robust to be able to hold such a heavy system Usually thick non-combustible materials are used such as concrete. The other materials used for the greenery system are covered with a very thick layer of soil or substrate, so it is assumed that these materials will not have great influence on the fire performance. In these two systems the plant choice, the configuration of the plants with respect to the façade and the build-up of the façade are the most relevant aspects in terms of fire safety.

Figure 2.25: Vegetation relatively close to the façade (van Onna, n.d.)

Figure 2.26: Vegetation relatively far from the façade (van Onna, n.d.)

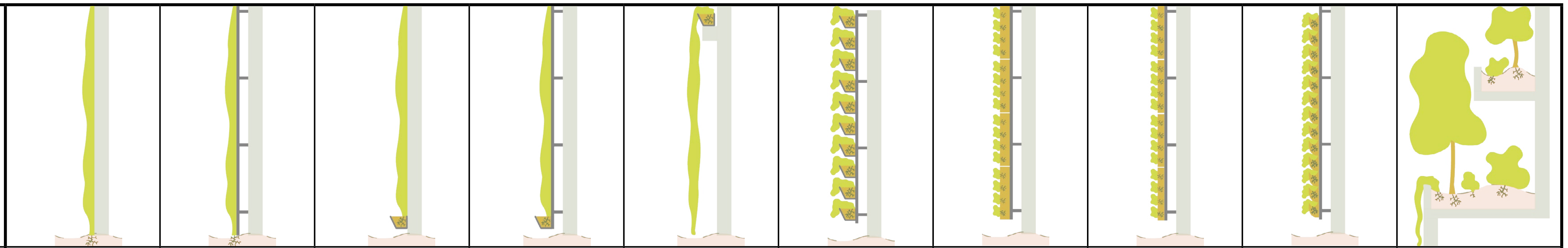
Overview materials per system

In table 2.1 an overview of the different aspects, including the materiality of the different components of the different systems is shown. These aspects will be taken into account in the fire risks analysis and design solutions. The information filled in the table is based on an analysis of information found in the different research papers and information found from different manufacturers. The filled in information is what was found to be the most common and most generally found situations. Since there are many different products on the market for every different system, there could be products found which use different or additional materials not listed in the table. It is always important when looking at the risks of a design to critically look at the build-up of the specific product used or considered in a design. Especially the materials chosen and their fire behaviour is important to take into account. The most influential materials on negative fire performance are shaded red.

Since system 12 and 13 are rather different from the other systems, a different approach is needed for these systems. The build-up and materials used are not as influential in these systems, as they will be covered by a thick layer of soil. The design of the support structure is rather robust to be able to hold the heavy soil and plants. Here the choice of plants themselves and their configuration with respect to the façade is more influential in terms of fire safety than the materials used in the support structure.

The prices mentioned are taken from several sources. These are rough indications, as per system and specific material used and type of irrigation system the costs can vary. These costs do not include the maintenance, it is solely about the installation cost. For the vertical forests there is no number stated, since these systems are part of a balcony or roof system it is not easily quantifiably how much these systems cost. Since a very robust structure is needed which are generally rather costly, the cost is stated as ‘high’.

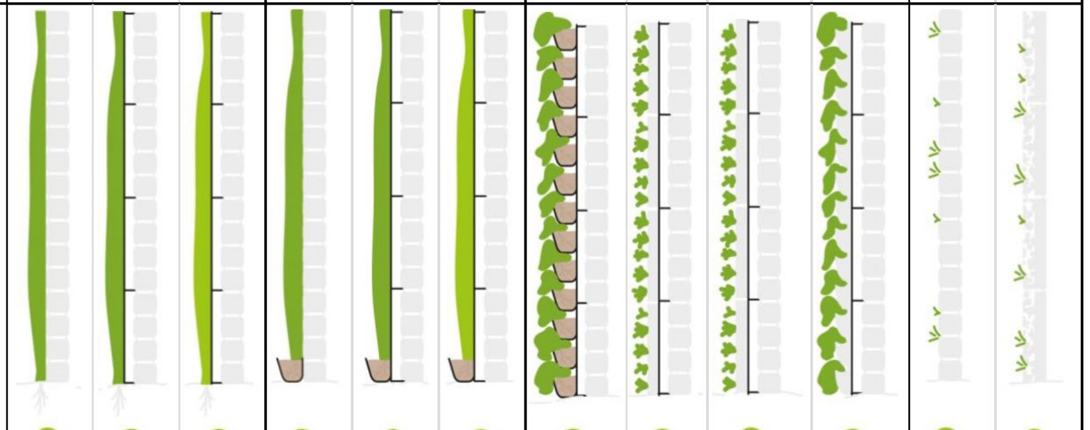
Table 2.1: Overview of VGS and their characteristics (Own work)



Name		Direct green façade rooted into the ground	Indirect green façade rooted into the ground	Direct green façade rooted into potting	Indirect green façade rooted into potting	Hanging green façade	LWS based on planter boxes	LWS based on foams	LWS based on mineral wool	LWS based on felt	Vertical forest with terrace and balcony
Needs irrigation											
Air cavity											
Vegetation		Self clinging climbers	Climber plants	Self clinging climbers	Climber plants	Hanging plants	Shrubs, grasses, perennials, succulents	Shrubs, grasses, perennials, succulents	Shrubs, grasses, perennials, succulents	Shrubs, grasses, perennials, succulents	Plants, bushes and trees
Growing media		Ground soil	Ground soil	Soil based Organic substrate Inorganic substrate	Soil based Organic substrate Inorganic substrate	Soil based Organic substrate Inorganic substrate	Soil based Organic substrate Inorganic substrate	Foam	Mineral wool	Felt	Soil
Support structrue	Plant guide	-	Steel Aluminium Plastic Wood	-	Steel Aluminium Plastic Wood	-	-	-	-	-	Wooden plantsupport Steel cable for wind support
	holds growing media and plants	-	-	Plastic Metal sheet Wood Ceramic	Plastic Metal sheet Wood Fiberglass	Plastic Metal sheet Wood	Plastic (HDPE, EPP, PP) Metal sheet Wood	Foam	Plastic Metal	Felt/fleece (plastic) layers	Green roof system
	to attach to façade	-	-	Steel or aluminium profiles Wooden beams	Steel or aluminium profiles Wooden beams	Steel or aluminium profiles Wooden beams	Steel or aluminium profiles Wooden beams	Steel or aluminium profiles Wooden beams	Steel or aluminium profiles	Steel or aluminium profiles	-
	water retention			-	-	-	Cement bonded particle board Plastic board	Cement bonded particle board Plastic board	Cement bonded particle board Plastic board	PVC foam plate Wooden board	-
Irrigation		-	-	PE, EVA, PVC pipes	PE, EVA, PVC pipes	PE, EVA, PVC pipes	PE, EVA, PVC pipes	PE, EVA, PVC pipes	PE, EVA, PVC pipes	PE, EVA, PVC pipes	PE, EVA, PVC pipes
Drainage		-	-	Plastic or aluminium drainage pipe or gutter	Plastic or aluminium drainage pipe or gutter	Plastic or aluminium drainage pipe or gutter	Plastic or aluminium drainage pipe or gutter	Plastic or aluminium drainage pipe or gutter	Plastic or aluminium drainage pipe or gutter	Plastic or aluminium drainage pipe or gutter	Plastic or aluminium drainage pipe or gutter
Plant life expectancy (years)		50	50	50	50	50	10	3.5	3.5	3.5	Differs between plant, bush and tree
Maintenance		Low	Low	Low	Low	Low	High	High	High	High	High
Installation cost (€/m²)		30-45	40-75	200	100-800	200	400-600	750-1200	500-750	350-750	*High

2.1.5 Advantages of VGS

The reason to make use of VGS is because it has several benefits regarding sustainability. There are many researches performed on the advantages of VGS, but the benefits and disadvantages are not always clearly laid out per different system in literature. When tests are performed, it is often not clearly mentioned what the exact system build-up and used plants were and in which climate it was performed. Therefore it is hard to compare different studies and state clear conclusions from these studies (Ascione et al., 2020; Radic et al, 2019). Since the focus of the current research is providing a guide into the safe use of the different systems, the advantages will be briefly explained but will not be discussed in extreme depth, because that is not the focus of this study. Previous studies are used for understanding how the different systems score on the different advantages, as shown in Figure 2.27. Very generally speaking, the LWS score better on the advantages than the green façades. Unfortunately vertical forests were not taken into account in these studies.



Vertical green type	Rooted into the ground			Rooted in artificial substrates and potting soil mixtures								
type	Green façade						Living wall system				Wall vegetation	
direct or indirect	direct	indirect	indirect	direct	indirect	indirect	indirect	indirect	indirect	indirect	direct	direct
Effects	1	2	3	4	5	6	7	8	9	10	11	12
Reduce the urban heat island effect	+	+	+	+	+	+	++	++	++	++	-	-
External shading	+	+	+	+	+	+	++	++	++	++	-	+
Create a microclimate	+	+	+	+	+	+	+	+	+	+	-	-
Improve insulation properties	-	-	-	-	-	-	+	+	+	+	--	--
Improving air quality	+	+	+	+	+	+	++	++	++	++	-	-
Provide sound insulation	+	+	+	+	+	+	++	++	++	++	-	+
Increase biodiversity	+	+	+	+	+	+	+	+	+	+	-	-
Aestetical effects	+	+	+	+	+	+	+	++	++	++	--	-
Social and psychological benefits	+	+	+	+	+	+	+	++	++	++	-	-

Figure 2.27: Advantages of different Vertical Greenery Systems (Wagemans, 2016)

The advantages can be effective on an urban scale or on a building scale or both. Especially the advantages on urban scale are very hard to quantify according to literature (Ottelé et al., 2011). Even though the advantages on urban scale are the once that make it the most interesting to make use of these systems in a dense and hardened habitat. Following is an overview of the found advantages:

Urban advantages

Mitigation of urban heat island (UHI) effect

One of the main advantages of greening vertical hardened surfaces is the cooling effect it provides. There are many studies stating that VGS can help mitigate the urban heat island (UHI) effect (Radic et al, 2019), which is an increasing problem in cities due to climate change and the heating of the earth. The covering of the hardened surfaces prevents them from heating up and holding the warmth in the city and the evapotranspiration also helps cooling the surrounding air. Since the covering of a single wall, will not have a great effect on the UHI effect in a city, is the quantifying of this advantage rather hard. But it is very plausible and safe to assume that when covering many of the hardened surfaces in a city, the UHI effect can be reduced. And thus providing a healthier living environment.

Contribution to urban biodiversity

In cities space is scarce and valuable. Many surfaces are hardened and where there is greenery, it is often monotonous. It is hard for different species of animals to thrive in these conditions. By greening more surfaces in the city, especially with many different native species, a more animal friendly habitat can be created in the city (Ottelé, 2011). This will help insects, birds and small mammals to survive in the city.

Reduction of air pollution

There are studies that show that plants can absorb pollutants and fine dust particles by filtering the air (Ottelé, 2011). These particles are unhealthy for humans. So by providing more greenery in the city, the air in the city becomes more healthy for its residents.

Storm water management/Positive effects on hydrology

There is an increase of heavy rains due to climate change. This increases the risk of the cities flooding, due the hardened surfaces preventing the water to enter the ground and the sewage systems not able to guide the water away. VGS can have a positive effect on the water management in a city. The systems can collect and hold rainwater to relieve the sewage partly (Radic et al, 2019). Due to evapotranspiration of the water in the plants, the runoff will not only be delayed, but also less (Roehr & Laurenz, 2008).

Improvement of human health and psychological wellbeing

There has been quite some research in the effect of greenery on human health. For example it is shown that people in hospitals recover more quickly when they have a view over greenery as opposed to when they have not (Ulrich, 1984). Also it is shown in a study that people living in neighbourhoods with abundant green spaces experience better overall health. (Maast et al, 2006).

Building advantages

Thermal performance on building

The VGS works as an insulation layer, thus keeping the building warm in winter and keeping the building cool in summer. It is shown in studies that the cooling effect is more prominent than the heating effect (Ottelé et al., 2011). This is also due to the fact that the VGS shades the façade of the building and thus preventing the façade from heating up and storing the heat.

Reduction of noise

It is shown in several studies that the insulation layer the VGS provides also works in noise reduction. This is spefically noticable in narrow city canons where a lot of hard surfaces are present (Radic et al, 2019).

Economical benefits

The implementation of a VGS on a building can improve the real estate value or rent and thus be economically attractive (Perini & Rosasco, 2013). Furthermore the VGS protects the rear façade structure of weather condtions such as UV, rain and wind exposure and thus protecting that façade from damage (Ottelé et al., 2011).

2.1.6 Disadvantages of VGS

In literature several disadvantages of vertical greenery systems are mentioned. The main problems mentioned include cost, maintenance, material use, insects, damage to façade and, ofcourse, fire hazards.

Cost

The use of vertical greenery systems can be rather costly. The green façades are found to be the cheaper systems. Depending on the materials used these can be relatively cheap, where the choise of stainless steel is useally the most expansive one. The living wall systems vary greatly in their cost depending on material choice and irrigation system chosen. Those costs are mostly related to the installation cost, but on top of that there are also great costs related to the maintenance. The more maintenance is needed, the costlier the system (Perini & Rosasco, 2013).

Maintenance

As mentioned before, depending on the system chosen, certain maintenance is necessary for vertical greenery systems to flourish. Green façades need relatively little maintenance, of which most the most important one is pruning. In case manual irrigation is used, this is also part of the maintenance. When automatic irrigation is used, the irrigation system will need maintenance from time to time. In living wall systems the maintenance also includes the replacement of species. As the lifespan of species used in these systems is much shorter than the once used in GF the plants need te be replaced every few years. Usually the amount of plants replaced lies between 5-10% of the plants per year (Perini & Rosasco, 2013). Furthermore it should be recognized that if a building were to be vacated, a VGS should be kept healthy. So even in empty buildings, the maintenance and irrigation should not be neglected.

Material use

Depending on the choise of material, the system can have a big impact as environmental burden. The used material influences the embodied carbon footprint of the system and the recyclability of the system. Since these systems are often implemented with a goal to be sustainable, the influence on the burden of material choice should not be taken lightly. It was found that especially in the living wall systems, the materials can have a great burden, where the system based on felt layers scored the worst (Ottelé et al., 2011). Unfortunately, it is found that in general the more environmentally friendly materials are also the more combustible materials.

Damage to façade

In green façades the vegetation can reach the rear façade and might cause damage to it. In living wall systems a proper water retention layers is necessary or change of water damage on the façade is possible. Also failure or damage to the irrigation system can cause water problems or leakage to the façade and the building.

Fire hazard

Lastly the introduction of combustible materials on the façade can pose as a fire hazard. In later parts of the thesis this topic will be discussed in more depth.

2.1.7 Key aspects

Vertical greenery systems can be devided into several different systems. These different systems have a different set up of their components and are made up of different materials. System choice and material choice greatly influences the environmental burden of the system but also its reaction to fire. The differences in options of material choice and amount of materials used in the different systems are important parameters to take into account when evaluating the fire safety risks of the different systems.

In general it can be concluded that the Green Façade systems (1-5) are relatively safe in terms of materiality. Most found materials used are incombustible (steel cables) and even if combustible materials are used, it is not a lot of material. Much less than in the Living Wall Systems. The Living Wall System based on planter boxes (system 6) and based on mineral wool (system 8) cán be made with (mostly) incombustible materials. But they can also be made with plastics or wood. The more plastic or wood which is involved, the more combustible the system. The felt system (system 9) always includes combustible materials. Especially systems which are placed on plastic backboards can have high risk due to the combination with the air cavity behind the system. The foam system also uses combustible materials.

In case of system 12 and 13 the materials used in the system itself is not the most influential, but more the configuration and choice of the plants is of more influence in these systems. Specifically when using trees or woody vegetation, the fuel load can become relatively high.

Furthermore there are several advantages and disadvantages found and the different systems score differently on these. It is important when looking further for fire safety issues, to not forget the advantages. There should be a balance between the accaptable risk and the sustainability gains of the system's design. One only takes a risk if there is something to gain from it. As most incombustible materials do have a higher carbon footprint than combustible 'sustainable' materials, during the design, a balance between these two aspects needs to be found.

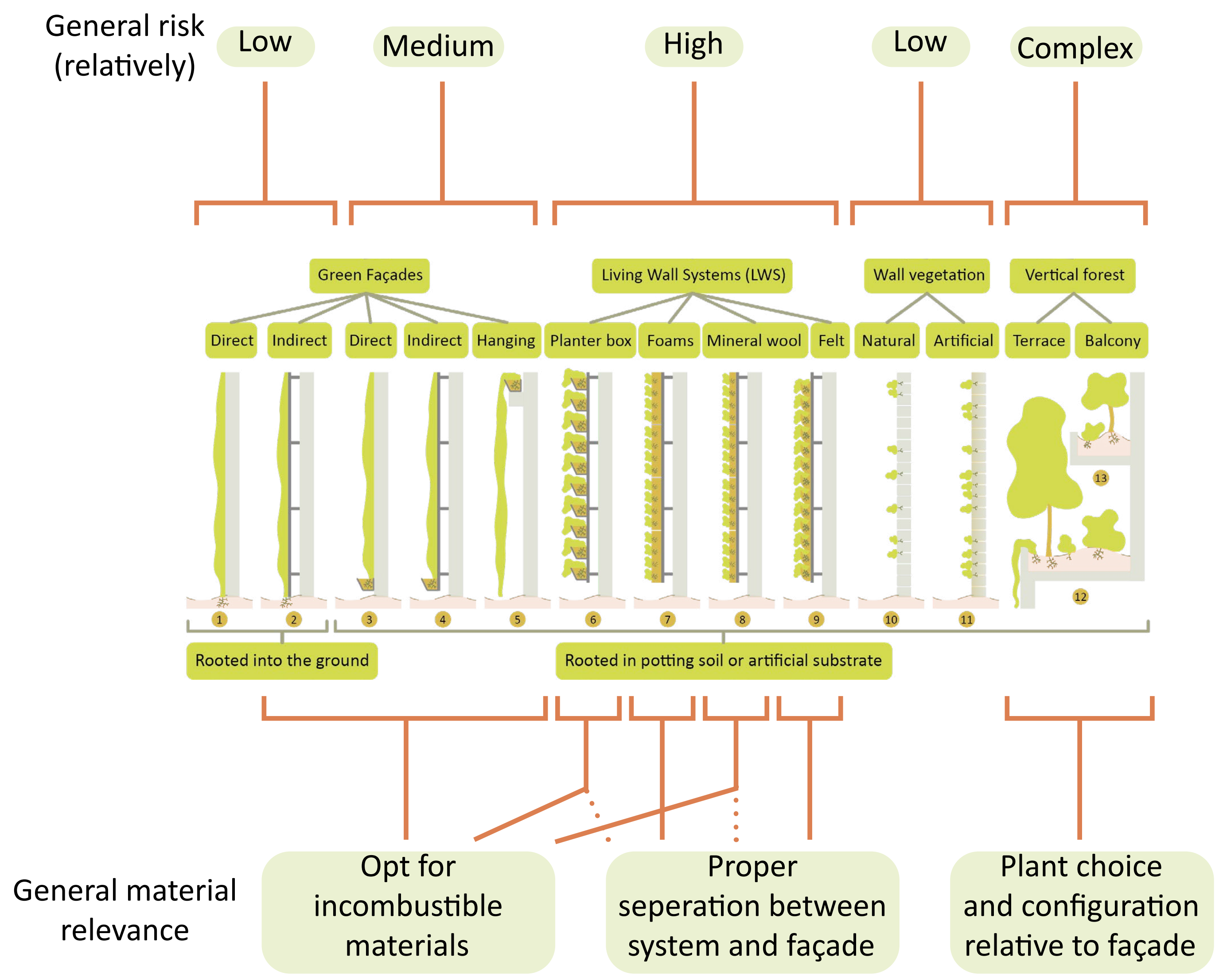


Figure 2.28: General findings on materiality of different systems and the fire safety influence (Own work)

2.2 Fire safety

This chapter provides a basic overview of how fire safety is treated in the Netherlands. First an overview of fire behaviour is given. Then an overview of relevant regulation and legislation is explained. Furthermore the way testing is currently performed and how testing methods are developed is explained.

2.2.1 Introduction of fire safety

Fire safety is the protection of humans and structures against the consequences of fire. Fire safety measures include those that prevent the occurrence of fire (prevention) and those that reduce the spread and impact of fire once ignited (mitigation).

Legislation focuses on the safety of the people and prevention of fire-spread to other buildings. Damage control to buildings or inventory is a matter for the owner and users of the building and are not taken into account in legislation (van der Veek & Janse, 2005a, p. 10-12). Insurance companies can also ask a higher performance in terms of fire safety than the law, since insurance companies look at the risk of financial damage.

2.2.2 Fire development

Fire is a state, process, or instance of combustion in which a material is ignited and combined with oxygen, giving off light, heat, and flames (Dictionary, n.d.). There are four conditions necessary for a fire to ignite and stay active (Vorenkamp et al., 2005):

- Presence of fuel;
- Sufficient air supply for presence of required oxygen;
- Ignition temperature;
- Environmental conditions allowing combustion to be maintained, as a progressive chain reaction.

If one of these four conditions is missing, the fire will not occur or progress. Fire prevention and firefighting is based on this principle (Vorenkamp et al., 2005).

A fire can be divided into five phases, namely (van der Linden et al., 2018, p. 215):
- The smouldering phase (before the fire turns in to actual open flames);
- The creation of the fire (at time t=0);
- The development phase of the fire until the moment of flash-over at the location of the fire (flash over does not always occur);
- The completely developed fire created after the flash-over;
- The dying down phase which occurs after time has elapsed as a result of fuel deficiency or active withdrawing of fire capacity (extinguishing).

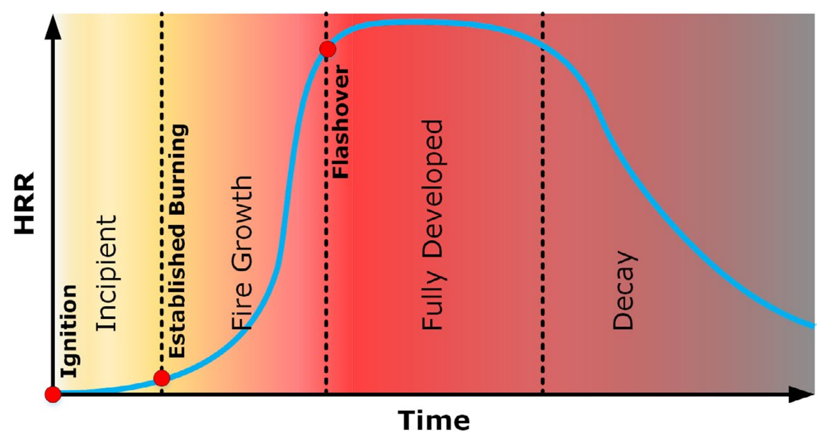


Figure 2.29: Fire curve (OFS, n.d.)

The spread of a fire

Once a fire is ignited it can spread through a building or to other buildings in two different ways. As treated in NEN 6068 a fire can spread through the structure (fire penetration) or through the outside air (fire spread) (van der Linden et al., 2018, p. 216-217). In Dutch this is called 'branddoorslag' and 'brandoverslag' respectively and is shown in Figure 2.30. The way 'brandoverslag' can occur can be by radiation, spreading flames or flying fire, as shown in Figure 2.31. For the radiation it is assumed in the Netherlands that when the receiving space is subjected to 15 kW/m² heat flux or more the fire is spread (this assumed value differs per country, e.g. in the UK the value of 12 kW/m² is used). Fire spread can occur at façade openings. In terms or fire safety façade openings are not per se the parts of the façade where one can see through. Façade openings relevant for fire safety, as defined by NEN 6068, are those parts of a façade which have a low fire resistance, which is set at 30 minutes or less. (van der Veek & Janse, 2005a, p. 60-61).

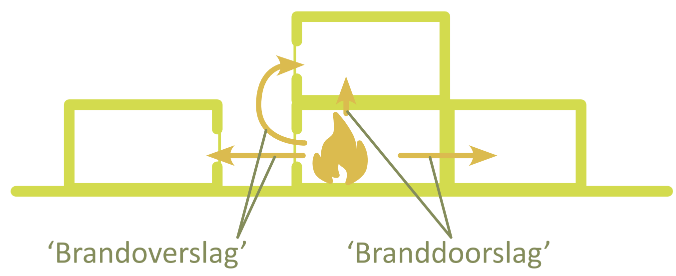


Figure 2.30: 'Branddoorslag' and 'brandoverslag' (Own work based on van der Veek & Janse, 2005b, p. 22)

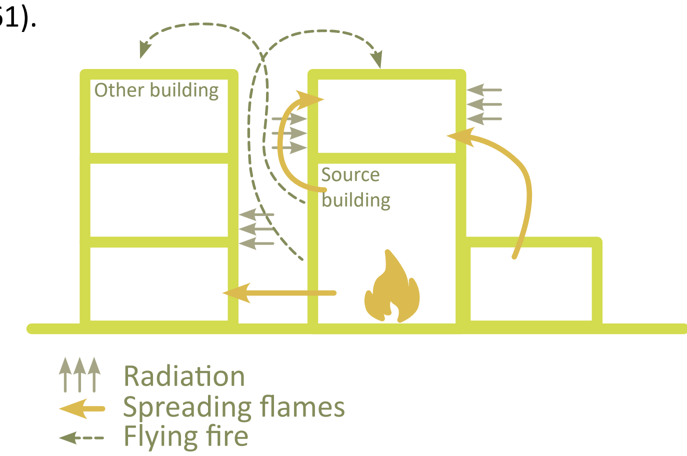
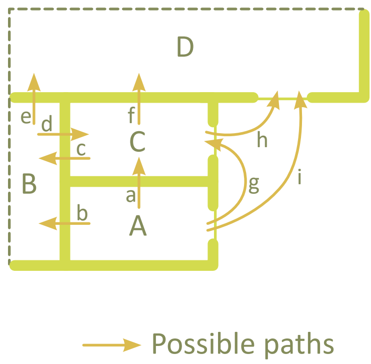


Figure 2.31: 'Brandoverslag' (Own work based on van der Veek & Janse, 2005a, p. 60)

In a construction the resistance to fire penetration and fire spread between two spaces or rooms under normal circumstances can be determined. This is called WBDBO ('Weerstand tegen BrandDoorslag en BrandOverslag') as stated in NEN 6068. In determining the WBDBO between two rooms, the quickest path is decisive (van der Veek & Janse, 2005a, p. 65). In Figure 2.32 an example of determining the WBDBO between two rooms is shown, where can be seen that the quickest path is not always the shortest path. Special care needs to be taken into account to holes and openings in the walls, since fire can spread through small openings.



WBDBO:	Possible routes:	WBDBO:
a = 55 min.	a + f	55 + 55 = 110
b = 12 min.	a + c + e	55 + 12 + 25 = 92
c = 12 min.	a + h	55 + 12 = 67
d = 12 min.	b + e	12 + 25 = 37
e = 25 min.	b + d + f	12 + 12 + 55 = 79
f = 55 min.	b + d + h	12 + 12 + 12 = 36
g = 30 min.	g + c + e	30 + 12 + 25 = 67
h = 12 min.	g + f	30 + 55 = 85
i = 65 min.	g + h	30 + 12 = 42
	i	65 = 65

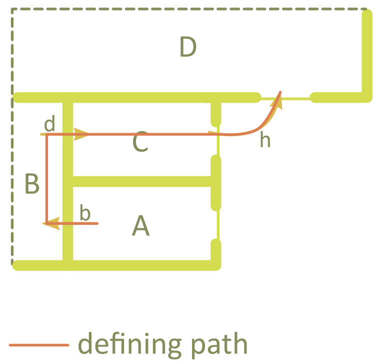


Figure 2.32: WBDBO between room A en D (Own work)

Usually the WBDBO needs to be a certain amount between fire compartments, fire sub compartments and/or (extra) protected escape routes. A fire compartment is a part of one or more buildings wherein a fire is allowed to spread and needs to be contained for a certain amount of time. During this time people can escape the building and the fire department can take measures to prevent further expansion of the fire. A fire compartment is at maximum 1000 m² and rooms or spaces which pose as fire hazard need to be their own fire compartment (van der Veek & Janse, 2005a, p. 67).

For determining the 'Brandoverslag' to buildings on an adjacent plot, mirror symmetry ('spiegelsymmetrie') is used, as explained in NEN 6068 (KNNI, 2020). With this method the source building is projected onto the other plot using the plot boundary as a the mirror axis, as shown in Figure 2.33 and Figure 2.34. The requirements are based on the projected building and not on a possibly existing building on the other plot.

Another important aspect in a fire is the development and spread of smoke. The WRD ('Weerstand tegen RookDoorgang') is the resistance to smoke passage. In a fire most casualties occur not directly from the fire but because of suffocation due to the expulsion of oxygen by smoke (van der Linden et al., 2018, p. 219). Furthermore smoke hinders the visual capability of people to find their way out.

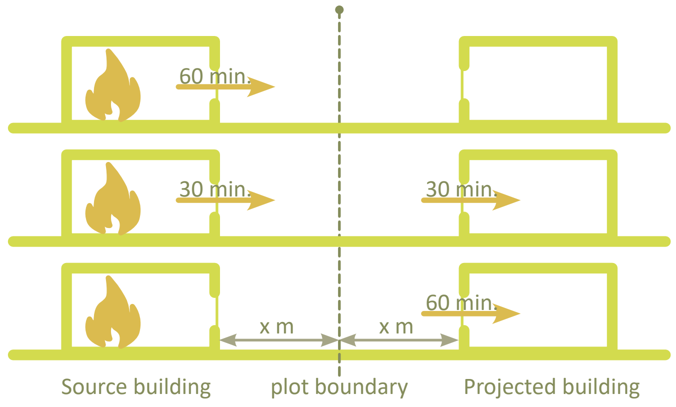


Figure 2.33: Mirror symmetry in cross section (Own work)

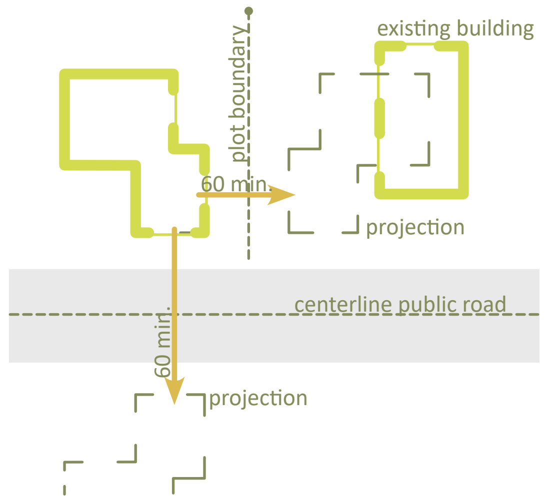


Figure 2.34: Mirror symmetry in plan view (Own work based on van der Veek & Janse, 2005c, p. 32)

2.2.3 Legislation and regulations

Introduction

As mentioned in the boundary conditions (1.7) rules and regulations differ from one country to another and in the current thesis the focus will be on the Dutch legislation. As of the 1st of January 2024 The Environment and Planning Act ('Omgevingswet' (Ow)) came into effect in the Netherlands. This single law, replaces 26 existing laws, where The Environment Buildings Decree ('Besluit Bouwwerken Leefomgeving' (Bbl)) replaces the Building Decree ('Bouwbesluit'), which was the previous relevant document which states rules for the fire safety qualities of buildings (Business gov, n.a.). With this change in laws the new main document has become the Bbl, which is freely accessible at: https://www.bouwbesluitonline.nl/docs/wet/bbl.

The basis for the legislation is that in case of a fire there should be no casualties and no damage to neighbors. Legislation does not focus on saving the building itself in case of a fire. The following subjects are relevant for the required level of fire safety for buildings (Rijksoverheid, 2024):

- Constructive safety in the event of fire;
- Limiting the occurrence of a fire hazard situation;
- Limiting the development of fire and smoke;
- Limiting the spread of fire;
- Further limiting the spread of fire and limiting the spread of smoke;
- Escape routes course;
- Escape routes design and capacity;
- Fire assistance;
- High and underground buildings;
- Fire and explosion regulations areas;
- Use of buildings.

Distinction new built, existing and renovations

The Bbl is performance-oriented and requires certain fire safety levels of different types of buildings. The document makes a distinction between existing buildings, new buildings, and renovation, where existing buildings require the lowest acceptable level and the new builds require the most strict levels. For renovation the required level is often somewhere in between the levels for new buildings and existing buildings or requires the legally required level ('rechtens verkregen niveau') of the existing situation, which is explained in article 5.5 of the Bbl. This means that the level of the new situation cannot be lower than the level of the old situation, with exception if the old situation exceeds the level for new buildings. In that case the new situation has to be at least of the level of new buildings. This legally required level always has to be at least the level of the required level for existing buildings (Rijksoverheid, 2024).

Equivalence ('gelijkwaardigheid')

A relevant term important in the legislation in the Netherlands is equivalence ('gelijkwaardigheid'). The principle of equivalence ('gelijkwaardigheidsbeginsel'), as stated in article 4.7 of the The Environment and Planning Act ('Omgevingswet'), offers the opportunity to comply with the rules by using a different method than stated in the Bbl. The importance here is that the required performance levels are still met using this different method (IFV, 2017).

Building functions

Another main distinction in the Bbl is the function of the building. 12 main building functions are distinguished as shown in Table 2.2 Different requirements are demandend for different building functions as some functions pose greater risks in terms of consequences (e.g. when children are present) or when there is a greater chance of ignition (e.g. in industry). Sometimes special requirements are necessary for specific subfunctions of a building function (Rijksoverheid, 2024). The relevant subfunctions in terms of fire safety are also shown in Table 2.2.

Table 2.2: Building functions (Rijksoverheid, 2024)

	Building function	Explanation	Special subfunctions relevant for fire safety
1	Residential	Building function destined for dwelling	*in a residential building *living wagon *for care
2	Assembly	Building function for the gathering of people for art, culture, religion, communication, childcare, providing refreshments for on-site use or watching sports	*for childcare with sleep area *for childcare for kids younger than 4 years old
3	Detention	Building function for forced stay of people	
4	Healthcare	Building function for medical research, nursing, care or treatment	*with sleep area
5	Industrial	Building function for commercial processing or storage of materials and goods or for commercial agricultural purposes	*light industry function for commercial animal husbandry *other light industry
6	Office	Building function for administration	
7	Accomodation	Building function for providing recreational accommodation or temporary shelter to people	*in an accomodation building
8	Educational	Building function for providing education	*primary education
9	Sports	Building function for the practice of sports	
10	Retail	Building function for the trading of materials, goods or services	
11	Other	Building function for activities where the residence of persons plays a subordinate role	*for passenger transport *for parking motor vehicles
12	Structure not being a building	Structure or part of it as far as it is not a building or part of it	*tunnel or tunnel-shaped structure for traffic *road tunnel with a tunnel length of more than 250 m

Fire classification

The Bbl demands certain classifications of construction products and building elements. These classifications are determined according to EN 13501-1, which is a European norm. In the norm the classifications and how they are determined is explained (KNNI, 2019). In Table 2.3 the classification system is shown. The classification consists of 3 parts. The first part is based on the contribution of the material or product to a fire on heat capacity, heat content, ignitability and contribution to flame spread (van der Veek & Janse, 2005d, p. 17). The second part is based on smoke production of the material or product once ignited. The last part is based on whether or not there are flaming droplets or particles coming from the material or product once ignited. The most fire safe materials are A1 and the least fire safe materials are F. This classification and the tests performed to determine the classification of a products is performed the same way in Europe, so that products can be traded between countries.

Table 2.3: Euro classification according to EN 13501-1 (KNNI, 2019)

Euroclassification	Behaviour of the material		Smoke production		Flaming droplets/particles	
A1	Non-flammable	No contribution to fire	s1	Little or no smoke	d0	None
A2	Almost non-flammable	No significant contribution to fire	s2	Limited smoke production	d1	Some
B	Limited flammability	Very limited contribution to fire	s3	Substantial smoke production	d2	Quite a lot
C	Flammable	Limited contribution to fire				
D	Highly flammable	Large contribution to fire				
E	Very highly flammable	Very large contribution to fire				
F	Extremely flammable	Extreme fire behaviour; or product not tested				

For façade products the demanded classification depends on the height of the building, the function of the building, how high on the building the specific product is implemented and whether or not it is a door, window or other part which is an exception. In Table 2.4 the demanded classifications which are required under different circumstances is shown. It has to be noted that the two A2 classifications are not yet implemented but will most likely be implemented somewhere in the near future. Also the note for the exemption rule is not yet implemented but there are plans to make this a rule as well (Personal communication with Paul Hoondert).

Table 2.4: Requirements euroclassification outside part of façade for new buildings (Rijksoverheid, 2024)

Location on the façade	Euroclassification	Notes
Façade > 13 m	B	
Façade < 2.5 m, when highest floor > 5 m	B	
Façade between two fire compartments if fire spread is possible	B	
Façade next to escape route Extra protected escape route Protected escape route Deviation for escape routes detention function	 C C (sleep function), D (other) B	
Façade > 30 m (sleep function for non self-relient people)	A2, or larger scale test*	*Probably as of January 1, 2026 (Hoondert & van Mierlo, 2024)
Façade > 50 m (sleep function)	A2; or larger scale test*	*Probably as of January 1, 2026 (Hoondert & van Mierlo, 2024)
Façade other	D	
Deviation: doors, windows, etc.	D	
Exemption (no requirement): for 5% of outer surface	-*	*But should not comprise the qualitiy of the 100% (not in legislation but advice)

The Bbl requires a certain WBDBO between fire compartments, sub compartments and (extra) protected escape routes. The requirement is dependent on whether the building is a new building, existing building or is being renovated, as shown in Table 2.5. There are quite a few exemptions noted in the Bbl, so the table only shows the most generic situations.

Table 2.5: Minimum required WBDBO between spaces in and between buildings (Rijksoverheid, 2024)

Situation	Existing	Renovation	New building
Fire compartment to other fire compartment or to a confined space through which an extra protected escape route leads	20 min.	30 min. or the legally required level if that is higher	60 min.
Fire compartment to a confined space through which a protected escape route leads	20 min.	30 min.	30 min.
Sub compartment to other room in same fire compartment	20. min	30 min.	30 min.

2.2.4 Tests

Current methods

Façade products need to be classified according to EN 13501-1. In the norm the tests necessary for determining the classification off a product are explained. Depending on the classification a product applies for, certain tests are necessary, as shown in Table 2.6. The next characteristics of a product are determined by the different tests (KNNI, 2019):

- Ignitability;
- Flame spread;
- Heat release;
- Smoke production;
- Flaming droplets.

Independent companies perform the tests and hand out the classification and test report for the tested products. In the respective norms explaining the different tests (mentioned in the brackets in Table 2.6), it is also explained what should be mentioned in the test report.

Table 2.6: Tests used for classifying building products according to EN 13501-1 (KNNI, 2019)

Test name	Explenation	Relevant for the classes
Non-combustibility test (EN ISO 1182)	This test identifies products that will not, or not significantly, contribute to a fire, regardless of their end use.	A1, A2
Heat of combustion test (EN ISO 1716)	This test determines the potential maximum total heat release of a product when completely burned, regardless of its end use. It allows the determination of both the gross heat of combustion (PCS) and the net heat of combustion (PCI).	A1, A2
Single burning item test (EN 13823)	This test evaluates the potential contribution of a product to the development of a fire, under a fire situation simulating a single burning item in a room corner near to that product.	A2, B, C, D Under specific conditons also: A1
Ignitability test (EN ISO 11925-2)	This test evaluates the ignitability of a product under exposure to a small flame.	B, C, D, E, F

Figure 2.35: Ignitability test at Efectis (Own work)

Figure 2.36: Cone Calorimeter test at Efectis (Own work)

The main test currently used in determinging façade products is the Single Burning Item test (SBI). In this test a corner setup of 1000x1500 mm and 500x1500 mm of a product are subjected to a 30 kW gas burner. The burner simulates a trash fire. The following aspects are measured in this test (Tromp & Mierlo, 2014, p. 176):

- FIGRA; Fire Growth Rate;
- THR: Total Heat Release;
- SMOGRA: Smoke Growth Rate;
- TSP: Total Smoke Production;
- LFS: Lateral Flame Spread;
- Production of flaming droplets/particles (this is not measured but observed).

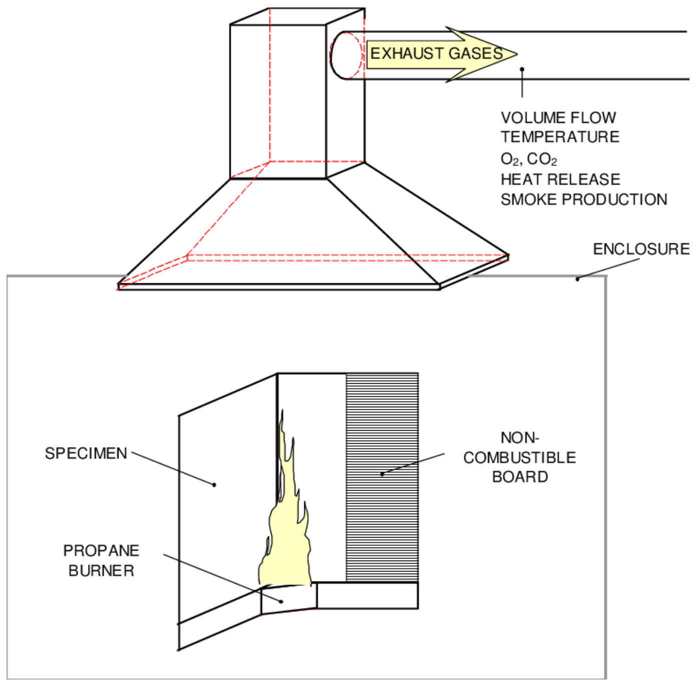


Figure 2.37: A schematic picture of the SBI test aparatus (Hakkarainen, 2002)

It is important to test a product the way it is applied in practice. So if a cladding system in its end use application is applied with an air cavity, the testing should also be performed with a cavity. The achieved classification is then also only valid when used as the tested end use application (KNNI, 2022b). Because it is economically not possible to test every single unique way of application, certain standard applications which represent the majority of end use conditions are valid enough (KNNI, 2010).

Also the test specimens need to be conditioned according to EN 13238 (KNNI, 2022b). Test specimens shall be conditioned at a temperature of (23 ± 2) °C and a relative humidity of (50 ± 5) % and test specimens shall be conditioned either until constant mass is achieved or for a fixed period.

Developments in test methods

The SBI test was developed like this because it had to be repeatable, be able to be performed quick (many in a day) and not cost too much for manufactureres to perform. 'The Room Corner Rest' for example is much more costly and can only perform one test a day, wich is not ideal (Węgrzyński, 2024).

There is presently an ongoing discussion whether this test is suitable enough for façade products, since it was not originally designed for testing façade products. There is a development of a new testing method in Europe. This new test will be of a larger scale than the SBI test. The already existing bigger façade tests in England (BS 8414) and Germany (DIN 4102-20) will be the basis for this new European test (Efectis, n.d.).

This development of new European rules goes very slow, so in the Netherlands an initiative has therefore been started to make use of an interim solution with which the actual fire behaviour of a façade can be better determined. This will be in the form of a Dutch Practice Guideline ('Nederlandse Praktijk Richtlijn' (NPR)), using an Intermediate Scale test according to ISO 13785-1. This method also uses a corner installation, but in these tests the dimensions are 1200 x 2400 and 600x2400 and the fire load is 100 kW which is placed underneath the test specimen (Efectis, n.d.). So this test is significantly bigger than the SBI test, where only a 30 kW gas burner is used which is also not placed underneath the specimen, but in front.

2.2.5 Key aspects

To determine the fire risk, it is important to understand how fire behaves. A fire's behaviour is dependent on ignition possibility and the possibility to spread. So for the rest of the studies it is important to keep in mind how a fire can be ignited and how a fire can develop and spread through the different parts of a building.

Relevant to take into account for the rest of the studie are the requirements determained by the Bbl. For this certain parameters are substantial in determaining the required safety measures. Important aspects are building function and building height. Because the current thesis is about vertical green on façades, the Eurocassification for façade products comes into play, which will be discussed in chapter 2.3.

Current method of testing is being reviewed in Europe. The new tests which are being developed could prove useful in beter determaining the actual fire behaviour of vertical greenery systems.

2.3 Fire safety of vertical greenery systems

2.3.1 Introduction

In the previous chapter fire safety in general was discussed. In this chapter fire safety in regards to VGS is discussed, to show which aspects of fire safety are the most relevant for VGS. First three cases of reported fires in VGS are discussed. Then an overview of the existing research on fire safety in VGS is shown. Current regulations and testing methods are explained and an overview of the influence of materiality in the different components is discussed. In this chapter also the main findings from interviews with experts is given. Existing measures from literature is given. The chapter finalises with an overview of all the found relevant parameters for the next steps.

2.3.2 Fire incidents involving VGS

Even though there are concerns about the fire safety of VGS, there are not many reports of fire incidents in literature. It is not clear if this is due to the fact that there are relatively few of these systems in place, whether the case of such fires is a rare event or because the fires that do occur are of insufficient severity or perceived significance to be reported (Kotzen et al, 2023). Three cases of fire in VGS have been found.

Beer garden, Sydney Australia 2012

One reported fire happened in a semi-enclosed beer garden in Sydney, Australia in 2012. The plants had caught aflame when a patron wanted to light a cigerate with a candle. The fire had spread across the whole wall in mere seconds (Kotzen et al, 2023). It was mentioned that the system did not have an automatic irrigation system, but what irrigated manually and that there were artificial plants included in the wall as well (Dahanayake & Chow, 2018). The literature does not mention if there was any more damage other than the plants which had caught fire.

So the problems found from this case is that there is a risk when people can reach the plants, since the fire was caused by an inandvertent customer. Furthermor the wall did not have an automatic irrigation system, which could've caused the wall to not be properly moist.

Mandarin Oriental Hotel, London UK, 2018

In late spring in 2018 a large VGS in the courtyard of the newly renovated Mandarin Oriental Hotel in London caught fire, see Figure 2.38. It is believed that the felt lining of the VGS had caught aflame due to byproducts from arc welding activities on the roof. The fire was able to spread along the VGS and also reached inside of the building damaging several floors (Kotzen et al, 2023). It is not mentioned whether or not the VGS had an automatic irrigation system or not, but since the wall was only newly placed during the recent renovation, it is assumed that the wall and the vegetation was most likely healthy and alive.

Again in this case the fire was caused by unintended carelessness of human activity, where the VGS was set aflame by an external source of flying fire. The fire was able to spread along a large portion of the façade and was even able to entere the building.

Block of Flats, Ealing, London, UK 2018

This fire happened in a residential building in London. The fire is believed to have been caused by a thrown away cigarette or match. The fire spread across the VGS even crossing over the part of the façade where no VGS was installed and was also able to enter the building, damaging corridors on two floors (Kotzen et al, 2023). As can be seen in Figure 2.39, the plants in the systems seemed to have been dry (either in dormancy or dead) when the fire occured.

Figure 2.38: Fire at Mandarin Oriental (Ma, 2018)

Figure 2.39: Green wall fire in London in 2018 (Kotzen et al, 2023)

This fire was again started by human carelessness, enabling a fire source to fall onto the VGS. The VGS was probably not moist and the plants seemed the have been dry when the fire started as observed from the footage. The fire was able to spread along the façade and also entered and damaged the inside of the building.

Key findings from case-studies

From these three reported VGS fires a few aspects stand out. All fires were started by human activity, setting the walls on fire with external fire sources. It is thus important to take into account the possibility of people being able to accidentally or purposely setting a VGS aflame. Furthermore in two of the cases it is quite clear the VGS were most likely not in the wet and healthy state one would expect and want from a VGS. The drying out of the system and dying of the plants clearly poses a risk in setting aflame the system and spreading the fire along the system. Even though one would assume people would want their walls to be in a proper condition, these two examples show that there is always a chance of failing of the systems. Lastly in two of the cases the fires were able to enter the building and damaging the inside. It is thus important to take into account how and where on a building a VGS is placed and if in case of a fire there is an opportunity for the fire to enter the building through façade openings.

2.3.3 Fire safety of VGS in research literature

Even though there has been a lot of research into VGS, there is not much research into the fire safety of VGS. Fire safety is sometimes briefly mentioned in research literature but in total only a few papers had been found which really focused on the topic of fire safety of vertical greenery systems, namely:

- Moisture content, ignitability, and fire risk of vegetation in vertical greenery systems (Dahanayake & Chow, 2018);
- Study on the fire growth in underground green corridors (Dahanayake et al., 2020);
- Green facades from a fire protection perspective (Engel & Noder, 2020);
- Fire spread along vertical greenery systems from window ejected flame: A study based on a fire dynamic simulator model (Karunaratne & Chow, 2022);
- Fire safety risks of external living walls and implications for regulatory guidance in England (Kotzen et al, 2023);
- An exploratory investigation into moisture content and wind impact on the fire behaviour of modular living walls (Bielawski et al., 2024).
- Fire Safety for Green Façades: Part 1: Basics, State-of-the-Art Research and Experimental Investigation of Plant Flammability (Engel & Werther, 2024).

Furthermore another master thesis was found exploring the fire safety of vertical greenery. This thesis focused on mapping the risks and gave a checklist of aspects to take into account when designing a VGS (Calvo, 2021).

Also some public videos of several tests performed on VGS by Thomas Engel were found, where climbing plants on metal support structures in wet and moist conditions were compared (Engel, 2023).

Moisture content

The found researches explore the influences on fire risks of vertical greenery systems. It is found that the moisture content of the systems is of great influence in the fire behaviour of the systems. The dryer the system, the easier it ignites and the quicker the flames spread (Bielawski et al., 2024; Karunaratne & Chow, 2022). So moist has a positive effect on the fire resistancy of a system. But when exposed to thermal radiation for a longer period, even a moist wall can dry out and be set aflame (Bielawski et al., 2024).

During tests on a fire retarded polypropylene potting LWS it was observed that there would be peaks at several moments, which corrolated with the seperate ignition of the plants and the plastic potting support structure (Bielawski et al., 2024). It was also observed that a dry wall would ignite easy and the flame spread was quick, but once the dry plants are burned away the fire died down, as the flames did not ignite the support structure. Only after a longer exposior during the test did the support structure ignite (Bielawski et al., 2024). This could mean that if the fuel load of the plants is not strong enough, the fire spread to surrounding structures would not be an issue.

It can be useful to make use of plants that have better resilience to dry conditions, because these species could behave better in maintaining their moisture content. But further research specific to this characteristic of different plants would be necessary (Bielawski et al., 2024).

It was also found that the spread of the fire is most significant in vertical direction and the fire spread in horizontal direction is relatively slow (Dahanayake et al., 2020; Karunaratne & Chow, 2022). In the FDS models performed by Karunaratne & Chow it was found that higher moisture contents slowed down the upward flame spread (UFS) and decreased the heat release rate (HRR) over time and also the total heat release rate (THR; Karunaratne & Chow, 2022). These models show that the main direction the flame spread is upwards, which can also be observed the in tests performed by Thomas Engel (Engel, 2023).

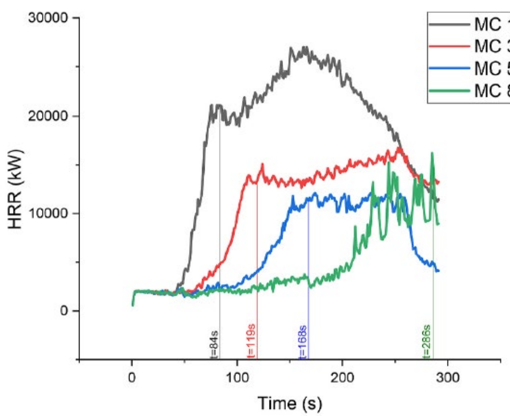


Figure 2.40: Variation in HRR with time in the four scenarios with VGS MC 10%, 30%, 50% and 80% (Karunaratne & Chow, 2022)

In a found case-study, the consequences were determined for an indoor VGS in dry conditions. It was found that the consequences would be catastrophic. But it was determined that the chance of that occuring due to failure of all systems was so small that this was still found acceptable (Calvo, 2021).

Plant density

It was also observed that the packing ratio was shown to have influence on the flammability of the vegetation. A denser package reduces the fire spread, but a denser package also add to the fuel load and thus to the total heat release rate (Karunaratne & Chow, 2022). From this it can be concluded that a dense and healthy VGS system is of great importance in minimising its fire spread abilities.

Air cavity

It is also relevent if there is an air cavity between the system and the rear façade, as this provides the posibility of the chimney effect which can cause rapid fire spread (Bielawski et al., 2024). Due to the way these sytems are connected to facades the LWS usually have an air cavity behind them. Specifically if the material facing the air cavity is plastic, fire can spread very rapidly if a fire were to get into the air cavity.

Figure 2.41: Chimney effect in air cavity in façade (Own work)

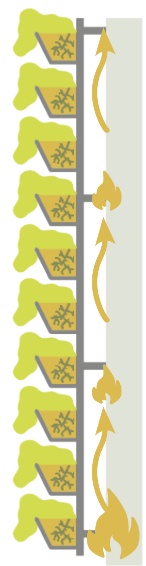


Figure 2.42: Chimney effect in air cavity behind VGS (Own work)

2.3.4 Regulations and testing of VGS

Vertical greenery systems which are implemented as exterior façade elements and are part of the building permit need to comply with the legislation for façades as discussed in the previous chapter. Therefore VGS are to aqcuire a Euroclassification according to EN 13501-1.

Testing method for VGS

VGS are tested according to EN 13501-1 and there are plenty of systems found on the market that advertise their achieved classification. However, currently it is under discussion whether or not the testing method is valid for vertical greenery systems. As mentioned in the previous chapter, products tested in the SBI test need to be tested in their end use application and the samples need to be conditioned. This proves to be not so simple in the case of VGS.

The systems are generally tested in a wet condition, which is the end use application. But there are those that say that this is 'cheating' the test, as you are protecting the materials with water (FPA, 2022). Also there is a chance of the system drying out during its use on a façade (e.g. due to failure of the irrigation system) and then the end use application is not in accordance anymore with the tested situation. Significant differences in results were found when using the tests. This shows that only testing the most optimal condition is not reliable to be the sole indication for the fire properties of a VGS. (Bielawski et al., 2024). Another way of testing would be without plants and without moisture, only testing the support structure and growing media (FPA, 2022). This is the way Sempergreen tested their Flexipanel A2 and reached a Euroclassifcation of A2-s2-d0 (Sempergreen, n.d.a). But on the other hand, this is not the end use of application, as it is applied with vegetation and irrigation system.

Furthermore the vegetation cannot be 'conditioned' in the way that non living products would be conditioned according to EN 13238. Therefore when testing VGS, the support structure is conditioned but the vegetation is not.

From the interviews conducted for this research, several opinions on the testing methods were found. Hereafter is a brief overview of the different findings of the different parties interviewed.

One party stated that the test needs to be performed in the worst case state possible, or the worst case state the systems is ever present in a forseeable situation. For example, if a system is automatically irrigated the system is at a certain moisture content. When the irrigation fails, the system will start to dry out. How long does it take for the irrigation system to be fixed? How low does the moisture content drop in that time period? Test under those conditions (personal correspondance with ARUP).

Another party stated that the current testing method is not the biggest issue, but that the focus could be in improving regulations in terms of inspections of proper installation and working of the irrigation system (personal correspondance with Efectis).

Another party also stated that it could be enough with an examination of proper implementation. This is for example already possible for solar power installations, using SCIOS Scope 12. Which includes a first special inspection and periodic inspections. This is not currently obligated other than for cattle sheds, but it can be enforced by insurence companies. A similar inspection system could be used for VGS (personal correspondance with Univé).

It is clear the current way of testing and implementation is not very representative or informative on the actual fire behavior of the VGS. Improvements should be made in the testing method. Tests should not be performed in the most optimal condition, but in a condition to be expected to be relevant for a fire scenario. Thus with lower moisture content and a certain amount of dead voilage. Furthermore these exact conditions should be part of the test report. It can be included in the respective norm of the test, that it is demanded that this information needs to be included in the test report.

Furthermore it can be demanded by authorities when applying for a permit, that a maintenance contract has to be in place. This way it can be ensured that the conditions of the VGS will not drop below the conditions in which the tests were performed.

2.3.5 Materiality of the components and their influence

As described in part 2.1 VGS consist of different typologies which uses different components. These components can be made up of different materials. The materials used and the typologies have a very strong influence on the behaviour of the VGS in case of a fire.

Vegetation

The choice of vegetation needs to be made thoroughly. Different plants respond different to fire. It is best to avoid woody plants and plants with volaitle oils and resins as these will increase the fuel load. But most importantly is to pick plants appropriate for the climatic conditions of the place of the wall. When using plants which are suitable for the specific climatic conditions such as temperature and shade the chance of the plants dying is smaller. As the greatest risks occur when the plants die. Furthermore the type of plant influences it's seasonal behaviour. If the plant changes with the seasons and goes into dormancy during winter, it's influence is different in the winter from it's influence in the summer.

Growing media (substrate)

The growing media (or substrate) can either be soil based or hydroponic based with (in)organic substrates.
Growing media in tests non flammable (Fire Performace of Green Roofs and Walls). The less organic mater in the growing media, the less flamable it is (Al-Kodmany, 2023).

Support structure

The support structures can be made of many different materials. It is found that in case of LWS the choice of the material for the support structure is the most relevant in terms of fire safety, more than the plant choice.

Euroclassification A1 or A2:
- Brickstone
- Sand-lime brick
- Concrete stone
- Aerated concrete
- Natural stone
- Ceramics
- Stucco
- Mineral wool
- Glass
- Steel
- Iron
- Coper

Euroclassification A1 or A2 melting:
- Aluminium
- Zinc
- Lead

Other Euroclassifications:
- Plasterboard (A2-B)
- Fibre cement board (A2-C)
- Wood wool cement board (B-C)
- Brick slips on flammable background (B-E)
- High Pressure Laminate, fire retardant treated (C-D)
- Wood, fire retardant treated (B-D)
- Wood (D)
- Chipboard, OSB, MDF (D)
- Chipboard, LDF (D-E)

Insulation product with a core of:
- EPS, XPS (E-F)
- Resol (B-C)
- PIR (C-D)
- PUR (C-D)

Figure 2.43: Euroclassification of materials accrording to NEN-EN 13501-1 (Nieman & DGMR, 2022)

Different materials behave differently in case of a fire and score differently in the classification according to EN 13501-1, as shown in Figure 2.43.

Irrigation

The materials of the irrigation systems are found not to be of significant influence for the fire behaviour as it is of relative little volume and are usually filled with water. The denisity of the irrigation system has influence on how well the wall is kept moist. Less denisity has higher chance of dry spots on the wall. A denser system also allows for more specific conditions appropriate for the different types of plants used in the wall. Not every plant needs the same amount of water and nutrients. With a more appropriate care system per plant, lowers the chance of the plants dying.

Drainage

The drainage consist mostly of the same materials as the irrigation system. It was also found that these do not significantly influence the fire behaviour of the system as a whole.

2.3.6 Placement on façade

As also mentioned in the previous chapter, the building characteristics also influence the fire risk. So the placement of how the VGS is to be installed on the façade needs to be considered thoroughly. If the system is placed on top of a façade, and the rear façade is fire class A1 or A2, the risks are significantly less from if the rear facade is fire class B or lower. If the rear material is insulation (possibly with reflective coating), the fire spread behaviour of the material of the VGS is increased.

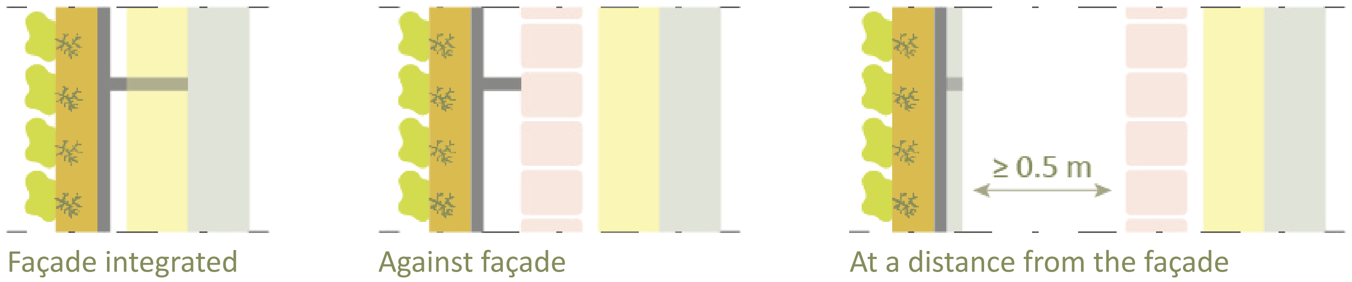


Figure 2.46: Three ways of attaching to the building (Own work)

Furthermore if the system is placed at a distance from the façade, for example stretching from protrusion to protrusion or placed on the balustrade of a balcony or gallery changes the way it can effect fire spread to and from the inside of a building.

With this also the way system 12 and 13 are treated is of great significance. The distance at which the vegetation grows from the actual façade, influences the fire spread possibility from and to the façade.

2.3.7 Existing measures

In literature and in practice several existing measures were found which influence the fire safety of a design with VGS. The use of fire breaks has been mentioned. This can be in the form of a non-combustible material as in Figure 2.44 or by keeping vegetation free zones between parts of the VGS is done in Figure 2.45. Using these fire breaks can help prevent or slow down the upward fire spread in case of a fire. Fire breaks can also be implemented in a vertical direction.

Figure 2.44: Fire breaks at every floor in a VGS on a hotel (Sempergreen, n.d.b)

Figure 2.45: Fire breaks as non-continuing VGS (Sempergreen and Mastop Totaaltechniek BV, n.d.)

There are several sources which mention the use of fire breaks and vegetation free zones (Bachmeier, 2020; EFB, 2022; FuHH, 2022; Martin, 2021). But it is found that there is not a constistent mention of the distances necesssary to be effective and most of these mentions were not based on physical testing. The mentions of the protrusion of the fire break, mostly state it has to protrude past the vegetation. It would be useful if more explorative testing, as is shown in Figure 2.49, would be performed to get a clearer understanding of how far the fire break should protrude. The same goes for the distances of how wide the vegetation free zones should be to be effective.

It is also mentioned that the system can be placed with enough distance from the façade as to not be able to be ignited in case of a façade fire. Again for this more explorative testing would be advised to get a clearer understanding of what distance is needed to be effective.

Furthermore a mention of a 'fire mode' of the irrigation system has been mentioned. When a fire is detected in the system the irrigation system switches to 'fire mode' providing an extra amount of water, and thus effectively working as a sprinkler system (Calvo, 2021).

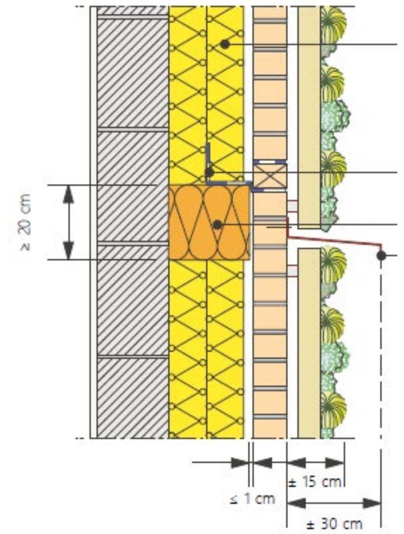


Figure 2.47: Metal (not aluminium) fire break seperating parts of the VGS (Martin, 2021)

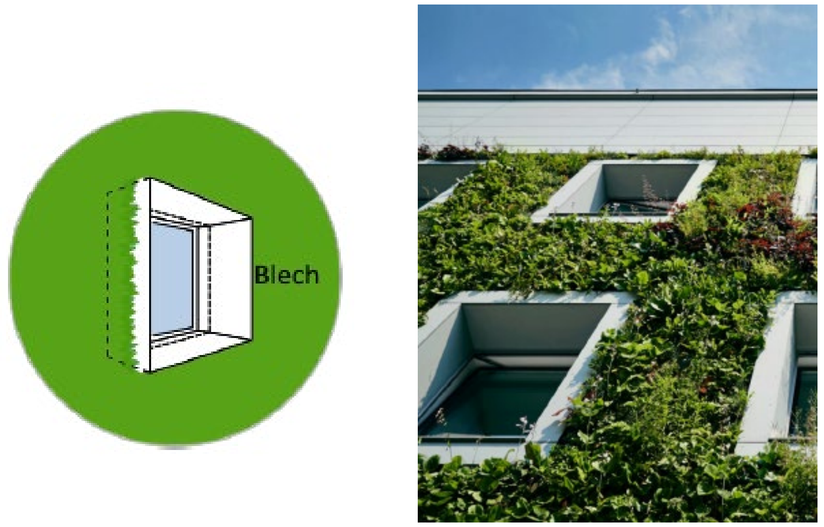


Figure 2.48: Fire break around façade opening parts of the VGS (FuHH, 2022)

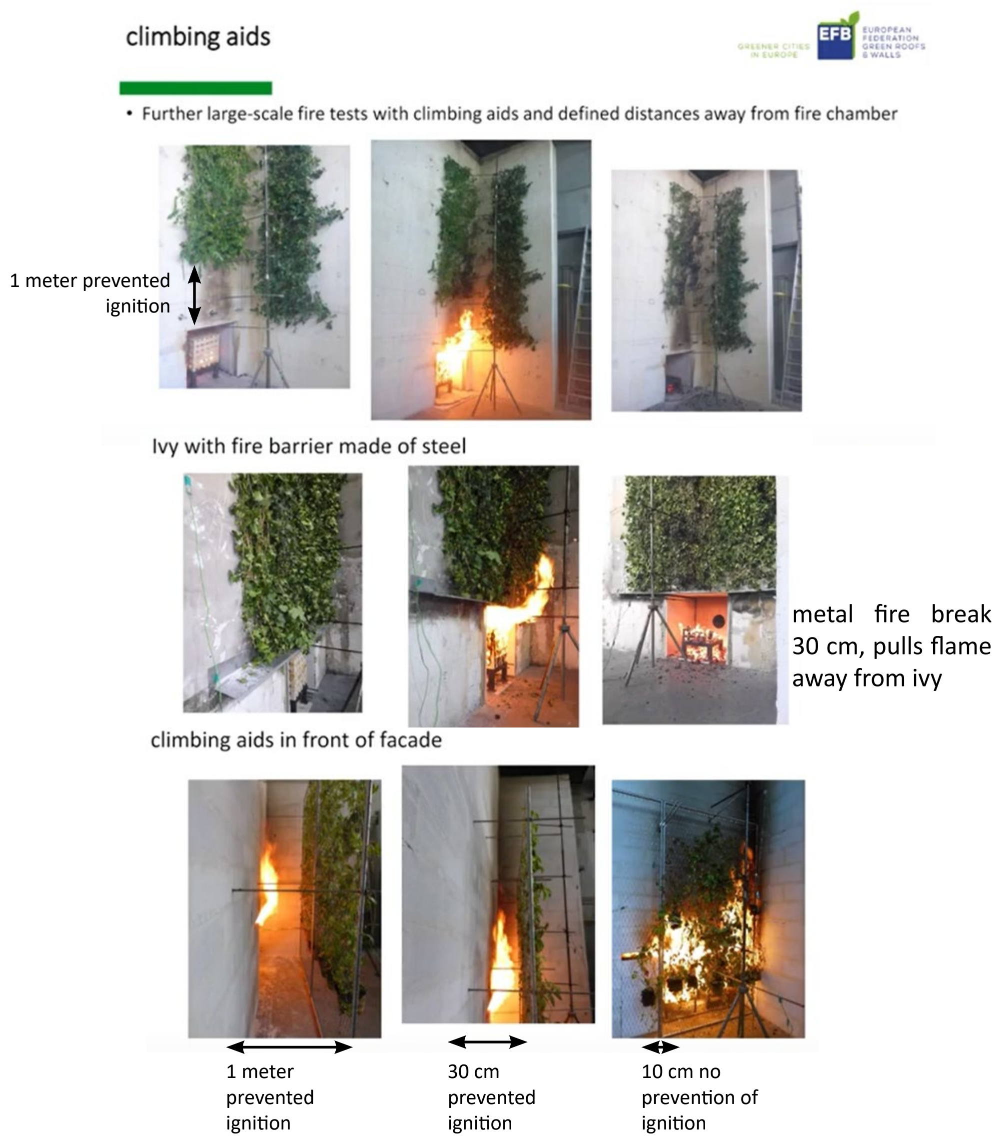


Figure 2.49: Several set-ups of explorative tests performed on VGS (EFB, 2022)

2.3.8 Key aspects

Several relevant parameters have been found in legislation, existing research and through the interviews, which will help in developing the "What-if" scenarios in the risk assessment. These parameters and the found measures and design options will be used to give guidance in the decision-making framework. The following aspects have been found to be of importance:

Ignition sources:
- Human behaviour, accidental or arson;
- Hot works;
- Lighting & heating systems in proximity;
- Window-ejected fire plume;
- Adjacent building on fire;
- Lightning strikes. (this source is found to not be of significant importance in the Netherlands, so will not be taken into further account. In differenct climates, this might be of more significance.)

Parameters that influence ignition and fire spread:
- Materiality and vegetation choice;
- Configuration and location of system;
- Materiality and structure of rear façade;
- Breaks in the system/fire compartmentation;
- Moisture content;
- Plant density;
- Wind;
- Openings in the façade;
- Accessibility fire brigade.

Parameters that influence the probability of the vertical greenery system failing:
- No proper vegetation choice for climate conditions;
- Irrigation failure;
- No proper maintenance;
- Presence of monitoring system.

Parameters that influence the lifesafety:
- Building function;
- Building height;
- The abililty of "fire spread";
- Proximity to escape routes;
- The presence of multiple escape routes.

Furthermore it was found that the current method of classifying VGS is not very reliable in determining the actual fire behavior in practice and thus assessing the risks involved. Therefore in the research the classification of VGS is not taken into account, but the systems are assessed by the materials used.

It was found that healthy plants and moisture are of great influence on the fire behaviour of the VGS. In literature it is often mentioned that as long as the system is wet, there is no fire risk. But even wet systems can catch fire and irrigation systems can fail. So solely trusting on this is not enough, but having a good working irrigation system does improve the fire safety. Also maintenance is of great importance for a working VGS. When applying for a permit it could and should be demanded by the authorised supervision that a maintenance contract has to be in place.

Lastly some interesting design measures were found using vegetation free zones, fire breaks and distance from the façade. But further physical testing should be performed to determine what dimensions are necessary to be effective.

Chapter 03
Risk assessment and design research

3.1 Introduction

In this chapter a risk analysis is performed to identify the relevant parameters which influence the fire safety of designs with VGS. First an overview of different existing risk assessments is given. Then the used method for the current thesis is explained. The performed risk analysis is described using the found parameters in chapter 2 and using case-studies to develop scenarios to identify all the relevant parameters. After this an overview of all the found parameters and their influence is shown. These parameters were used for the development of the decision-making tool (see chapter 5), which was developed in collaboration with Bo Valkenburg. Lastly it is explained how the weighting of the different risk factors was determined.

3.2 Risk assessments overview

A risk assessment is a procedure in which hazards and their possible consequences in a certain situation are being identified and evaluated. In these assessments answers to the following questions are sought after: 'What could happen? How bad would it be if it happens? How likely is it to happen?'. It is important to note the difference between hazard and risk. A hazard is the potential of something causing harm. Risk is the likelihood of this hazard occurring and the negative consequences the occurrence has (Watts & Hall, 2016). This is often visualised in a risk matrix, where the risk value is determined as the product of the consequences and the probability.

In terms of fire risk assessment the hazard is the fire. When performing a building fire risk analysis, there needs to be an understanding of the fire hazards which can occur in a building, what the consequences of such a fire would be and the likelihood of such a fire and the negative consequences occurring. A fire hazard assessment aims to identify the possible fire ignition sources, without taking into account the likelihood and the consequences (Meacham et al., 2016).

It is important to know that risk can never be completely eliminated. There will always be a certain amount of risk. Therefore it is important to determine an acceptable risk. An acceptable level of risk is dependent on several factors, including the problem context and the people judging the acceptability level (Watts & Hall, 2016).

There are numerous risk analysis methods, such as Preliminary Hazard Analysis (PrHA), Checklist, What-If (WI), What-If Checklist (WIC), Hazard and Operability (HAZOP) Study, Fault Tree Analysis (FTA), Event Tree Analysis (ETA) and Bow-Tie Analysis (BTA; Primatech Inc., n.d.). They often involve the use of several experts on the topic brainstorming about the risks.

For the current thesis a 'What-If' analysis is sufficient, as the goal of the research is to show an approach in solution seeking. A 'What-If' analsyis can be performed relatively simple and quick as compared to the other analysis methods and for the goal of the research is precise enough in determining the risks. The approach can be further developed in the future with a more precise risk analysis and with more input from experts in the field.

A What-If analysis is a structured risk assessment in which 'What-If' questions are asked for a certain scenario to determine likely sources of errors and failures. The answers to the 'What-If' questions are then evaluated on their potential consequences and the likelihood of it occuring, which determines the risk level. According to the found answers, recommendations are made to prevent or mitigate the found risks (OSA, 2021). Questions can be related to several aspects such as potential of human error and the potential of equipment failure (ACS Institute, n.d.).

3.3 Used method for risk analysis

For the current thesis a 'What-If' analysis is used. Using the information from the literature research and by analysing case-studies, scenarios were developed. These scenarios were used to determine the relevant parameters which influence the risk level of different design options.

A proper 'What-If' analysis works best in a defined case. Since in the current research looks at many possible situations, the 'What-If' analysis cannot be as comprehensive as it would be for a defined case. It is assumed that by looking at many different case-studies with an 'What-if' approach and way of thinking, the most of the relevant parameters can be identified.

The information from the literature research and common sense are used to go over a numerous amount of cases to identify the possible sources of ignition, possible flame spread routes, obstacles in fire control and possible risks related to safe escaping of the people in the different situations. By looking at as many different types of scenarios it is assumed the most relevant and important risks can be identified this way. However there is also an awareness that it is possible certain aspects have been overlooked by this method. For the current thesis this method is sufficient enough, but for future research a more intensive risk analysis could be performed, which could identify more relevant parameters.

3.4 Performance of risk analysis

3.4.1 Developed scenarios based on literature research and case-studies

Keeping in mind the infomation found in chapter 2 and the key aspects found, scenarios were developed for the different case-studies. The overview of all the looked at case-studies is shown in Appendix B. The way the case-studies were chosen was by determining certain differentiations based on the found key aspects in chapter 2, and collecting case-studies which would cover all the differentiations of these aspects. The main distinctions used for choosing the case-studies were:

- Building function;
- Building height;
- Façade typology and configuration.

Furthermore certain cases (mainly the residential buildings) were chosen due to the fact that they are frequently found in the Dutch built environment and are thus representative for large amount of buildings.

During the analysis several questions were raised to identify possible relevant parameters. With relevance of the parameters it was kept in mind what the likelyhood and the consequences would be. The consequences can be split into possibility of fire spread and loss. The questions included:

- What could potential ignition sources be?;
- If ignited how would the flames spread?
- Can the flames reach into the building?;
- Would the flame spread actually impact the users of the building?
- Would the flames reach an area where people reside?
- Would the flames threaten the possibility of escaping?

3.4.2 Examples of performed risk analysis on case-studies

Residential single-family home

If a VGS were to be placed on the blind brickstone façade, a fire would not easily spread inside the building. This would also not impact the possibility to escape. In this case, any type of VGS would be fine.

When placing a VGS on the light panel façade, there is a risk of a fire spreading into the building. Escape possibilities are quite positive and the fire department can easily access the system, so there is still not much risk. It would be advisable to use ground based systems or an automatic irrigation system and have the support structure made of incombustible material.

Also take into account what the situation at the neighbours could be. If the neighbours would also have a VGS, the fire could spread to the other building. Still no massive risk, as escape possibilities are fine. Would be more prefered to make use of systems without combustible materials.

Figure 3.1: Single-family house case-study

Residential appartment building

If a VGS were to be placed on the blind brickstone façade of the building. The façade can be ignited by a passersby, either accidental or on purpose. If this were to ignite the system, the flames would not easiliy spread into the building and threaten the residents or their escape. To even lower the risk of the system being set aflame, it could be chosen to start the system at a height of 2.5 meters. This would not be possible for ground based Green Façades.

Figure 3.2: 4 floors gallery appartments

A VGS can also be placed on the balcony balustrades. It can be ignited by neglect of the residents and threaten other fire compartments by spreading over the balconies. Depending on what people have on their balconies, the flames could spread towards the façade and reach the inside of the building. The balconies are no escape routes, so the possibility to esacpe timely is not threatened. A positive thing in this case is that the balconies themselves work as a fire break between the appartments. But adding VGS on the balustrade increases the chance of flashover from one appartment to another. In this case it would be advisable to use systems without combustible materials and use automatic irrigation.

When using a Green Façade with incombustible material configurated like in the right situion, there is also not so much risk, as the fuel load of the plants is very little.

Figure 3.3: Balcony cases

When the VGS is placed on the façade itself or as the façade itself, there is a possibility of fire spread into the building, but chance of flashover in vertical direction is limited due to the fire break working of the balconies. The fire still has the posibility to spread horizontally if the system is applied continuous.

Figure 3.4: Balcony cases

Figure 3.5: Brickstone ground level

Placing a VGS on the brickstone façade of the storage level, has limited risk. A fire could spread into the storage area through the windows, but this would not threaten the residents. The gallery works as a fire break to prevent spread to the upper floors.

When applying a VGS on the galleries, the escape possibility is threatened. If a system is set afflame and it spreads horizontally, it could block off all posibile escape routes for the residents. When placing VGS in a patern, the fire could not spread easily along the escape routes, which would prevent the blocking of all possible escape routes.

Figure 3.6: Gallery cases (escape route)

Residential building

Large residential building with one escape route. Placing the green next to these escape routes is a very high risk, as a fire would block all possible ways of escaping.

If the VGS is placed on the façade next to the appartments, there is a chance of flashover to vertical fire compartments. Especially the higher façade parts pose great risk due to inaccessibility of fire fighters. Better possibility is only applying on the lower floors.

Figure 3.7: High rise residential building (Own work)

When applying a VGS on the blind side wall of the building there is no no easy fire spread to the inside of the building when set aflame. It also doesn threaten the escape route. Could still be useful to leave the bottom 2.5 meter vegetation free, to prevent easy ignition at ground area. To further prevent possibilty of leaping around the corners or onto the balconies at the back, a vegetation free stroke can be kept a the side of the wall. Due to higher wind speeds higher up the building, this vegetation free zone can be bigger the higher on the building the system is applied.

Figure 3.9: Blind façade high rise residential building (Own work)

Secondary School

Low risk for function and height building. Due to stroke of water there is no easy access, so ignition is only likely due to a window-ejected fire plume. Left situation can cause flashover to above floors, but if these are in the same fire compartment that is not a big issue. The right situation has a lower risk of flash over. There is easy access for firefighters.

Figure 3.8: Education building next to water (Own work)

University building

Low risk functionality but very high building. The façade consists of a curtain wall. The VGS can be placed at a bit of a distance from the façade, which would decrease the ease of fire spread. In the left situation, vertical fire spread is possible. This can be prevented by using a patern. The vertical strips can also be interrupted by fire breaks.

The blind façade has a lower chance of spreading into the building in case of a fire. It can still be useful not to place the system on the first 2.5 meters and not above 20 meters so fire fighters have proper access.

Figure 3.10: High rise curtain wall university building (Own work)

Residential building

High rise residential building, relatively risky. Escape routes are in the core, so are not threatened by the greenery. The greenery stretches over several façades and especially the trees can have significant fuel load. The greenery also stretches all the way up the 77 meter high building, where fire fighers have no easy access to fight the a potential fire. Potential ignition sources are the residents which have balconies next to the green balconies or window ejected flame plumes.

Figure 3.11: Trudo Toren Eindhoven with system 13 (van Onna, n.d.)

3.5 Parameter overview and design options

3.5.1 Overview of parameters used in tool

Using the scenarios and the information found in chapter 2, the following relevant parameters were found and are used in the tool. The parameters are categorized by scale (building scale, façade scale and product scale) and per parameter a short description is given what different design options can be considered and how they influence the fire risk. The parameters were used to develop the decision-making tool (see chapter 4), which was developed in collaboration with Bo Valkenburg. The choices of which parameters were used and why had been made partly together. Furthermore some parameters and their options were inspired by two developed tools by DGMR and Nieman: 'Borgingsprotocol' (Nieman & DGMR, 2022) and 'Handreiking beoordeling veilige gevels' (DGMR, 2019).

Building scale

Building function

Certain building function have a greater risk in their consequences in case of a fire. This has mainly to do with if people are able to detect a fire in time (consciousness) and if they are able to evacuate in time by themselves (self- reliance), which both pose as a greater risk due to slowing down the possibility of evacuating. As mentioned in section 2.2.3, The Environment Buildings Decree ('Besluit Bouwwerken Leefomgeving' (Bbl), makes a distinction in 12 building functions and several subfunctions, which influence the required performance in the regulations. For the tool the distinction is made between functions where people reside that sleep and/or have reduced self-reliance.

Building height

The height of the building has significant influence on the risk consequences in case of a fire. This has mainly to do with the difficulty of evacuating people from the building. In a high building the traveling distance is longer than in a low building and there are more vertical descents (see Figure 3.12). Especially the vertical descents can pose a problem when there are people present that are not self-reliant or have a difficulty walking.

Furthermore the height has influence on the access for the fire fighters. Higher buildings are harder for the fire fighters to extinguish as standard fire fighting equipment cannot reach the higher parts of the building. In buildings where distance of the highest staying area and the measurement level is 20 meters or more dry extinguisher pipelines and fireman's elevator are obligated. See also 'Firefighter accessibility'.

Lastly, wind speeds are usually greater at a higher height, as shown in Figure 3.13. Thus a fire in tall buildings is more influenced by the wind at the higher parts of the building, which can increase the fire spread significantly.

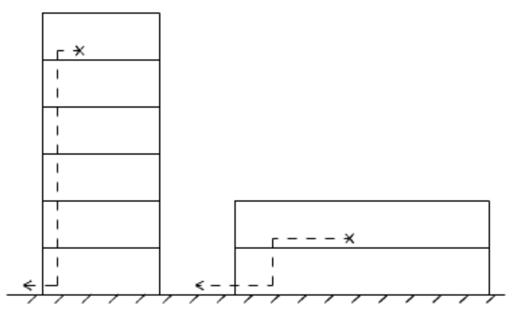


Figure 3.12: Height influences escape distance (own work)

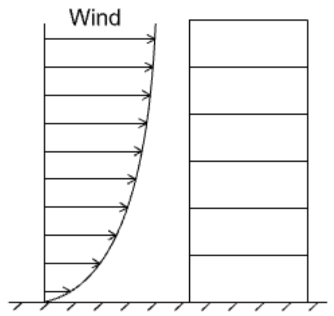


Figure 3.13: Height influences wind speed (own work)

Multiple functions

It is not uncommon for buildings to house multiple functions. If the building has more than one function, the most critical function is leading. This is however also influeneced by how high in the building the function is situated. The combination of the risk in how high the different functions are situated determines which function is the critical function. When designing a building with multiple functions, it could be considered to place the higher risk function lower in the building and the lower risk functions higher in the building.

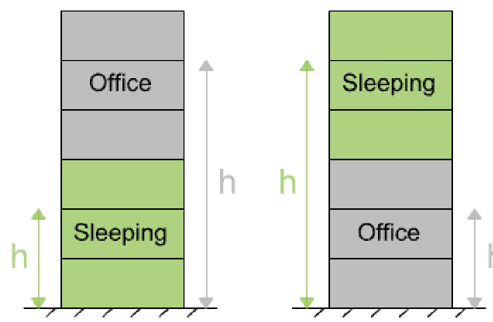


Figure 3.14: Multiple functions in a building. The left situation poses lower risks than the right situation. (own work)

Location of escape routes

Safe escape is one of the main drivers for fire safety. The location of the escape routes has great influence on whether people are able to evacuate safely and in time. If there is only one staircase, and the fire is threatening this escape route, there are no alternative routes, which is a huge risk. If there are two or more stairs, there is still an available escape route when one staircase is threatened by a fire. The distance between the staircases is of importance because if two staircases are close to each other, the chance of a fire threatening both staircases becomes higher. Furthermore a staircase not bordering the façade will not be threatened by a façade fire, which functions as a lower risk. If in a design there is a risk of people being blocked from all possible escape routes due to a single fire, it can be considered to change the location of the fire escapes.

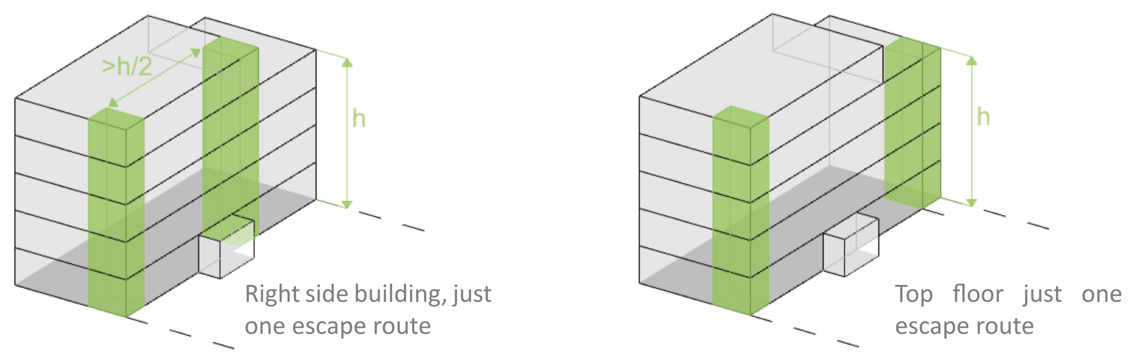


Figure 3.15: Escape routes locations. (own work)

Facade scale

Façade typology

The type of the façade to which the VGS is applied has significant influence on the risk. There are quite a few different ways to categorize different façades. The following categorization was used for the current thesis, because it was determined these are the relevant differences on this scale (materiality is covered in product scale). The following distinctions were chosen for the current thesis: whether the façade is of an opaque material with or without an air cavity or is made up as a curtain wall and whether or not a double-skin façade is applied in front of the façade. If an air cavity is present in the façade, there is a risk of chimney effect happening in the façade. Furthermore a curtain wall is a very different system than standard opaque systems, as these systems consists mostly of glass and frames. Lastly the presence of a second skin can have influence on the fire spread, again due to the possibility of chimney effect.

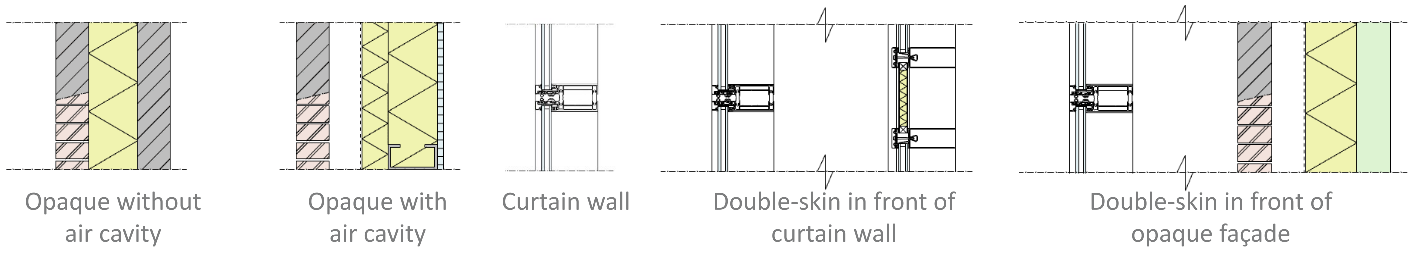


Figure 3.16: Façade typologies (own work)

If the façade has an air cavity, it can be considered to use fire breaks in the air cavity to prevent the chimney effect to occur in case of a fire.

Double-skin typology

There are four types of double-skin façades. For chimney effect to be able to happen in the double-skin façade, there needs to be an open trajectory over a height. This is a risk in the shaft-box façade and multi-storey façade. The box façade and corridor façade separate the double-skin area, which helps in preventing fire spread. If the double-skin façade stretches over several floors, choose to seperate them to lower the risks. This is mostly relevant when the floors are in different fire compartments.

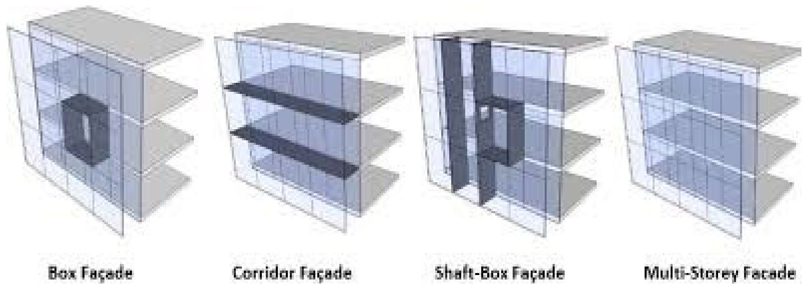


Figure 3.17: Double-skin typologies (Lim & Ismail, 2022)

Fire compartmentation

When the façade stretches over several fire compartments it has to be prevented that a fire can spread from one fire compartment to the other through the façade. Since fire has a quicker spread upward than sideways, vertically situated fire compartments are at more risk of being crossed by a fire than horizontally situated fire compartments. When choosing where to apply VGS on a building, it is important to take the fire compartmentation into account. It would be a saver design if the VGS does not stretches over multiple fire compartments or threatens to provide fire spread from one compartment to another.

Load-bearing façade

If the façade is load-bearing it can threaten the collapse of the main supporting structure if subjected to damage from a fire. This causes risk for people trying to escape and for fire fighters needing to enter and search the building. If the façade is not load-bearing, its collapse does not risk the collapse of the main supporting structure. The building decree does have regulations on the requirements for the main support structure to prevent collapse in case of a fire. But there is always the chance that there are construction errors. Then the risks for a load-bearing façade are greater than for a non-load-bearing façade. It can be considered to over dimension the structure to make sure the structure stays structurally sound when attacked by a fire.

Interruptions along the façade

If there are protrusions along the façade, either vertical or horizontal, the fire spread can be slowed down or even prevented. These interruptions can be there for another purpose such as balconies or galleries or shading. For these to work as a hindrance for the fire spread, the protrusions should be off incombustible material (not aluminium, as it melts away). Otherwise the protrusions can add to the fuel load and increase the fire spread. This is a useful design feature which can be used to mitigate the fire spread possibility. Also fire breaks can be used as protrusions to prevent or mitigate fire spread.

Figure 3.18: Protrusions on the façade mitigate fire spread from one house to another (Own work)

Figure 3.19: Protrusions on the façade mitigate upward fire spread (Own work)

Transparent parts

Windows contain a glass surface. When glass is subjected to fire, or more specific, heat differences, it breaks. Once the glass is broken there is a hole in the façade through which fire can spread freely. So a wall with transparent parts/windows pose a bigger fire spread risk than a closed façade. This works both ways, the façade can spread the fire to the inside of the building, but the façade can also be set aflame by a window-ejected flame plume. When designing with VGS it can be considered to focus on greening parts of the façade which are not near transparent parts.

Firefighter accessibility

In case of a fire it is very important the fire brigade has access to it to get the fire under control and prevent further fire spread. If the façade is not accessible, either by barriers on the ground or because the façade is too high, than a potential fire has more chance of spreading uncontrollably.

In NEN 6068 the following definition is stated (KNNI, 2020): '*Accessible to the fire brigade' in the case of facade parts under 20 m, unless those facade parts border on wide water or inaccessible terrain or terrain that cannot be entered without danger to emergency services.*

In NEN 6069 the following definition is stated (KNNI, 2022a): *In any case, 'not being safely accessible with fire extinguishing water by the fire brigade' includes the closed facade parts and closed parts of roofs required according to NEN 6068:*

— which are higher than 20 m above the measuring level; or
— at > 60 m distance from the public road or from the position of a fire brigade vehicle; or
— that are not accessible from the public road or public water.

NOTE 1 Examples of closed facade parts and closed parts of roofs that are not accessible are wide water and inaccessible terrain.

Figure 3.20: Courtyards which are not accessible by fire trucks (Google et al., n.d.)

Figure 3.21: Façade surrounded by water, not easily accessible for fire fighters (Own work)

Wind exposure

Wind amplifies the fire spread along a façade. So a façade subjected to strong winds is at more risk of fast fire spread than a façade that lies on the leeward side. For this it is important to know what the prevailing wind of the location is and if the façade is subjected to this wind. If this is the case, extra care needs to be taken as fire spread can be encouraged during strong winds. This is specifically an interesting point to take into consideration during a design, since fire tests for the Euro classification are performed without wind. In the Netherlands the prevailing wind is from the South-West. So façades exposed to strong wind are under higher risk of fire spread. It can be considered to only place the VGS on façades that are not exposed to the prevailing wind. Still it needs to be taken into account that wind can always come from a different direction, so even when the location is not exposed to the prevailing wind, the influence of wind should not be ignored.

VGS on façade

Choice of VGS

The choice of the type of vertical greenery system to be used on the façade influences the potential of fire spread. The different systems use different types and different amounts of materials. In general, the green façade systems use less materials than the LWS and therefore have lower risk as they contain much less fuel load. Of course the material choice is of great influence on the fuel load as well (see 'Materials used in VGS').

Ground based systems are not dependent on an irrigation system to stay healthy as they can use the groundwater. Therefore there is less risks of the system failing, which would pose a greater risk due to lower moisture content and increased dead and dry plants. Furthermore the LWS create an air cavity where the chinmey effect can happen, which is less of an issue with the green façades. Depending on the needs and the budget of a project a certain VGS can be demanded.

Lastly the vertical forests are a rather different type of system and need special attention when used.

How does the system cover the façade?

It is very important how the systems cover the façades. If there are vegetation free zones, fire spread can be prevented or mitigated. A completely covered façade has the potential for more fire spread than when strips or patterns are used. More research into what the exact working distances are needs to be done, but still, keeping a certain distance, will always help slow down the fire spread as opposed to a continuous application.

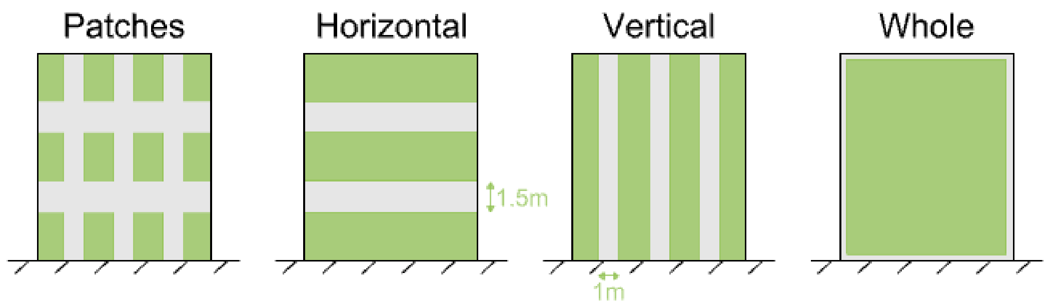


Figure 3.22: Different ways of covering the façade with VGS (own work)

Above transparent part

When the system is applied above a façade opening, there is a risk that a window-ejected fire plume sets the system aflame. Effectively spreading an inside fire onto the façade with risk of the fire traveling upwards on the building. If there is sufficient distance from the system to the opening, there is significantly less risk of this happening. Sources state that staying at least 1m above an opening, prevents flashover from the window to the system (Bachmeier, 2020; EFB, 2022; Martin, 2021).

Below transparent part

If the system is placed below a transparant part, there is a chance that if the system is aflame, the flames can spread into the building. It depends on the fuel load of the system and the plants how strong the flames are in if they are sufficient to break the glass. More testing needs to be done to determine how far below a window the system needs to be applied to prevent this from happening in different systems and with different plants. But keeping a distance will always help in decreasing the fire spread.

Beside transparent part

Having the system to the side of transparent parts also provides a risk. Since flames mostly spread upward, the distance can be closer than in vertical directions. There is not a consensus in literature what a proper distance is. One source had a drawing where 20 cm was enough (Bachmeier, 2020), another stated 40 cm (Martin, 2021) and again another stated 50 cm (EFB, 2022). Further testing is desired to get a better understanding thereof. Again even though the exact distance is not clear, keeping a distance always helps in decreasing the possibility of fire spread.

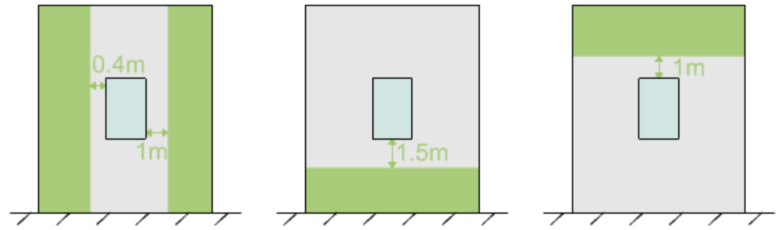


Figure 3.23: VGS next to transparent parts (own work)

Other than keeping a distance from transparent parts, using protrusions around transparent parts can also mitigate the possibility of fire spread.

Figure 3.24: Example of VGS in patches (EFB, 2022)

Figure 3.25: Protrusions around transparent parts (Own work)

How applied to the façade

If the system is placed on top of a façade, the façade can work as a barrier from the rear structure from the system. If the system is integrated in the façade and effectively works as the cladding, it is situated directly on top of the insulation material. This together with the air cavity can pose as a risk for fire spread through the façade. When the system is applied at a distance from the façade, for example on a balustrade of a balcony or gallery, there is less chance of the system and the façade igniting eachother in case of a fire. With enough distance, the chimney effect will be less severe as well.

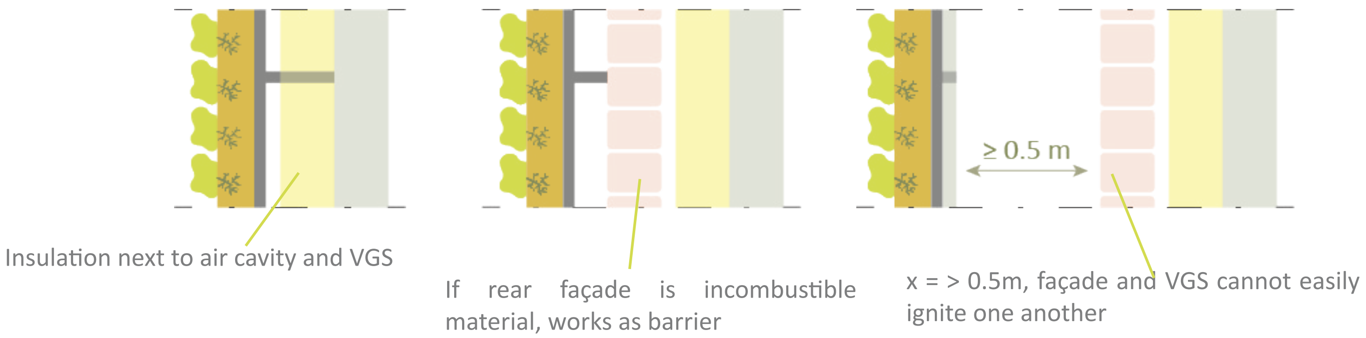


Figure 3.26: Integration in façade has influence on fire risk properties (own work)

Is there a clear fire trajectory to escape route

If the VGS is located in such a way that if set aflame it has a clear trajectory to an escape route, this poses as a high risk. With this it needs to be specifically taken into account if it would cause people to be 'locked off'. If an escape route is threatened but people can still escape in a different direction, the risk is much less then when this is not the case. It can also be considered to place a barrier between the system and the escape route to prevent flames from attacking fleeing people.

Figure 3.27: Different effects on the posibility of escape in case of fire (own work)

Applied above escape route

When the system is applied above an escape route there is a risk of parts of the system and materials falling on evacuating people if the system is attacked by a fire. Especially if the support structure is made of aluminium, there is a risk of the system falling. A protrusion or roof above the escape route can work as a barrier to protect escaping people from falling debris or it can be considered the systems is not applied directly above an escape route.

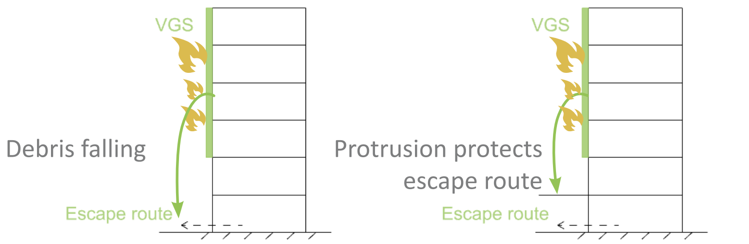


Figure 3.28: System above an escape route can drop burning debris on fleeying people (own work)

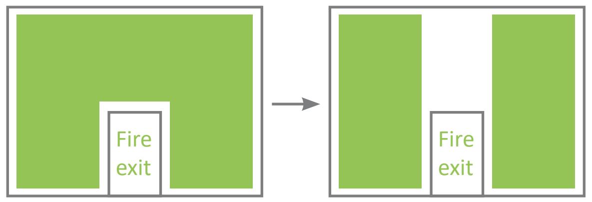


Figure 3.29: Consider not placing the VGS above an escape route (own work)

Easily accessible

If the system is easily accessible by people, there is a risk of being set aflame either by accident or on purpose. Human behaviour is a very common source of ignition for fires. This includes façade that are next to public streets, where there is also the risk of people setting something on fire next to the façade, such as 'sharing scooters' or garbage bins. Therefore it is often advised that garbage bins are not stored where public has access to it or when they threaten a façade if they are set aflame. It can also be considered to leave the first floor of the façade VGS free, to prevent easy ignition. Furthermore if the VGS is placed on or next a balcony or gallery people have easy access to it as well.

Product scale of façade

Material of cladding

The cladding is the outer most layer of the façade and has significant impact on fire spread, as this material is not covered or protected by anything else. Material choice determines whether or not the part of the façade helps in the fire spread. As mentioned in chapter 2.2, there is legislation in the Bbl which require a certain fire class of the materials used at certain heights of a building. When using incombustible material (class A1) there is much less risk of fire spread and ignition than when combustible materials are used.

Material of insulation

The insulation in a façade is often bordering the air cavity or placed directly behind the cladding material. In case of a fire penetration through the cladding, the insulation is the material that has significant impact on the fire spread possibilities. Specially if the insulation borders the air cavity, it has significant impact on the possibility of the chimney effect occurring, which causes rapid fire spread and enormous heat.

Seams

If there are seams in the cladding, the fire can spread more easily to the parts behind the cladding. If there are no seams, the cladding protects the rear materials. If the seams are smaller it is harder for the flames to spread through.

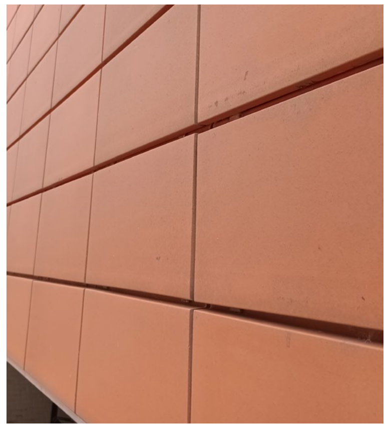


Figure 3.30: Ceramic tiles with seams, fire can spread behind the tiles through the seams (own work)

Connections

How the façade is connected is of importance for its integrity. Especially when aluminium connectors are used, these can melt in case of a strong fire due to the temperature, which would cause the cladding to fall off. Wooden connectors add to the fuel load of the system. It can be considered to use fire retardent wood, to prevent easy ignition.

Product scale of VGS

Materials used in VGS

The materials used in the VGS have great influence on the fire performance of the VGS. Here also the amount of material is of importance. Green Façades use less materials than LWS, so when using combustible materials, LWS have more fuel load. When using incombustible materials, there is much less risk of the VGS spreading a fire in a severe way.

Vegetation used

Different types of plants have different influence on the behaviour of a fire. Most importantly is to have a proper selection of plants for the climatic conditions of the specific location the plants are used, as this assures the plants to be healthy. Secondly certain attributes to plants influence the fuel load of a plant. It is best to avoid plants with oils or resins and woody plants. Also there is a difference between evergreens and perennials as the later changes with the seasons, and therefor influences the fire safety differently in different seasons.

Automatic irrigation and density

If the VGS is not ground based, but the plants are rooted in a substrate, the system needs to be irrigated. An automatic system is much more reliable than when the plants are watered manually. It is very important to keep the systems at a proper moisture content, both for plant health and fire retention properties. If the system is wet, the moist works as a heat sink, slowing down possible ignition and fire spread. With small fire sources it can even prevent ignition all together. A denser system ensures a better water distribution throug the system with a smaller chance of small patches occuring. Also when using different plants the conditions can be specifically tailored to the different plants in a dense setting, which would be harder to control in a less dense setting.

Additional equipment

Lighting can be placed in the system, which is usually applied to make the system more visible. Adding lighting in or near a VGS can cause short circuit fire due to the irrigation necessary. Also the heat from lighting can dry out the plants. If the lighting is relatively far from the system, it has minimal risk, since it will not contribute in drying out the plants and will not set the VGS on fire in case of a short circuit. If the lights are close to the system, it has the potential of drying out the façade. If the lights are in the system, it can easily set aflame the system in case of a short circuit, so this is highly unrecommended.

3.5.2 Overview of parameters that have influence but are not used in the tool

Since in fire safety there are an incredibly large amount of aspects that have influence on the risk, there are also parameters found that do have influence but are not incorporated in the tool. This was done to keep the tool relatively simple and clear. When designing these parameters should still be considered when making decisions.

Climate

Since the current thesis focusses on the Netherlands, only this climate is taken into account in the development of the tool. But in different climates the problems associated with VGS are different. In a more tropical, humid climate, where the vegetation is usually flourishing year round, risks of the plants dying is less likely to occur (Personal communication; Emily Pearson). So when designing, the local climate should be taken into account.

Distance to fire station

How quick fire fighters can be present at the scene is of great importance to make sure the fire can be under control. Therefore the distance to the fire station, has influence on the consequences in case of a fire.

Equipment available at the fire station

The specific equipment of the fire station that serves the area the building is located in, has influence on how well the fire brigade can extinguish and control the fire. For example if the fire station has access to fire boats, buildings located next to bodies of water (which are accessible by these boats) pose less risk than if the fire brigade does not have fire boats. Here it is also good to check what fire trucks are available and how high they can reach. If the fire station has (multiple) trucks which can reach greater heights than standard, than the risks for higher buildings becomes lower.

Proximity of surrounding buildings and other façades

In a more dense demographic, the chance of fire spread is higher. Also if there is greenery or other combustible objects surrounding the building, this influences the chance of fire spread and ignition of the system. Since there are many different situations possible for this, it is not taken into account in the tool. The exact situation of the building does influence the risk. Where a free standing building has much lower risk of fire spread than a building situated closely with other buildings in a compact matter.

If the building is a heritage building

In case of a heritage building, there is a bigger loss in case of a fire than in a building that is not a heritage building. For the tool this is not taken into account, as it is expected that when architects deal with a heritage building, extra care for fire safety will be taken regardless. The current thesis would advise to always consult with fire safety experts in case of a heritage building. The same holds up for buildings which houses priceless objects, such as museums.

Function directly behind the façade

The function directly behind the façade where the VGS is located influences its risks when the fire spreads to the inside. If for example the building is a residential building but the façade is located in front of a storage area, than the risks are significantly less than if the façade is in front of a sleeping area.

Openable windows

The parameter that is taken into account is whether or not the system is applied next to a transparent part in the façade. There is no distinction made between openable and permanently closed transparent parts in the façade. Openable windows do have more risk, since the glass will always protect a little bit, but an opanble window, when open, is literally a hole in the wall through wich a fire can spread freely.

Structure of the building

The building structure of the building influences its resistance against collapse during a fire. Concrete buildings are stronger than light wooden buildings or buildings of steel (steel can lose it's strength in case of high temperatures).

Complexity of building map

A straightforward building shape is easier for people to make their way through. Complex building layouts can cause disorientation and can prevent quick escape of the users in case of a fire.

If people present are familiar with the building

When people are unfamiliar with a building, the escape can be slower or more chaotic. It is also known that people tend to take the route they used to get into the building, regardless of whether this is the quickest escape. If the building function makes that there are more people in a building which can be unfamiliar with the routing, this can pose as a higher risk. This is usually the case in large public buildings such as hospitals, museums or conference buildings.

If people present are in a way inebriated

If alcohol is served people can be less focused and have a reduced self-reliance. For example in clubs the chance of many people present which are in a way inebriated is higher, and the risks for casualties during a fire is higher.

3.5.3 Overview of additional safety measures which are not used in the tool

On top of the decisions which can be made with the design parameters, additional measures can be taken. These are not taken into account into the tool because they are either not directly related to the façade design or are measures on management and use scale. The following list is nog exhaustive:

Smoke detectors inside the building: Installing smoke detectors throughout the building can provide early detection of fires, enabling prompt evacuation and intervention. Since VGS would be outside of the building, this would only work once the fire is already inside the building.

Sprinkler system inside the building: A sprinkler system can suppress fires effectively, preventing the fire from spreading and reducing the intensity of flames. A sprinkler system inside the building will not have immidiate effect on a fire in the VGS on the façade, but it will help with the posibility of people escaping if the fire reaches inside the building.

Fire mode in irrigation system: Implementing a fire mode in the irrigation system triggers extra water release upon detecting flames, helping to suppress the fire effectively.

Protecting the escape route with additional covering: Strengthening escape routes with additional covering can safeguard them from fire damage, ensuring safe evacuation.

Using fire protective glazing for openings: Incorporating fire protective glazing in openings can prevent flashover and limit the spread of fire through these areas.

Inspection of proper installation: Mandating proper installation inspections, which can be required in permits or by insurers, ensures that the VGS is installed correctly and complies with safety standards.

Active monitoring of the system: Regular monitoring of the VGS ensures early detection of any issues or potential fire hazards, allowing for timely intervention. Monitoring can focus on whether the irrigation system is working properly or measures the moisture content of the substrate. It can also be expanded that the sensors can also detect if there is a fire and be connected to the Fire Management Systems (FMS) of a building.

Maintenance contract in place: Establishing a maintenance contract, which can be required by insurers and permits, ensures that the VGS is regularly maintained and functioning optimally to mitigate fire risks effectively.

Further considerations in regulations:
If in future, people can be prohibitid from watering their gardens during dry periods, which is for example already the case in parts of Spain. VGS systems need to have an exhemption for this, as they would poze a fire hazard if not watered properly. It should be made aware with the autorities, that VGS should get an exhemption if such rules were ever to be installed in the Netherlands.

3.6 Weighing of the parameters

3.6.1 Development of risk factors and thresholds

In the previous chapter the relevant parameters are explained. Not every parameter is of the same significance as another. For use in the decision-making framework, risk factors were assigned to the different parameters and their design options. These factors were partly based on two tools developed by DGMR and Nieman:

• Guidelines for assessing safe façades. ('Handreiking beoordeling veilige gevels'; DGMR, 2019)
• Assurance protocol. ('Borgingsprotocol'; Nieman & DGMR, 2022)

Using the scenarios from the 'What-if' methodology and the input from the previously mentioned tools, the risk factors were determined for the relevant parameters which influence the risk level in terms of fire safety. Also the thresholds for which values would come out as 'green', 'orange' or 'red' risk levels (where green is low risk and red is high risk) were determined this way. This was party done in collaboration with Bo Valkenburg, with whom many decisions were made together.

The overall result of the comprehensive tool was determined by the results on the different scales. The resutls of the different scales woul be either Green, Orange or Red. Where Green has a value of 0, Orange of 1 and Red of 2. The total result was based on the outcome of the addition of these values.

A fine tuning of the risk factors and thresholds was done by filling in the case-studies mentioned in chapter 3.4 and in appendix B. Certain, relative clear, situations were pre-determined to be 'green', 'orange' or 'red'. So when filled into the tool, the respective results should be given. If that was not the case, the risk factors were analysed and it was determined what needed to be changed. Some of the filled in case-studies in the tool can be found in appendix C.

Lastly the tool was evaluated by using a set of different cases, not used in the development of the tool. These cases are existing designs with vertical greenery systems. For these cases it was determined beforehand what the expected outcome would be, by analysing the design on the relevant design aspects. Then the cases were filled into the tool and the results were compared with the expectations to see if the tool worked as intended.

3.6.2 Evaluation of risk factors and thresholds

4 cases were used for the evaluation. These cases were chosen due to the differentiation in the building function, building height and type of VGS used.

- Row house Delft with Sempergreen LWS (green; but side note, what if neighbouring dwelling does the same? then orange)
- University building Echo Delft (green, easy go)
- Eneco Rotterdam (orange)
- Stadskantoor Venlo (red).

Row house Delft
LWS based on mineral wool. Sempergreen. Used as cladding system. System has evergreens and automatic irrigation and monitoring system . Surrounds transparent parts, but does not transpass multiple fire compartments. Low building, easy accessible by fire fighters. But side note, what if neighbouring dwelling does the same. If using mirror symmetry here, the façade does stretch over multiple fire compartments with openening. So then a fire break should be added to keep it safe. Expected outcome in tool: green. Echo;

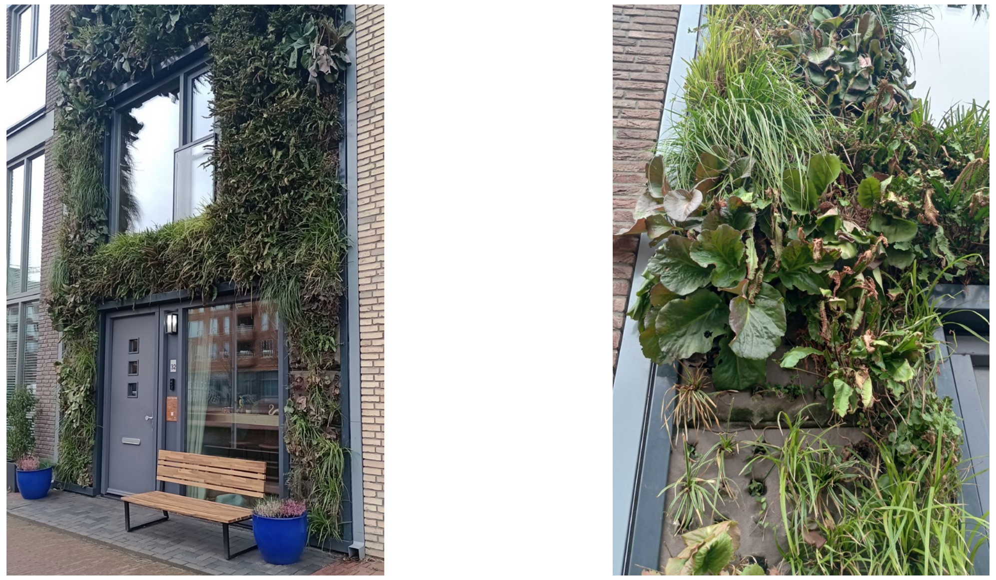


Figure 3.31: Row house. Sempergreen wall. Photos taken 23rd of January. Evergreens (Own work)

University building Echo Delft
Indirect green façade on steel cables. In front of transparent parts, but enough distance and little fuel load. Cannot eassily spread to the inside. Also not accessible by people, but accessible by fire fighters. Does not threaten escape. Expected outcome in tool: green.

Figure 3.32: Education building. Indirect GF. Photos taken 17th January. No evergreens. (Own work)

Figure 3.33: Education building. Indirect GF. Photo taken 29th April. No evergreens. (Own work)

Eneco Rotterdam

Felt pocket system on high rise office building, but only up to 15 meters is covered with VGS, so easily accessible for fire fighters. System is integrated in the façade with combustible material and stretches over multiple fire compartments and surrounds windows. The windows are surrounded by deep window sills. There is a blockade above the escape route so protects from falling debris in case of fire. Expected outcome in tool: orange.

Figure 3.34: Eneco office building in Rottermda (Eneco, n.d.)

Stadskantoor Venlo

Plastic planter boxes on combustible façade with air cavity on medium rise office building. Stretches over whole façade, below 2.5 meter and above 20 meter and stretches over multiple fire compartments. Aluminium cavity bariers, which melt away in case of fire. Excpected outcome: red

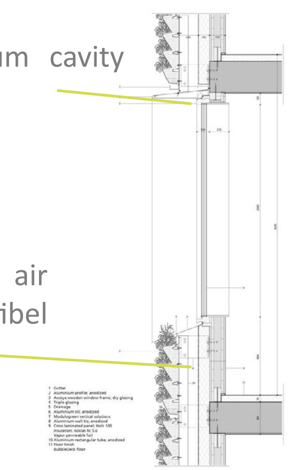


Figure 3.35: Stadskantoor Venlo (Mostert De Winter bv, n.d.)

Figure 3.36: Detail drawing façade Stadskantoor Venlo (Kraaijvanger Architects, 2018)

Some solutions for Stadskantoor Venlo which would make the design saver:

- Use steel for cavity barrierot aluminium but steel;
- Place gypsum board or cement fibre board between plastic and isovlas and air cavity;
- Use mineral wool instead of isovlas;
- Do not cover the whole façade: use some vegetation free zones or proper fire breaks;
- Do not use plastic pots;
- Do not place the LWS above 20 meters and below 2.5 meters.

Figure 3.37: Screenshot of the validation case-studies filled in the tool (Own work)

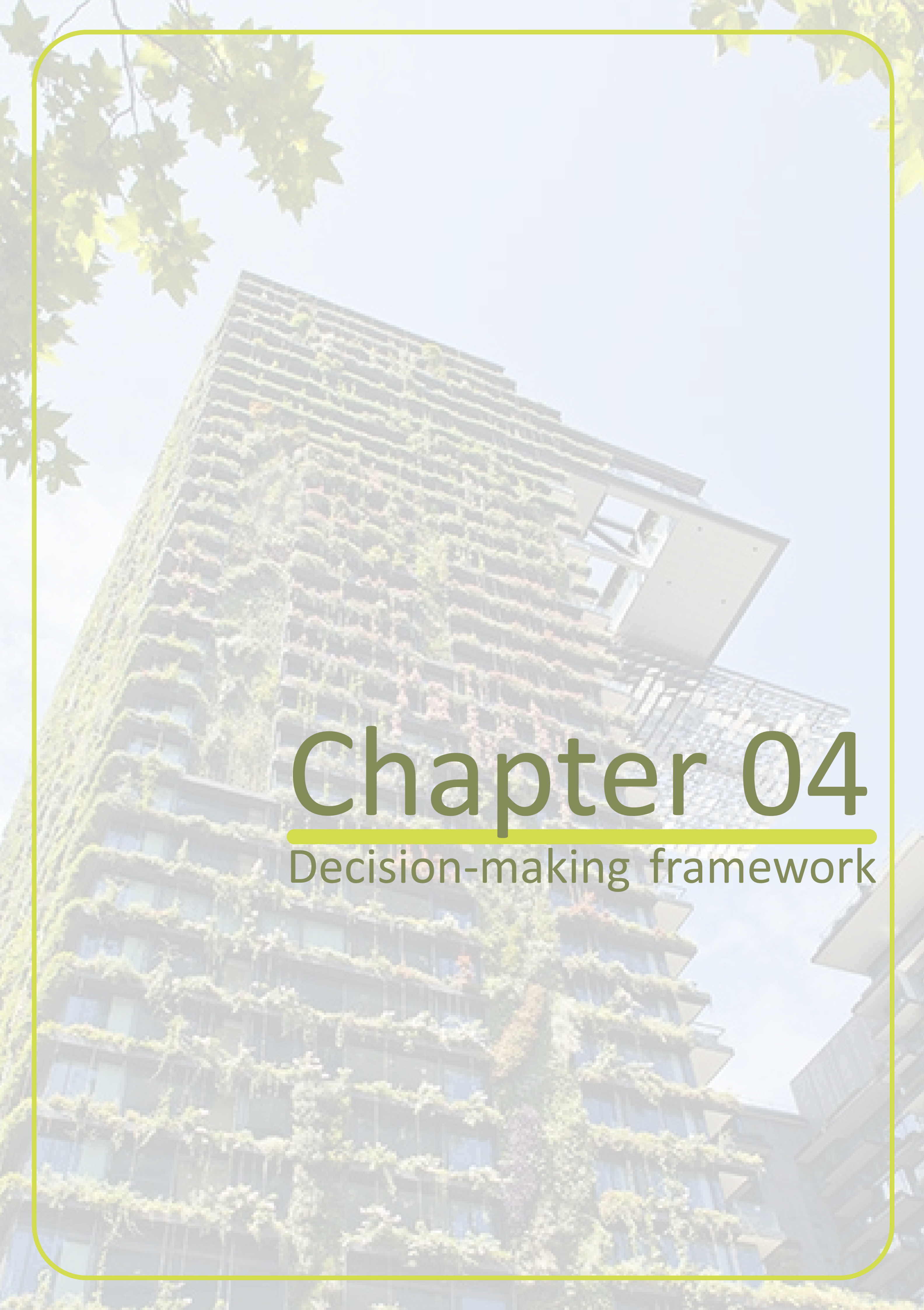
Result

As shown in the screenshot from the tool, the expected outcomes were achieved. This concludes that the tool works acceptably and the risk factors and thresholds are determined properly.

3.7 Key aspects

In this chapter the relevant parameters which influence the fire safety of a design with VGS are identified. This was done using a 'What-If' risk analysis and using a number of case-studies. It was shown that looking at the case-studies helped in determining which aspects have influence on the fire safety of a building design. These parameters were used in the development of the decision-making framework and tools. It is important when designing with VGS to understand all the parameters and their influence on the fire safety of a design. Using the case-studies the risk factors and thresholds were determined and this was evaluated to be valued properly.

It is found that there are many relatively simple design options which can be used to design safe designs with vertical greenery systems. These findings will be used in the decision-making framework and will be advised to designers to make use of when designing with VGS.



Chapter 04

Decision-making framework

4.1 Introduction to framework

To communicate the found parameters and design options, a decision-making framework is developed. For this the following definition is followed:

"Decision-making models are frameworks designed to help you analyse possible solutions to a problem so that you can make the best possible decision." (Range, n.d.)

The goal the developed framework is that users are able to analyse the different design options in terms of the fire safety performance and use this information to make informed decisions in the design process.

As a part of the decision-making framework a tool is developed in excel. In the tool relevant information is provided on fire safety of vertical greenery systems. The relevant parameters are shown and explained. As it was found that for designers, a simple and quick tool would be most useful, two versions were developed: a comprehensive tool and a quick and simple tool. Furthermore an infographic was designed to give a quick overview of best practices to achieve fire safe VGS designs.

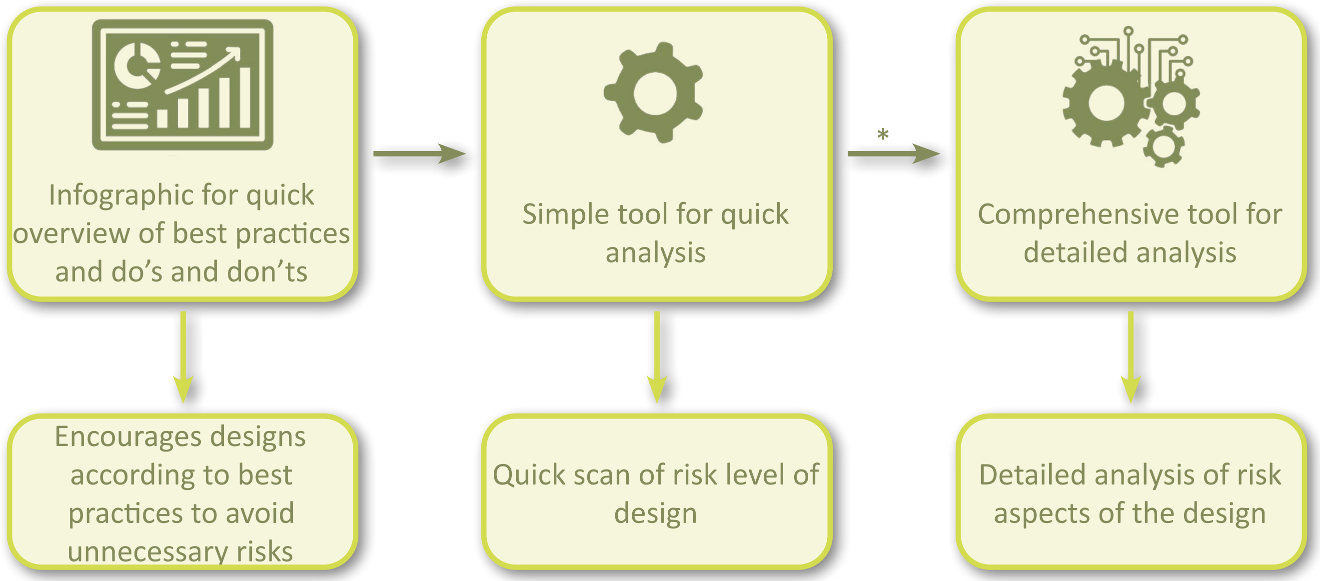


Figure 4.1: Components of the framework and their output (Own work)

*Not always necessary

In Figure 4.2 it is shown how the framework with the infographic and the risk tools works. The infographic gives a quick overview which can help guide the initial decisions in a design and helps in showing which aspects to think about in terms of fire safety of VGS. The simple tool can be filled in to get a quick response about the risk level of a design, specifically useful for identifying easy go or no-go situations. When necessary the comprehensive tool needs to be consulted, because more in depth questions on the design would be necessary to determine the risk level. The outcome of the comprehensive tool can still be a clear go or no-go, but it can also be determined that the design is necessary to be evaluated by a fire safety expert to determine if it is acceptable.

The way these tools help in the decision-making process is that it helps in understanding the influence of choosing different options in a design. By comparing several design solutions and the way they influence the fire safety level, an informed decision can be made. The information found in the tool can also be used in guiding a discussion between different parties during a design process. The knowledge gained from the tool can be used as arguments to convince other parties involved of the importance of certain decisions due to the fire safety. The tools and infographic can also be used by plan assessors to check if a proposed design is safe. If the authorised supervision needs to assess if a design is acceptable, they can use the information from the infographic and the tools to determine if the design is safe or not.

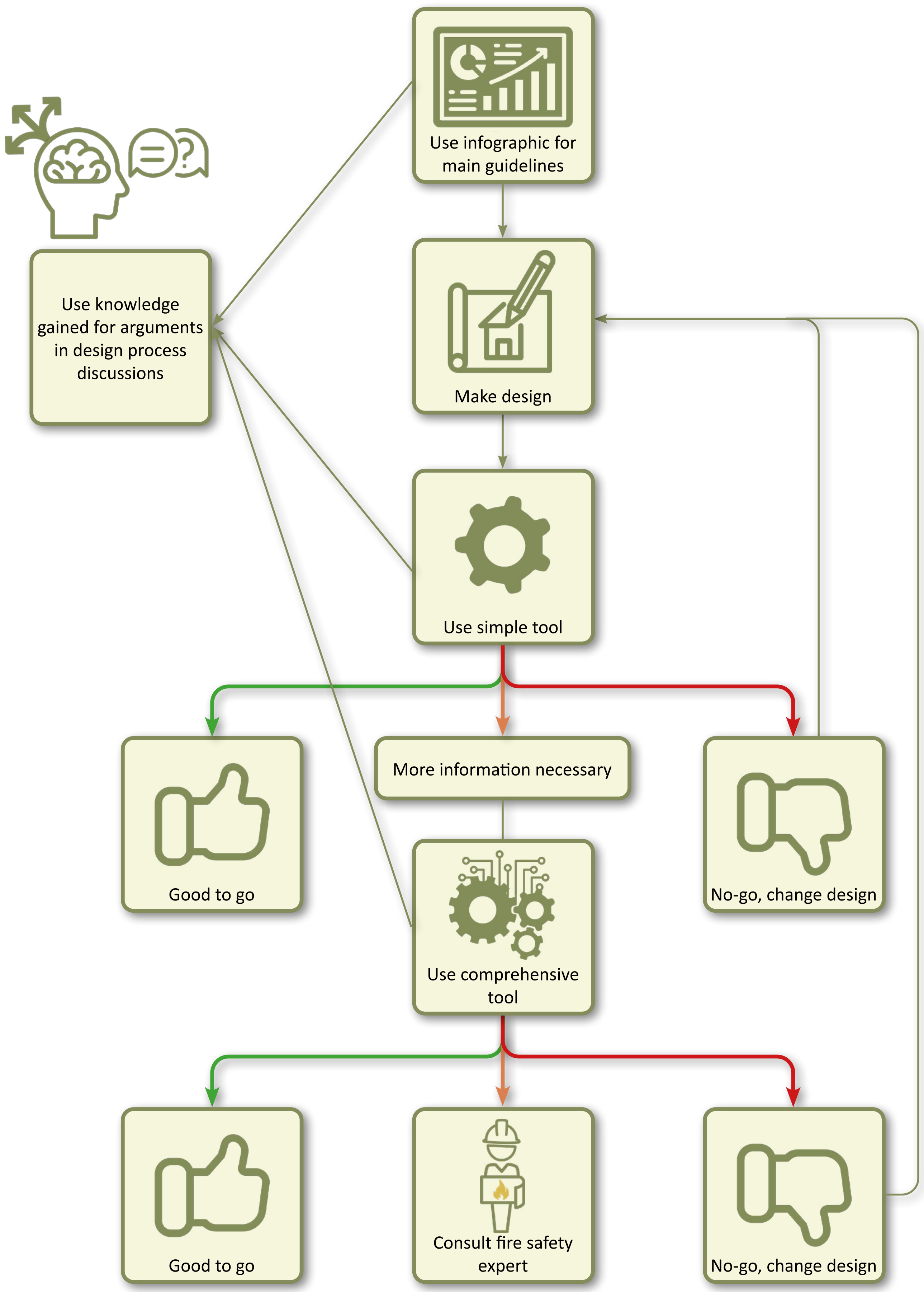


Figure 4.2: Decision-making framework with infographic, a simple tool and a comprehensive tool (Own work)

4.2 Infographic

The first step for the decision-making is to get a basic understanding of the fire safety aspects of VGS. For this an infographic is made, to give a quick overview for designers. The infographic includes best practice advise, do's and don'ts and some application suggestions. Also the main aspects to consider per VGS are noted, since the different systems have different aspects which are most relevant to focus on in terms of fire safety. The goal is that by following the suggestions in the infographic, simple and safe designs can be developed. By following the advise and suggestions from the infographic, designs will fall in the 'Good to go' category of the risk tools If a designer would want to do something more complex, that is still possible, but then they should be aware that a fire safety consultant will be necessary to assess the specific design.

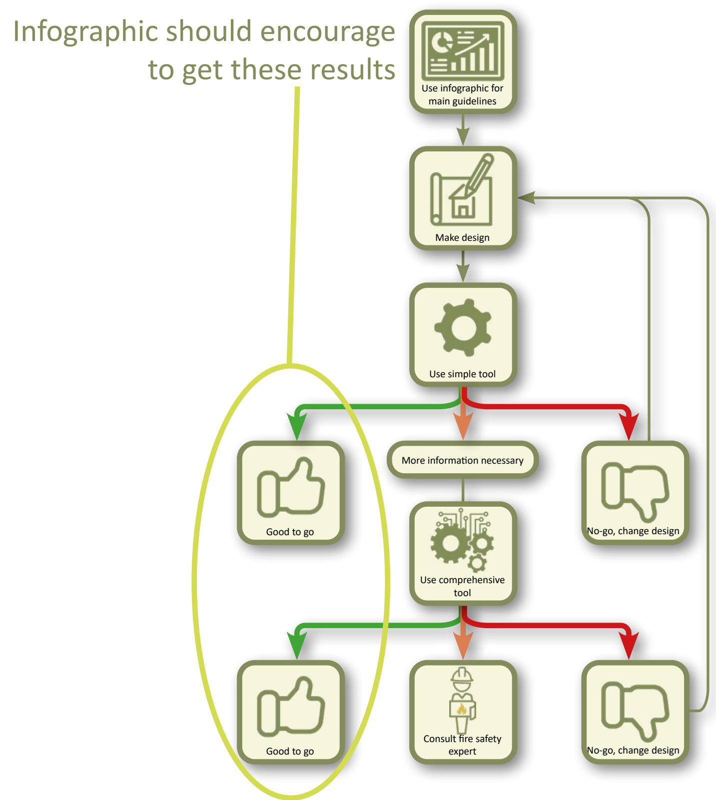


Figure 4.3: Infographic to encourage designs that result in "Good to go" situations (Own work)

How to read the infographic

Figure 4.4 shows the infographic and explains what can be found on the infographic. First a small introduction to the infographic is given which explains what the infographic is for. The relevant design choices are listed, so designers get a quick overview of which most important aspects will have influence on the fire safety of a design. Some extra measures are suggested which can be used to lower the risk of a design. An overview of do's and don'ts is listed.

Furthermore a quick overview is shown of what the differences between different VGS are in terms of fire safety. This way it can be determined early on whether or not a designer wants to make use of a certain system or not.

The infographic can be found in appendix D.

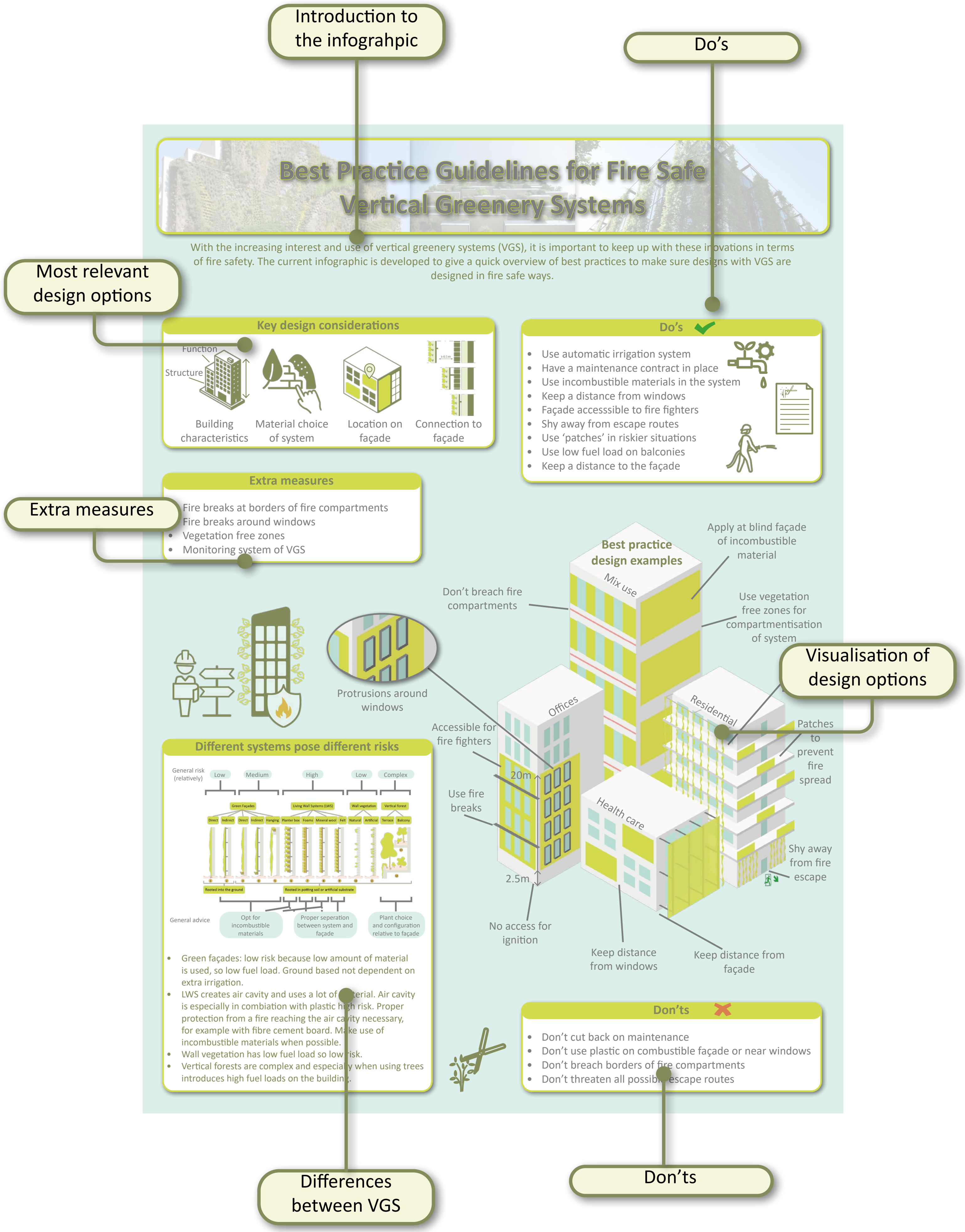


Figure 4.4: How to read the inforgrapic (Own work)

4.3 How to use the tool(s) in design process

Who the tool is for

The target group of the tool are architects, façade designers, sustainability experts and manufacturers. The designers and decision-makers involved in designing the façade of a building. Specifically people that would make decisions regarding the use of vertical green in the façade but that are not very familiar with fire safety engineering. The goal is to empower these individuals to identify low-risk design options, make informed decisions during the design process, recognize situations where consultation with a fire safety engineer is necessary and understand when a design is a no-go.

When to use the tool

The tool has a different function in different phases of the design. It will have most significant effect when consulted in the early stages of the design process. In later stages it works more as an evaluation or control tool.

- Beginning of Design: The infographic provides insight into the factors influencing fire safety, aiding in the development of holistic designs that prioritize fire safety from the outset.
- Sketch Design Phase: Design options can be filled in and compared, assisting in making informed decisions and identifying possible problems.
- Later Design Phases: The tool can be used to evaluate if design changes have affected the risk level and ensure that the desired level of safety is maintained.

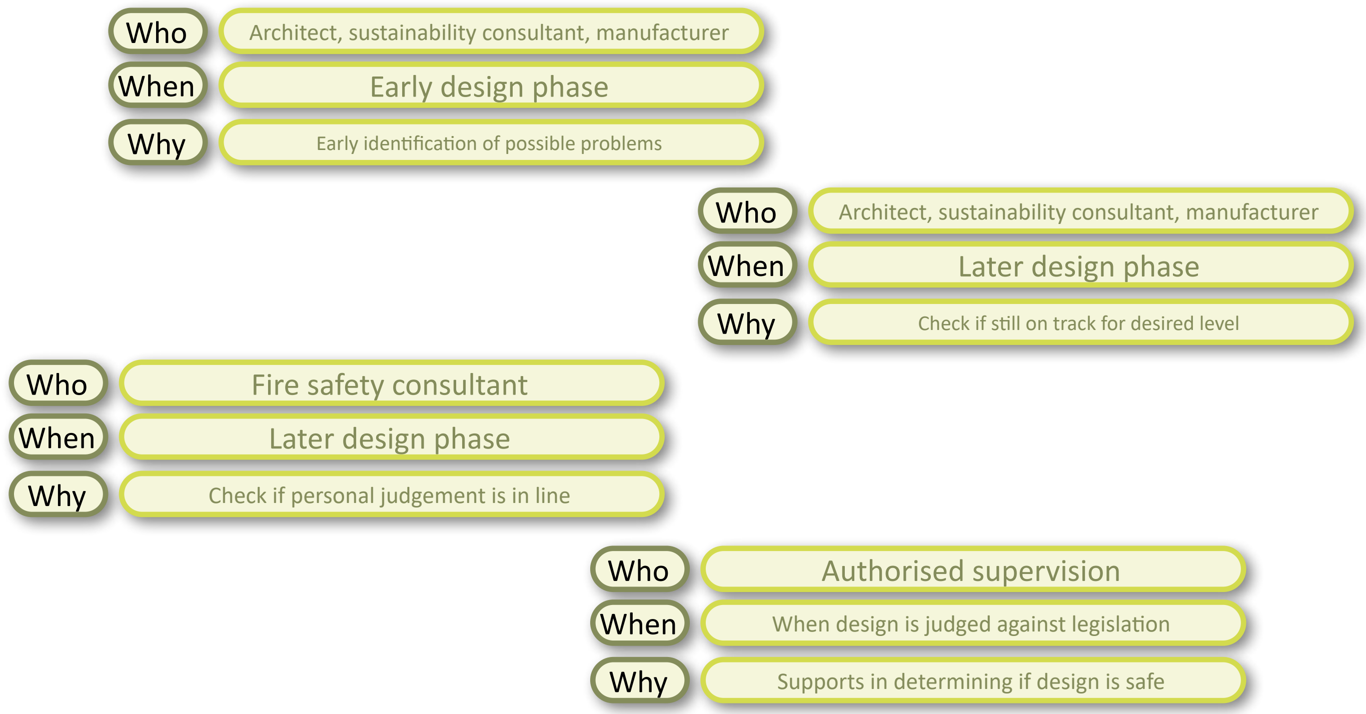


Figure 4.5: Users of the tool (Own work)

The output of the tool

The tool aims to raise awareness of fire safety risks associated with designing buildings with VGS. It provides insight into factors influencing fire safety risks, highlights decisions with significant impacts on risk, and suggests measures to lower risks. The tool's output can facilitate discussions during the design process and ensure that decisions consider fire safety implications. Multiple design options can be compared simultaneously. This can help in comparing what the influence is of different decisions in the design and can help in deciding what the best solution would be for the proposed situation.

The tool's output can be used to facilitate discussions among project stakeholders, including architects, designers, engineers, and clients. Tool provides leverage to bring to the discussion during a design process. With the information from the tool, others can be convinced of the importance and how with relative ease fire safety can be implemented in the design, and not be treated as the constricting, often subsequently addressed, problem it is viewed as.

Things not included in the tool

The tool does not value the risks against any gains which can be made. One only takes a risk because there is some advantage to be gained. When the gains are higher, one might accept a higher risk level. When making decisions in the design process, the advantages which are desired from the VGS should also be taken into account.

Disclaimer: The tool does not guarantees a 'fire safe' solution and one should not follow it's outcomes blindly. Fire safety always needs to be assessed in its unique situation. Always discuss with professionals and look critically at the specific situation.

Evaluation tool with multi-stake holder analysis

The tools has been tested by several parties, namely:

- Two architects;
- A LWS manufacturer;
- A landscape architect;
- A project developer.

It was found that the tools were rather informative for the different parties and they found that the tools could help in getting a better understanding and raising awareness on the topic. The tool seemed mostly of use for the architects and the manufacturer and they stated they would use such a tool in practice. The landscape architect still found it a interesting tool but had difficulty in filling in all the different questions, which would make the result of the tool less reliable. Also the project developer stated such a tool would not be relevant for them.

Unfortunately the tool could not be tested with authorised supervision. It is believed, also from correspondence with the different parties, that the authorised supervision could also benefit from using the tool when assessing building plans for permits. This could be checked in future research by testing the tool on this party as well.

Overall, the Excel tool serves as a practical and accessible resource for architects, designers, and other stakeholders involved in the design process. It empowers them to proactively address fire safety concerns, make informed decisions, and create designs that prioritize fire safety.

4.4 Tool guide

After learning the information from the infographic, a design with VGS can be made. When a first sketch or idea for a design with VGS is made, the simple tool can be used to determine if the direction of the design is going the right way in terms of fire safety. With the simple tool, the ease situations which are safe can be identified. Also when a proposal for a design is really not a good idea, this can already be identified. It can also be determined that more information is necessary, then the comprehensive tool can be addressed.

Simple tool

The first page of the excel tool is an introduction page which is shown in Figure 4.7. Here an explanation of who tool is for, when to use the tool, what the output of the tool is and what is not included in the tool is given. It is also explained how to fill in and read the tool.

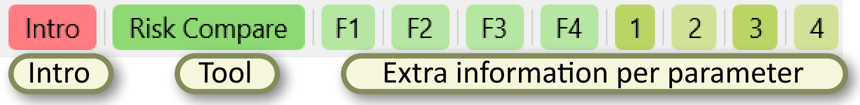


Figure 4.6: Pages in the tool. From left to right: Introduction page, fill in page, extra information pages for the different parameters (Own work)

The second page, called 'Risk Compare', is where the analysis can be filled in. Here a short description of the project can be given and an image showing the analysed design can be placed, as shown in Figure 4.8.

On the left the questions related to the parameters relevant to the fire risk are stated which can be answered with the drop down menus, as shown in Figure 4.9. The options for an answer are organised by risk factor, with the lowest risk always as the top option and the highest risk the bottom option. Within the brackets the risk factor is stated. The higher the number, the higher the risk. This is also visualised with color and a graph on the right side.

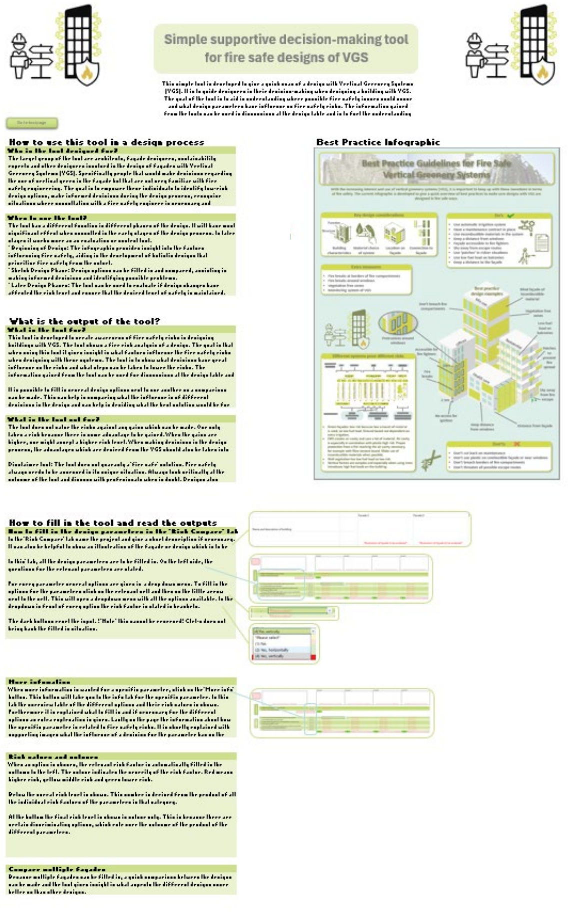


Figure 4.7: Introduction page of the simple tool (Own work)

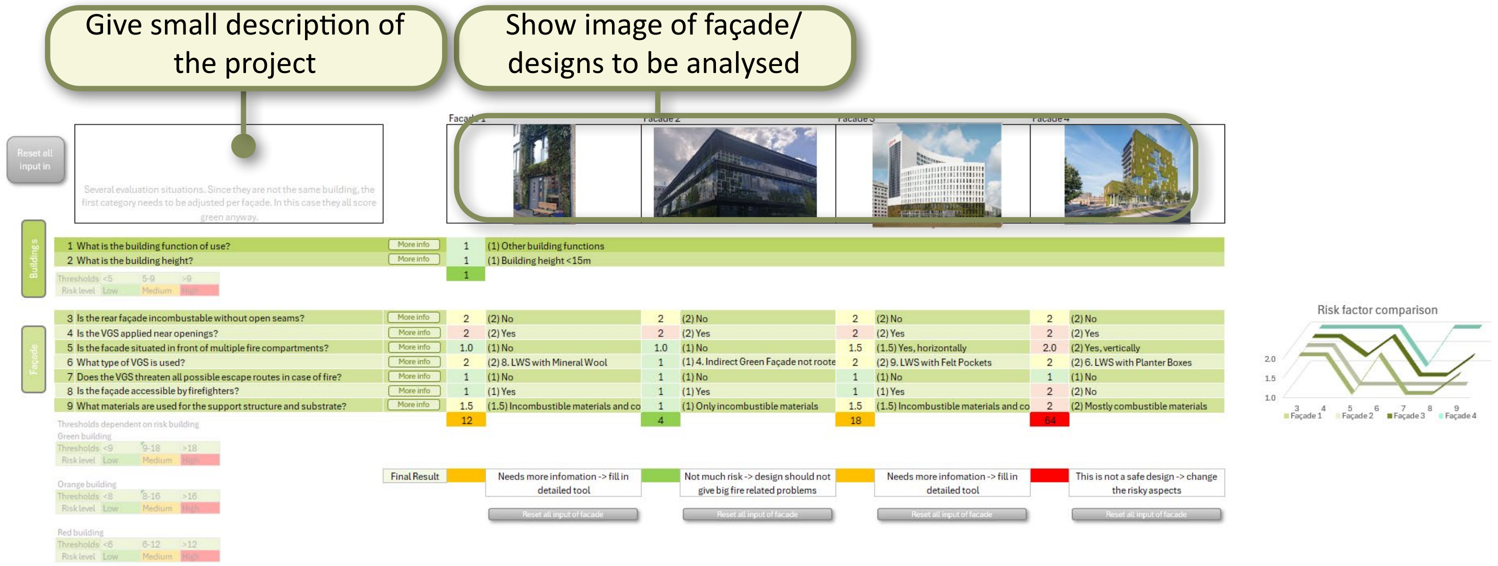


Figure 4.8: Simple tool fill in page explanation; 1 (Own work)

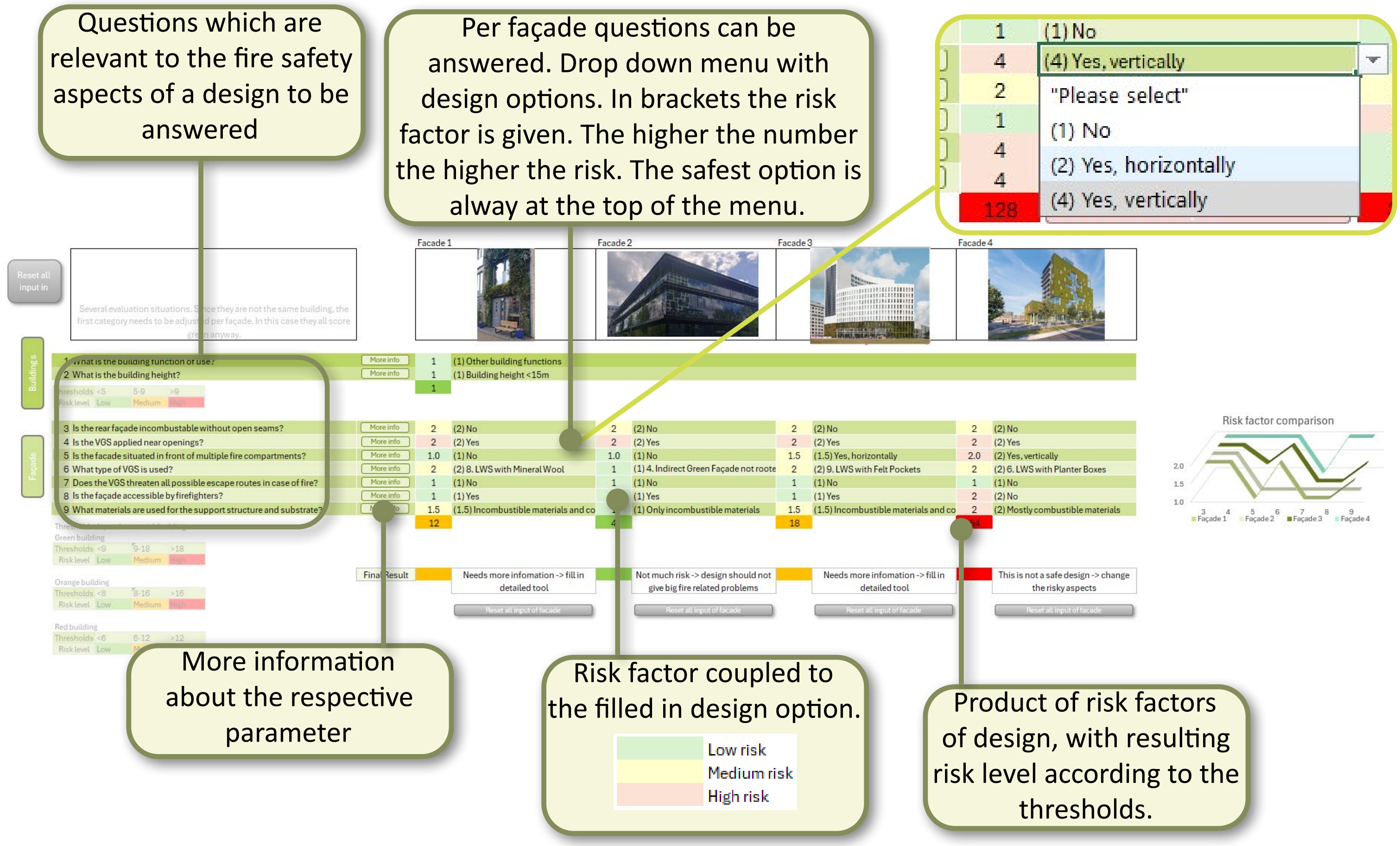


Figure 4.9: Simple tool fill in page explanation; 2 (Own work)

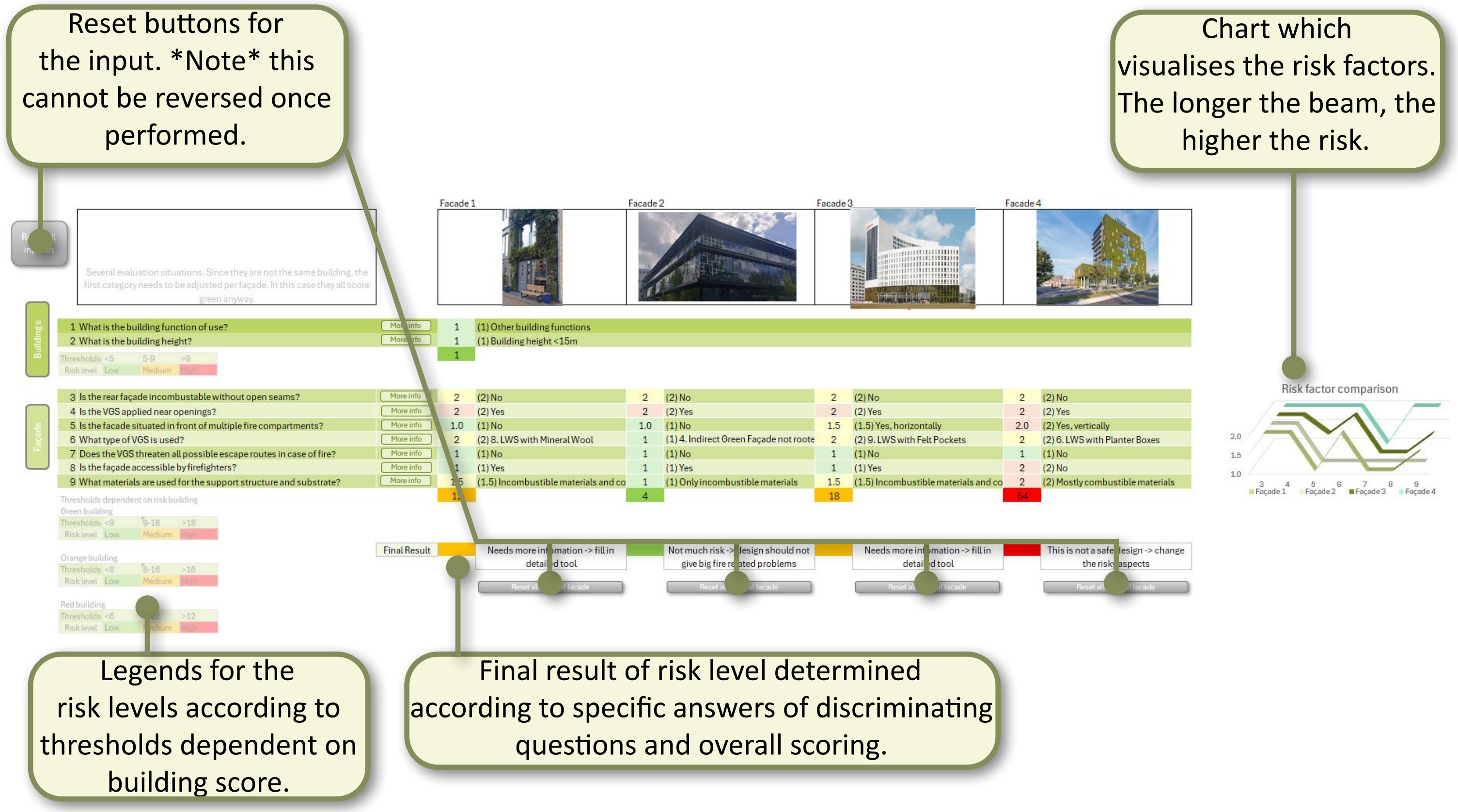


Figure 4.10: Simple tool fill in page explanation; 3 (Own work)

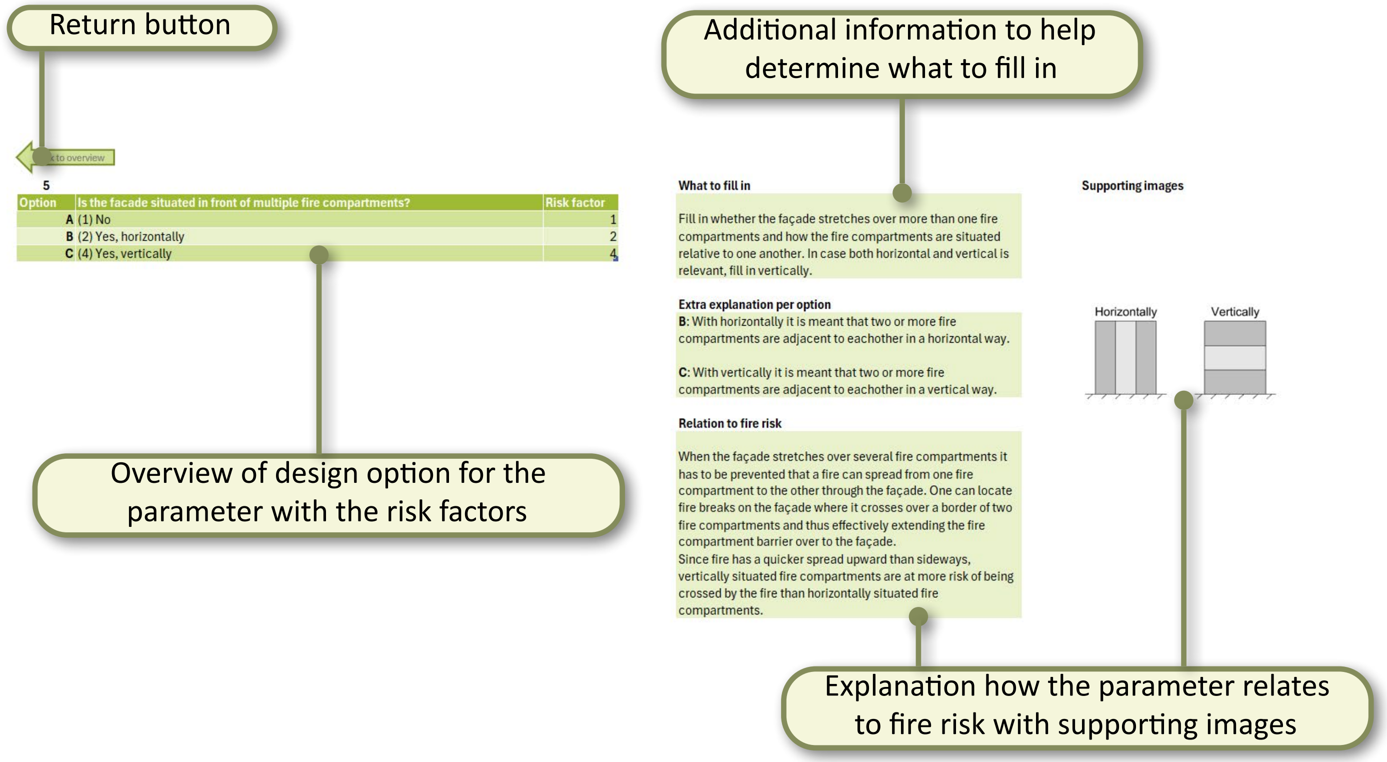


Figure 4.11: More information page explanation (Own work)

If more information about a specific parameter is desired, the button with 'More info' can be clicked. This will take the user to a new tab, where the relevant information on that topic can be found, as shown in Figure 5.10. Every information page is build-up in the same way. On the left a table with the question and the different design options are shown. Here the risk factors related to the different options can be found. On the right additional information is provided. First an explanation on what to fill in is given and in some cases extra information is provided for specific design options, as not all options are always very straight forward. Here also the relation to fire safety is explained which is supported by visualisations. Lastly, in the top left corner, a return button to the 'Risk Compare' tab can be found.

The result filling in the tool is a conclusion on the risk level of the design. This can be that the design is considered safe, Green, and is good to go. If no significant changes are made to the design, there shouldn't be any fire safety issues later on in the process. It can also be that the design is considered a no-go, Red. In this case the design should be changed as it is not a good idea to use the VGS in that design. It can be that the no-go occurs due to a combination of risky choices or because the overall risk is too high. It can also be that the result is indefinite, Orange. In this case more information is needed to determine the safety level. The comprehensive tool should be addressed to determine the risk level.

Furthermore the output of the tool is that the user gets insight in which aspects are critical in the design and may need to be changed if the desired risk level is not achieved. The tool communicates the relevant parameters to take into consideration when designing VGS in a fire safe way.

Detailed tool

The comprehensive detailed tool is a much more extensive tool than the simple tool. Instead of just 9 parameter questions, 28 questions are to be answered. This way a much more detailed analysis of the design can be performed. Most parts of the tool are still the same apart from being more extensive. The introduction page is still where an explanation of how the tool functions can be found. The 'More information' tabs of the different parameters are build-up the same way as in the Simple tool. The 'Risk Compare' tab still works the same in terms of answering the parameter questions, there is still a button for more info and there are buttons to reset the input.

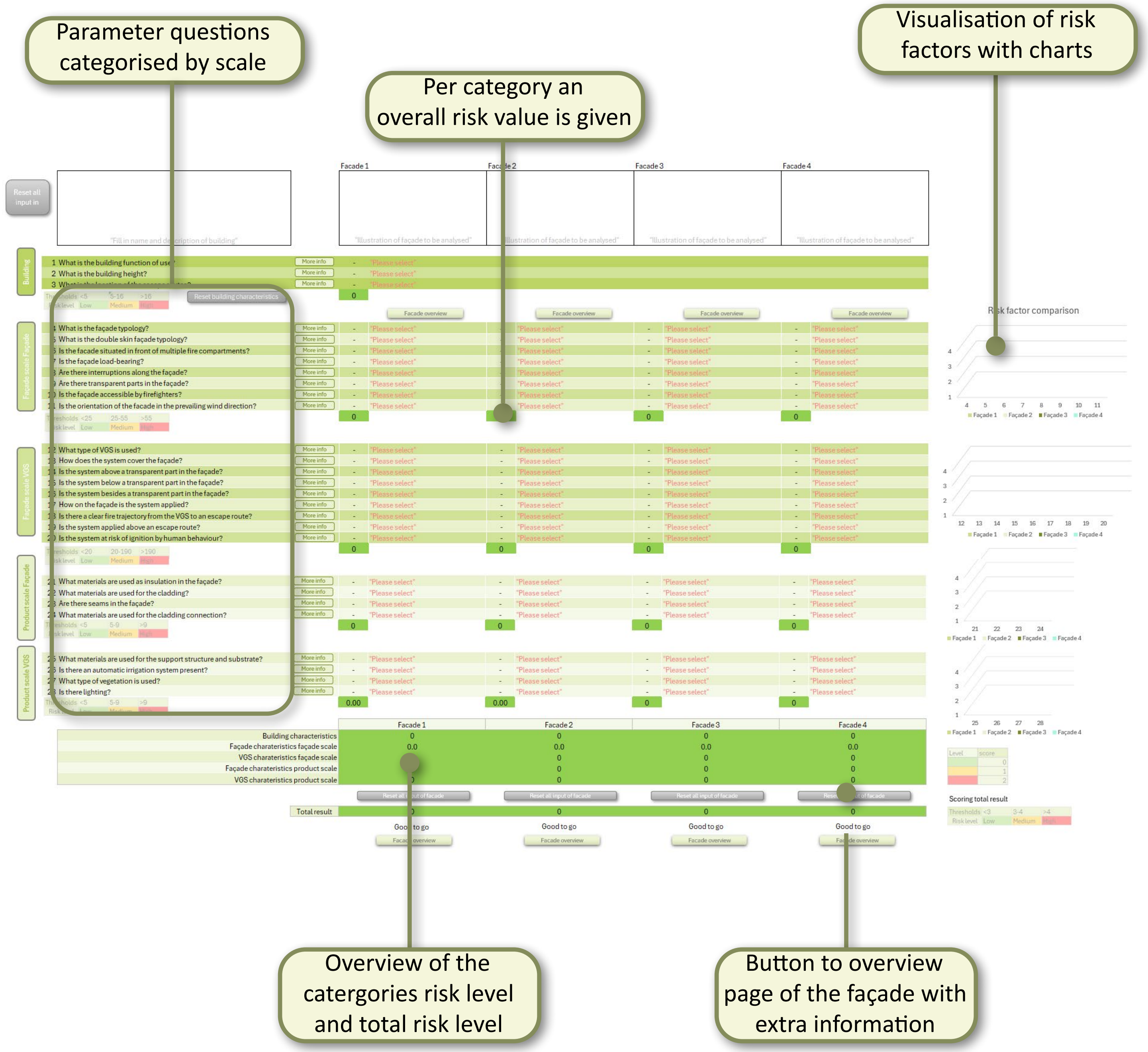


Figure 4.12: Differences comprehensive tool and simple tool 'Risk Overview' tab (Own work)

The questions are categorised by scale and also a risk level per scale can be found, so that it can be identified where exactly in the design a problem occurs. Several façades can be filled in so that they can be compared. When clicking the 'Façade overview' button, the user is taken to a tab which goes into more depth on the respective façade that is filled in on the 'Risk Compare' tab. Here an extra explanation on the relation to fire safety and, when relevant, design advices are given depending on the filled in options. The tabs are called F1-F4, to the respective number of the façade filled in and analysed.

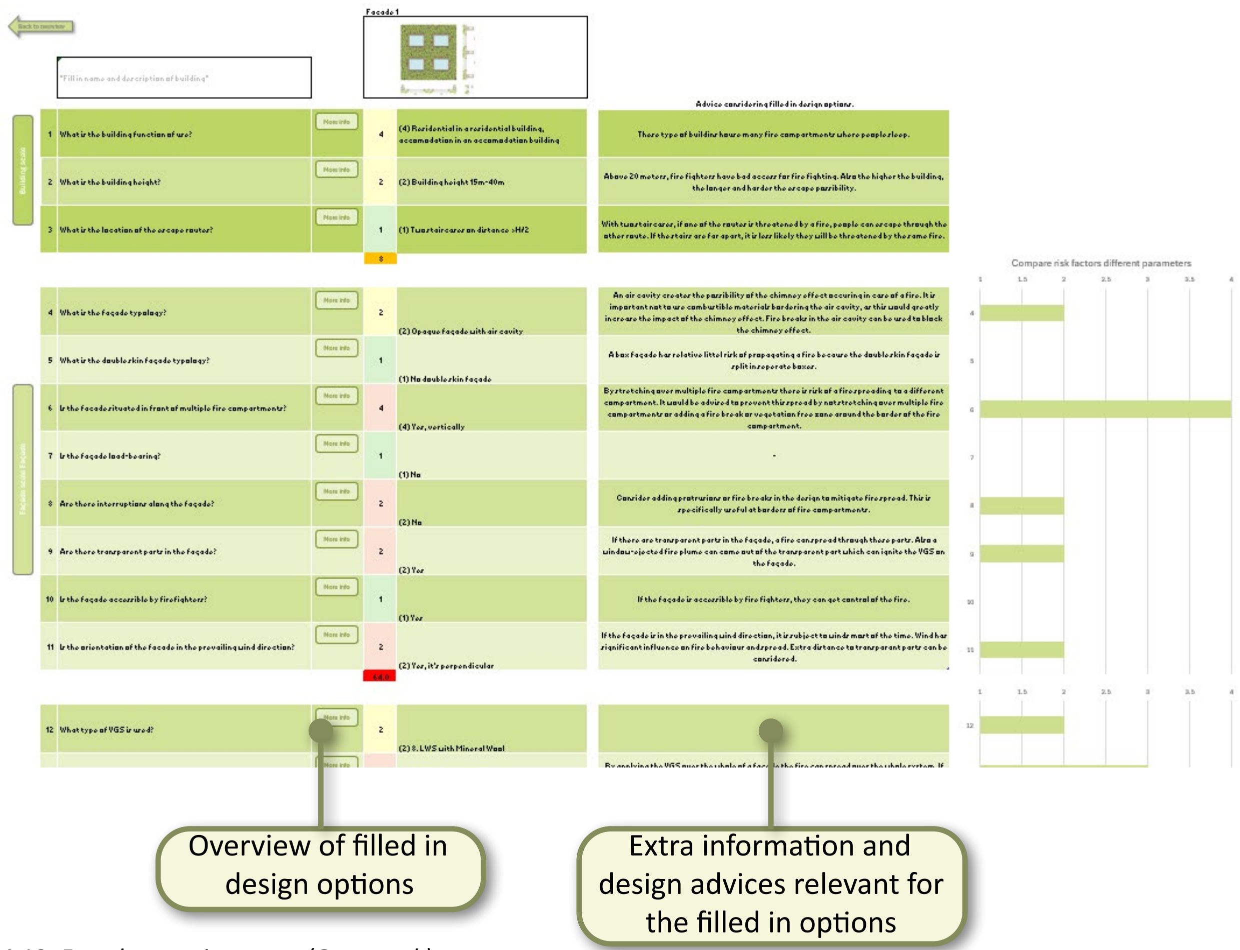


Figure 4.13: Façade overview page (Own work)

The result of the risk levels of the different categories can be compared. It must be noted that a red result, does not automatically makes the whole design red. It is the combination of the results that is important. But it does help identify where improvements can be made in the design. The overall score is the sum of the results of the different scales. Where green scores 0, orange a 1 and red a 2.

	Facade 1	Facade 2	Facade 3	Facade 4
Building characteristics	8	8	8	8
Façade charateristics façade scale	64.0	24.0	64.0	48.0
VGS charateristics façade scale	72	24	6	12
Façade charateristics product scale	24	3	6	6
VGS charateristics product scale	3.75	3.75	3.75	1.875
	Reset all input of facade	Reset all input of facade	Reset all input of facade	Reset all input of facade
Total result	6	2	4	3
	NO-GO, change the design	Good to go	Consult fire safety expert or change design	Consult fire safety expert or change design
	Facade overview	Facade overview	Facade overview	Facade overview

Level	score
	0
	1
	2

Scoring total result

Thresholds	<3	3-4	>4
Risk level	Low	Medium	High

Figure 4.14: Different results from the tool (Own work)

The result of filling in this tool is a conclusion on the risk level of the design. This can be that the design is considered safe, Green, and is good to go. If no significant changes are made to the design, there shouldn't be any fire safety issues later on in the process. It can also be that the design is considered a no-go, Red. In this case the design should be changed as it is not a good idea to use the VGS in that design. It can also be that the result is in between, Orange. In this case the design is not considered easily safe or unsafe. In this case a fire safety expert should be consulted. They can then determine with a more precise analysis is the design is acceptable or how an acceptable design can be achieved.

Furthermore the output of the tool is that the user gets insight in which aspects are critical in the design and may need to be changed if the desired risk level is not achieved. The tool communicates the relevant parameters to take into consideration when designing VGS in a fire safe way.

4.5 Quick wins

When developing the tool and looking at the parameters and their risk influence, certain 'easy' situations were identified. When ending up in the 'green' zone in the simple tool, their is a very small risk and the greenery can most likely be implemented in a safe manner. To showcase how effective it is to go for the simple solutions (a.k.a the low hanging fruit) some parts of Delft and The Hague were taken and all the simple situations identified.

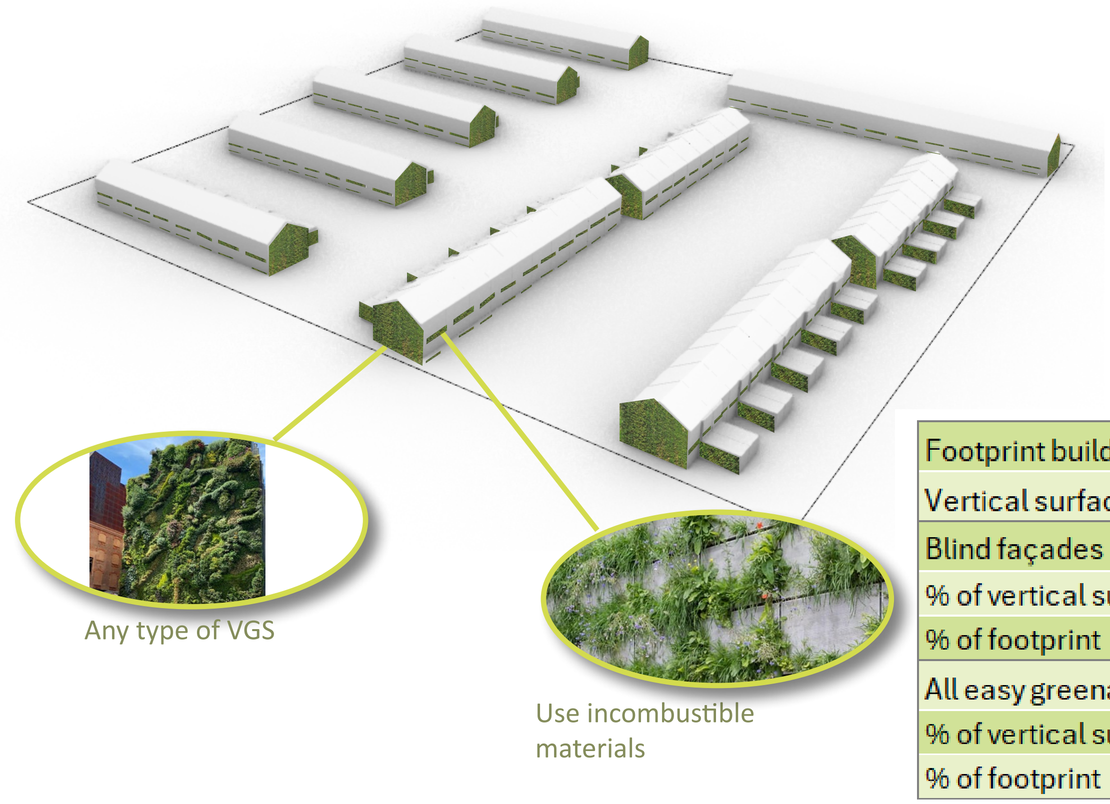
The areas are 150 by 150 m and represent different type of neighbourhoods. They were chosen because they showed great potential of 'easy' greening. The following three areas where studied:

- Row houses in a suburb of Delft;
- Medium high appartment flats in a suburb in Delft;
- Office high rise in The Hague.

The amount of m2 easily greenable in the area is identified. This is then compared to the amount of footprint these buildings take up and compared to the total amount of vertical surfaces of these buildings. It would have been prefered for the vertical surfaces to only take into account the opaque parts, since placing green in front of doors and windows is not always wanted, but this proved to be too difficult to perform in the time frame.

Row houses in a suburb of Delft

The blind brickstone façades in row houses can be easily greened with any type of VGS with minimal risk. Even if such a system would be set aflame, the spread would not get easily into the buildings and would not threaten any residents. In this case 15% of all vertical surfaces can be greened with minimal risk.



Footprint buildings	5720 m²
Vertical surfaces	8068 m²
Blind façades	1230 m²
% of vertical surfaces	15%
% of footprint	22%
All easy greenable	3034 m²
% of vertical surfaces	38%
% of footprint	53%

Figure 4.15: Quick wins in row houses in Delft (Own work; Greenroofs, n.d.; Vertical Meadow, n.d.)

Furthermore the closed parts of the façades where transparent parts are also present could be used for greening. Here the system should be build up of incombustible materials, as to not add too much fuel load to the façade. In case of a fire the fire would not easily reach into the building if the fuel load is kept low. Even then the escape possibilities are easy in this situation. In this case 38% of all vertical surfaces can be greened with minimal risk.

Medium high appartment flats in a suburb in Delft

Appartmentblocks which have a gallery access. They have a brickwork blind façade at the ends of the buildings, which can be easily greened without much problem. Also the balconies can be easily greened when using indirect GF with steel cables. Because of the low fuel load, this green would not be able to have the fire reach the inside of the building.

Footprint buildings	3693 m²
Vertical surfaces	8272 m²
Blind façades	822 m²
% of vertical surfaces	10%
% of footprint	22%
Easy greenable	1805 m²
% of vertical surfaces	22%
% of footprint	49%

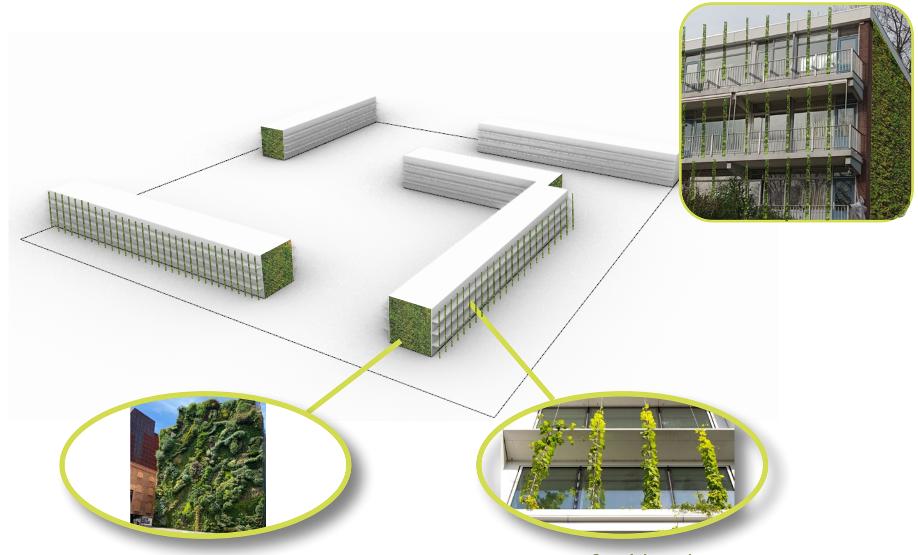
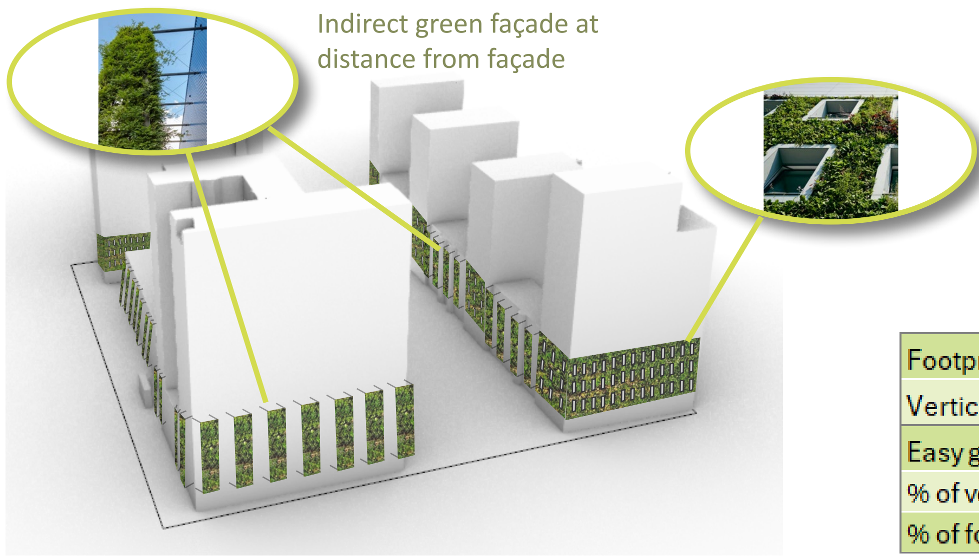


Figure 4.16: Quick wins in appartment buildings in Delft (Own work; Greenroofs, n.d.)

Office high rise in The Hague

High rise office buildings. Low risk function. If the VGS stays below 20 meters and doesn't start at street level, the following configurations are safe implementations of VGS. Some buildings have curtain walls, here indirect green façades at a distance from the façade in strips are quite safe. Other façades have brickwork with windows, here incombustible LWS with fire breaks around the windows are deemed safe.



Footprint buildings	11490 m²
Vertical surfaces	51200 m²
Easy greenable	5885 m²
% of vertical surfaces	12%
% of footprint	51%

Figure 4.17: Quick wins at high rise offices in The Hague (Own work; FuHH, 2022)

4.6 More complex design

The tool can guide in making a complex design safer. When the tool returns a high risk analysis of a design, the advice and information from the tool can be used to alter the design and reduce the risks. Here two examples of a design detail for using VGS in a relatively complex situation is given.

4.6.1 Indirect green façade

High risk design

A timber frame construction for a medium high residential building. The façade stretches in front of multiple fire compartments and consists of combustible materials (wood). The cladding will have to be class B, so the wooden cladding has to be fire treated. Still introducing vegetation with an indirect green façade in front of the façade effects the behaviour in case of a fire. When filled into the tool, this situation turns out red. Improvements can and should be made.

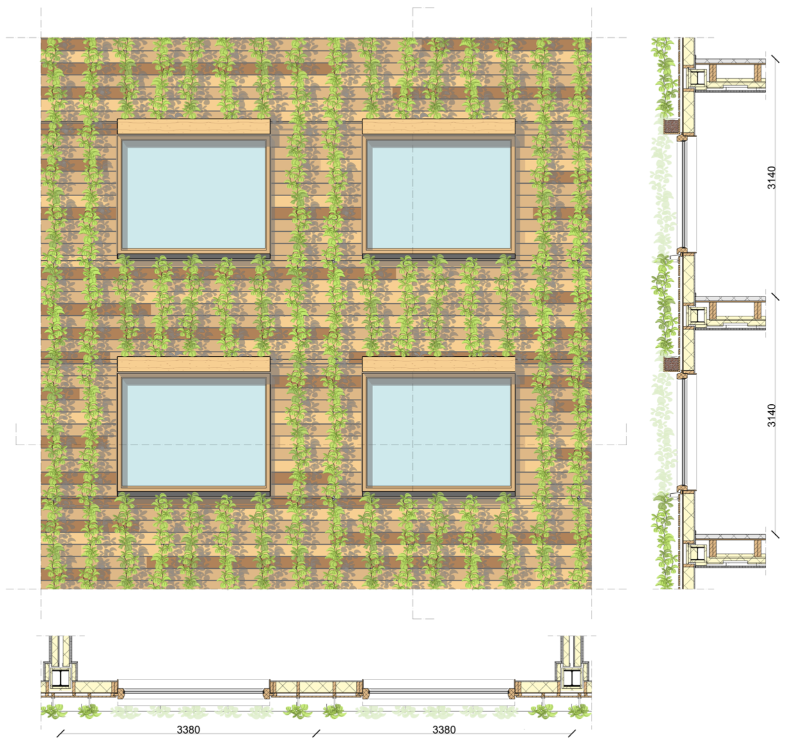
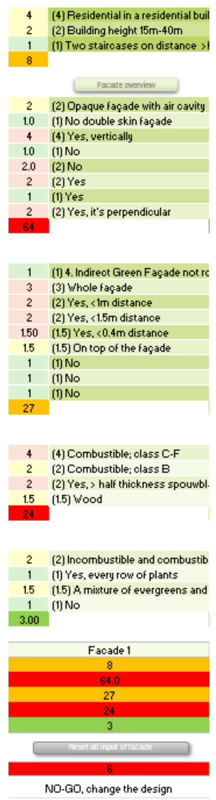


Figure 4.18: Higher risk façade view and sections with indirect green façade. Drawn 1:20 scaled to 1:100 (Own work)



4	(4) Residential in a residential buil
2	(2) Building height 15m-40m
1	(1) Two staircases on distance >I
8	
	Facade overview
2	(2) Opaque façade with air cavity
1.0	(1) No double skin façade
4	(4) Yes, vertically
1.0	(1) No
2.0	(2) No
2	(2) Yes
1	(1) Yes
2	(2) Yes, it's perpendicular
64	
1	(1) 4. Indirect Green Façade not ro
3	(3) Whole façade
2	(2) Yes, <1m distance
2	(2) Yes, <1.5m distance
1.50	(1.5) Yes, <0.4m distance
1.5	(1.5) On top of the façade
1	(1) No
1	(1) No
1	(1) No
27	
4	(4) Combustible; class C-F
2	(2) Combustible; class B
2	(2) Yes, > half thickness spouwbl.
1.5	(1.5) Wood
24	
2	(2) Incombustible and combustib
1	(1) Yes, every row of plants
1.5	(1.5) A mixture of evergreens and
1	(1) No
3.00	

Facade 1
8
64.0
27
24
3
Reset all input of facade
6
NO-GO, change the design

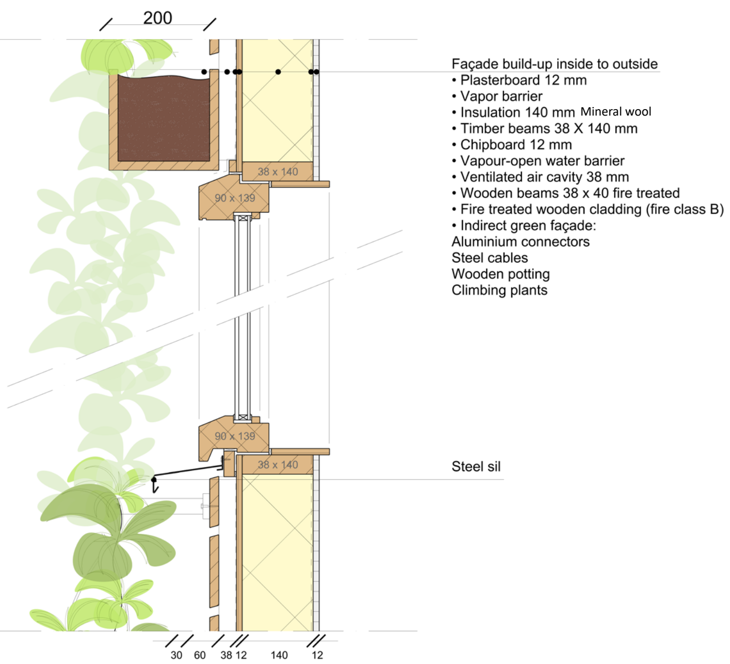
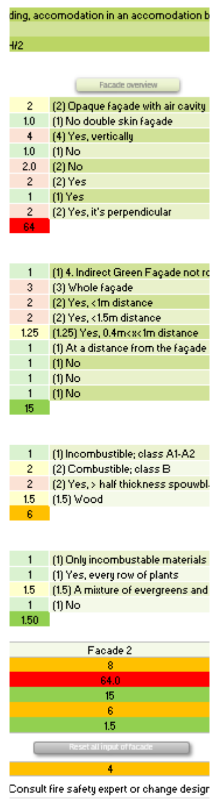


Figure 4.19: Higher risk façade detail with indirect green façade. Drawn 1:5 scaled to 1:15 (Own work)

Improved design

When placing the system at a distance from the façade the vegetation cannot easily contribute to fire spread into the building. Also protect the timber frame construction with a cement fibre board.

The orange result does not mean that it is not a safe design. But because it is a rather specific design (timber frame construction in a medium rise residential building) it would be adviced to check the design wiht a fire safety expert. But with the improvements made, the risks are already highly reduced compared to the initual situation.



	ding, accomodation in an accomodation b
	H/2
	Facade overview
2	(2) Opaque façade with air cavity
1.0	(1) No double skin façade
4	(4) Yes, vertically
1.0	(1) No
2.0	(2) No
2	(2) Yes
1	(1) Yes
2	(2) Yes, it's perpendicular
64	
1	(1) 4. Indirect Green Façade not ro
3	(3) Whole façade
2	(2) Yes, <1m distance
2	(2) Yes, <1.5m distance
1.25	(1.25) Yes, 0.4m<x<1m distance
1	(1) At a distance from the façade
1	(1) No
1	(1) No
1	(1) No
15	
1	(1) Incombustible; class A1-A2
2	(2) Combustible; class B
2	(2) Yes, > half thickness spouwbl.
1.5	(1.5) Wood
6	
1	(1) Only incombustable materials
1	(1) Yes, every row of plants
1.5	(1.5) A mixture of evergreens and
1	(1) No
1.50	

Facade 2
8
64.0
15
6
1.5
Reset all input of facade
4
Consult fire safety expert or change design

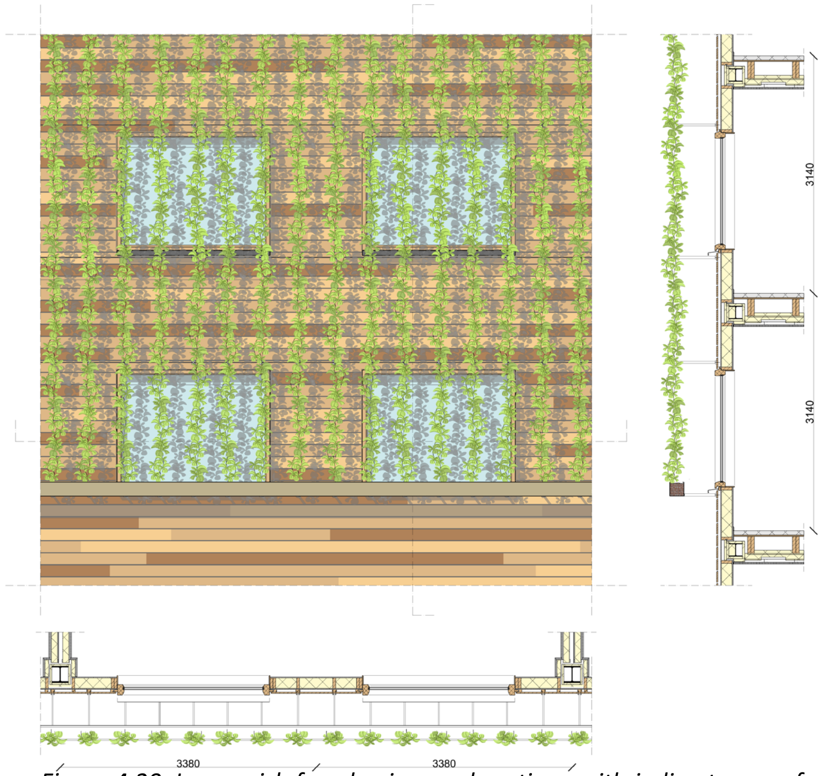


Figure 4.20: Lower risk façade view and sections with indirect green façade. Drawn 1:20 scaled to 1:100 (Own work)

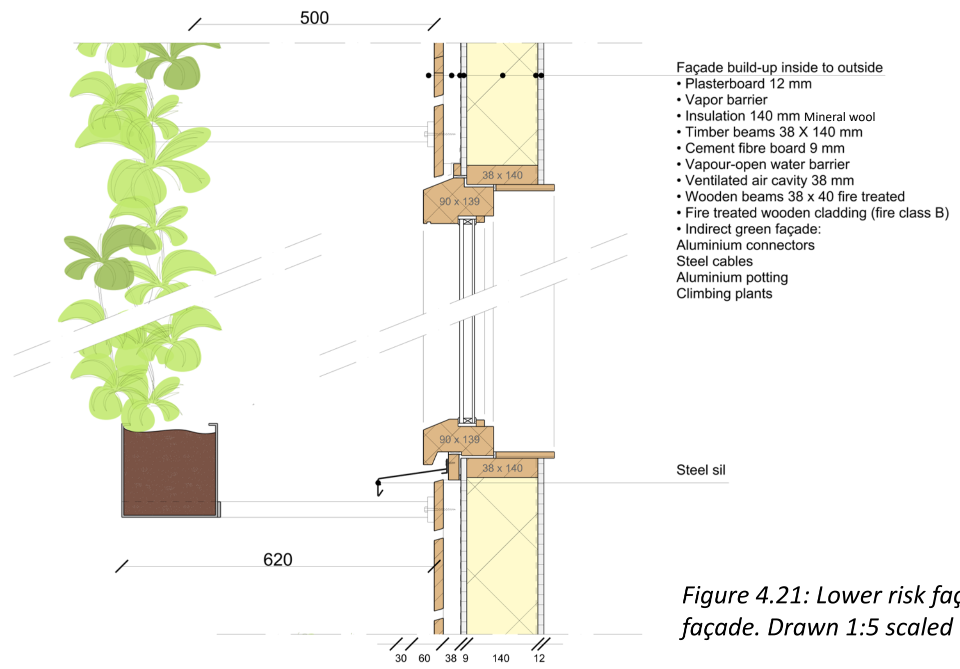


Figure 4.21: Lower risk façade detail with indirect green façade. Drawn 1:5 scaled to 1:15 (Own work)

4.6.2 LWS based on mineral wool

High risk design

Completely covering the façade with a LWS without any form of compartmentation is a high risk. In case of failure of the irrigation, a fire can easily spread over the façade and breach fire compartments. Also by using perennials, the façade would pose a fire risk during autumn and winter.

Improved design

By using strips or patches instead of covering the whole façade, a fire would spread less easily to different compartments in case of a fire. The wood used as cladding has to be treated and the timber frame construction can be protected with a cement fibre board. Also by introducing protruding fire breaks above and below the transparent parts or at the floor levels, flames can be kept contained.

Since the situation is rather complex (timber frame construction in a medium rise residential building) it would still be adviced to check the design wiht a fire safety expert. Therefore the orange result. But with the improvements made, the risks are already highly reduced compared to the initual situation.

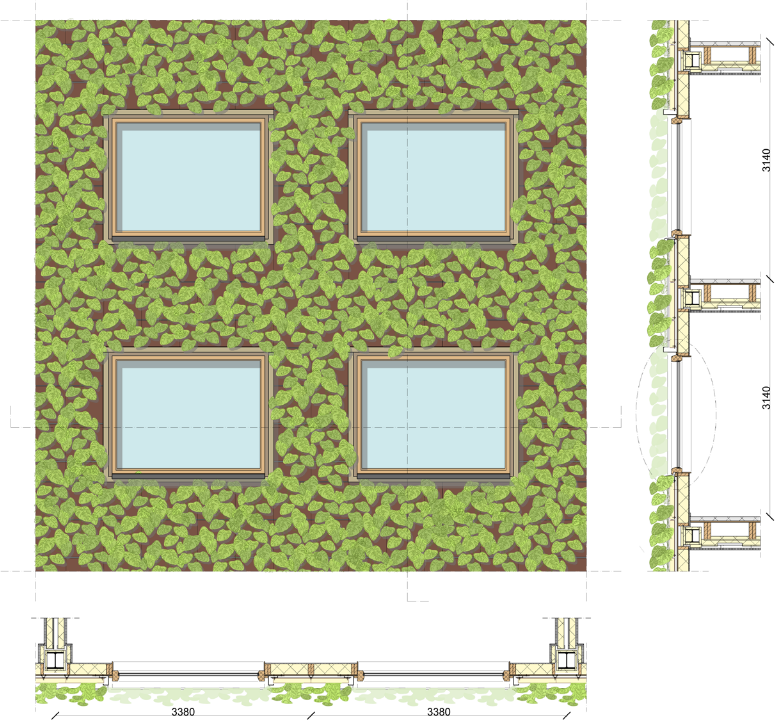


Figure 4.22: Higher risk façade view and sections with LWS. Drawn 1:20 scaled to 1:100 (Own work)

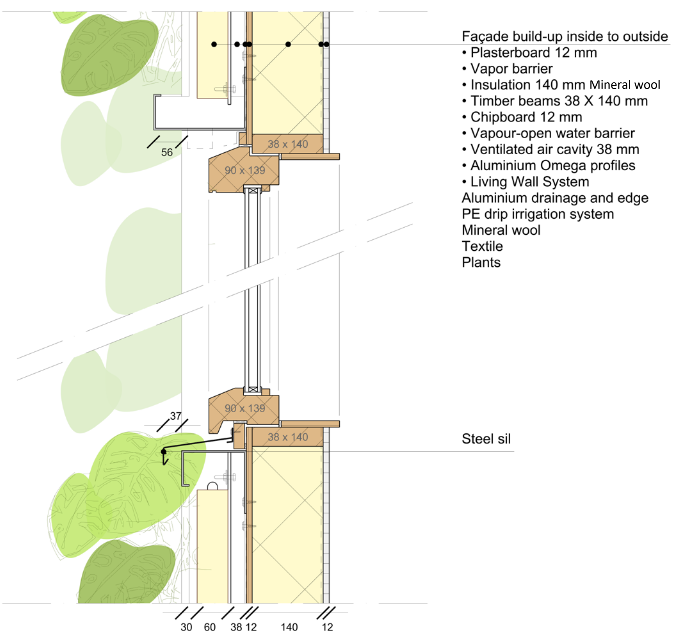


Figure 4.23: Higher risk façade detail with LWS. Drawn 1:5 scaled to 1:15 (Own work)

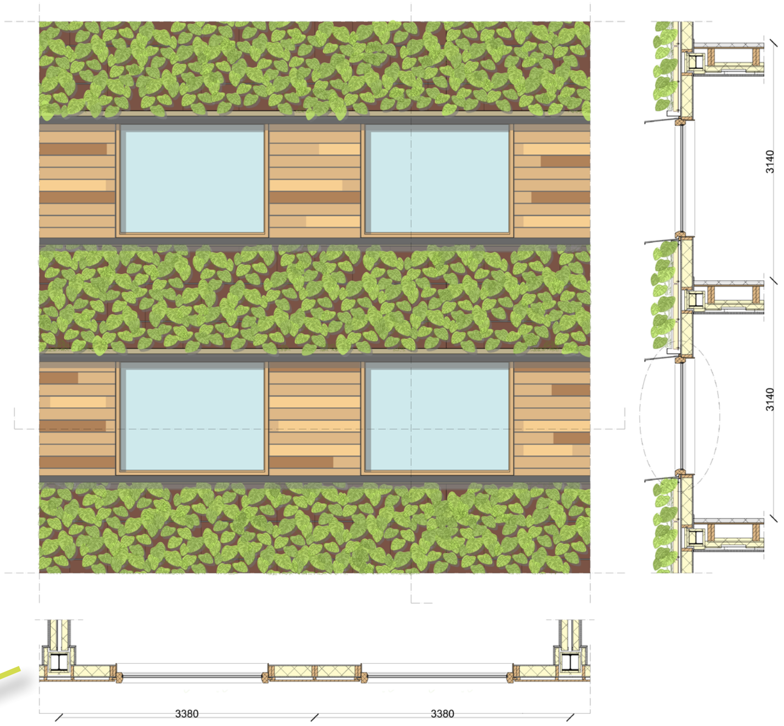


Figure 4.24: Lower risk façade view and sections with LWS 1. Drawn 1:20 scaled to 1:100 (Own work)

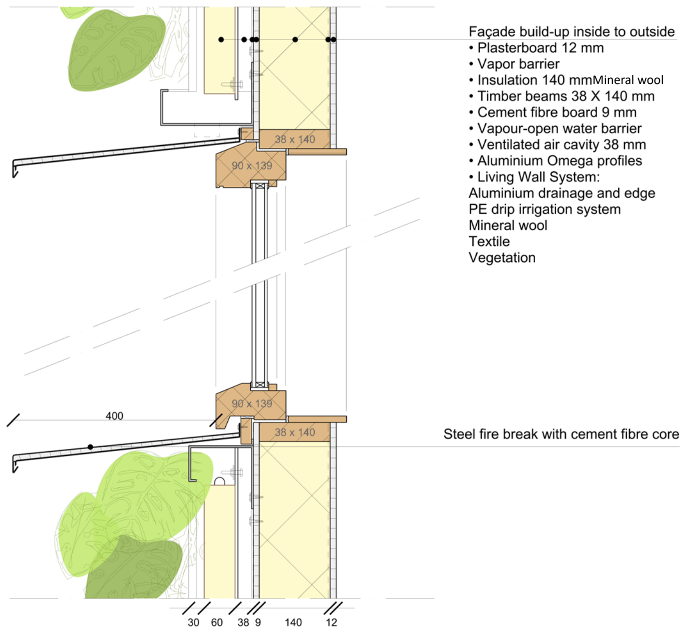


Figure 4.25: Lower risk façade detail with LWS. Drawn 1:5 scaled to 1:15 (Own work)

Facade 1		Facade 2		Facade 3		Facade 4	
4	(4) Residential in a residential bui	ding, accomodation in an accomodation building					
2	(2) Building height 15m-40m						
1	(1) Two staircases on distance >	H/2					
8							
Facade overview		Facade overview		Facade overview		Facade overview	
2	(2) Opaque façade with air cavity	2	(2) Opaque façade with air cavity	2	(2) Opaque façade with air cavity	2	(2) Opaque façade with air cavity
1.0	(1) No double skin façade	1.0	(1) No double skin façade	1.0	(1) No double skin façade	1.0	(1) No double skin façade
4	(4) Yes, vertically	4	(4) Yes, vertically	4	(4) Yes, vertically	4	(4) Yes, vertically
1.0	(1) No	1.0	(1) No	1.0	(1) No	1.0	(1) No
2.0	(2) No	1.5	(1.5) Yes, horizontal protrusion <(	2.0	(2) No	1.5	(1.5) Yes, horizontal protrusion <0.
2	(2) Yes	2	(2) Yes	2	(2) Yes	2	(2) Yes
1	(1) Yes	1	(1) Yes	1	(1) Yes	1	(1) Yes
2	(2) Yes, it's perpendicular	2	(2) Yes, it's perpendicular	2	(2) Yes, it's perpendicular	2	(2) Yes, it's perpendicular
64		48		64		48	
2	(2) 8. LWS with Mineral Wool	2	(2) 8. LWS with Mineral Wool	2	(2) 8. LWS with Mineral Wool	2	(2) 8. LWS with Mineral Wool
3	(3) Whole façade	1.5	(1.5) Horizontal strips	1	(1) Patches	2	(2) Vertical strips
2	(2) Yes, <1m distance	2	(2) Yes, <1m distance	1	(1) No	1	(1) No
2	(2) Yes, <1.5m distance	2	(2) Yes, <1.5m distance	1	(1) No	1	(1) No
1.50	(1.5) Yes, <0.4m distance	1	(1) No	1.5	(1.5) Yes, <0.4m distance	1.5	(1.5) Yes, <0.4m distance
2	(2) Integrated in the façade	2	(2) Integrated in the façade	2	(2) Integrated in the façade	2	(2) Integrated in the façade
1	(1) No	1	(1) No	1	(1) No	1	(1) No
1	(1) No	1	(1) No	1	(1) No	1	(1) No
1	(1) No	1	(1) No	1	(1) No	1	(1) No
72		24		6		12	
4	(4) Combustible; class C-F	1	(1) Incombustible; class A1-A2	1	(1) Incombustible; class A1-A2	1	(1) Incombustible; class A1-A2
2	(2 VGS is the cladding	2	(2 VGS is the cladding	2	(2 VGS is the cladding	2	(2 VGS is the cladding
2	(2) Yes, > half thickness spouwbl	2	(2) Yes, > half thickness spouwbl	2	(2) Yes, > half thickness spouwbl	2	(2) Yes, > half thickness spouwbla
1.5	(1.5) Wood	1.5	(1.5) Wood	1.5	(1.5) Wood	1.5	(1.5) Wood
24		6		6		6	
2	(2) Incombustible and combustib	2	(2) Incombustible and combustib	2	(2) Incombustible and combustib	1	(1) Only incombustable materials
1.25	(1.25) Yes, every row of modules	1.25	(1.25) Yes, every row of modules	1.25	(1.25) Yes, every row of modules	1.25	(1.25) Yes, every row of modules
2	(2) Perennials	1.5	(1.5) A mixture of evergreens and	1.5	(1.5) A mixture of evergreens and	1	(1) Evergreens
1	(1) No	1	(1) No	1	(1) No	1	(1) No
5.00		3.75		3.75		1.25	

Facade 1	Facade 2	Facade 3	Facade 4
8	8	8	8
64.0	48.0	64.0	48.[illegible]
72	24	6	12
24	6	6	6
5	3.75	3.75	1.25
Reset all input of facade	Reset all input of facade	Reset all input of facade	Reset all input of facade
7	4	4	3
NO-GO, change the design	Consult fire safety expert or change desigr	Consult fire safety expert or change desigr	Consult fire safety expert or change desigr

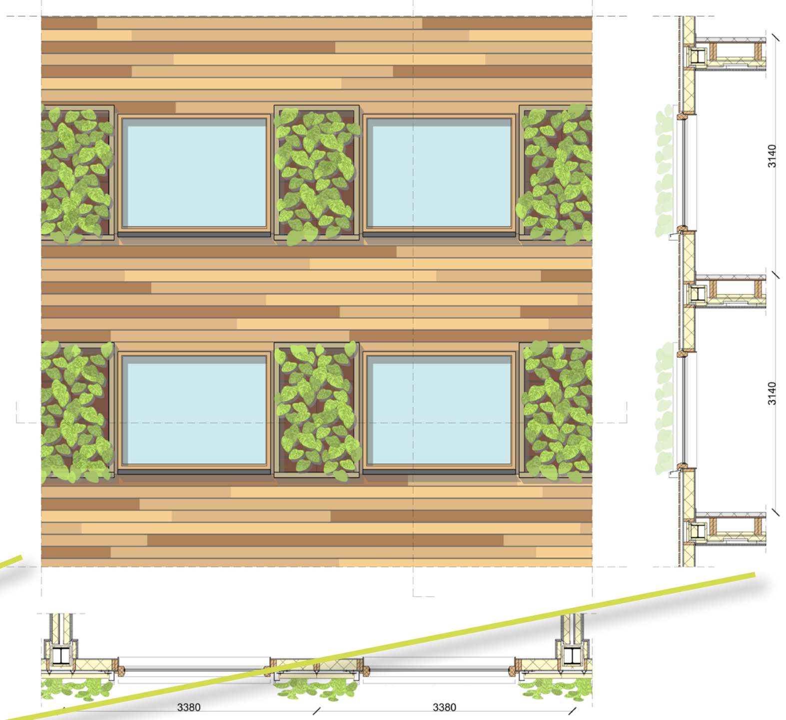


Figure 4.26: Lower risk façade view and sections with LWS 2. Drawn 1:20 scaled to 1:100 (Own work)

Figure 4.27: Lower risk façade view and sections with LWS 3 Drawn 1:20 scaled to 1:100 (Own work)

4.7 Future development tool

If the tools would be developed further there are some things which can be considered in expanding the tool.

The tool is now divided into two parts: a simple tool and an comprehensive tool. Ideally these two would be combined. So automatically the necessary more in-depth questions would appear when filling in the 'basic' questions. This way the tool would be more user friendly.

Also the risk of the parameters is dependent on other parameters. In future development of the tool, this intertwining of the parameters and their influence on each other can be further expanded. It could be that AI can help with this, since it is such a complex web of connectivity.

Furthermore the current tool only focusses on fire safety. Ideally the tool would also take into account the sustainability aspects. So measuring the fire safety aspects directly against the sustainability gains of a design. This way a more comprehensive decision can be made. This can be further expanded with also implementing a cost aspect into the tool.

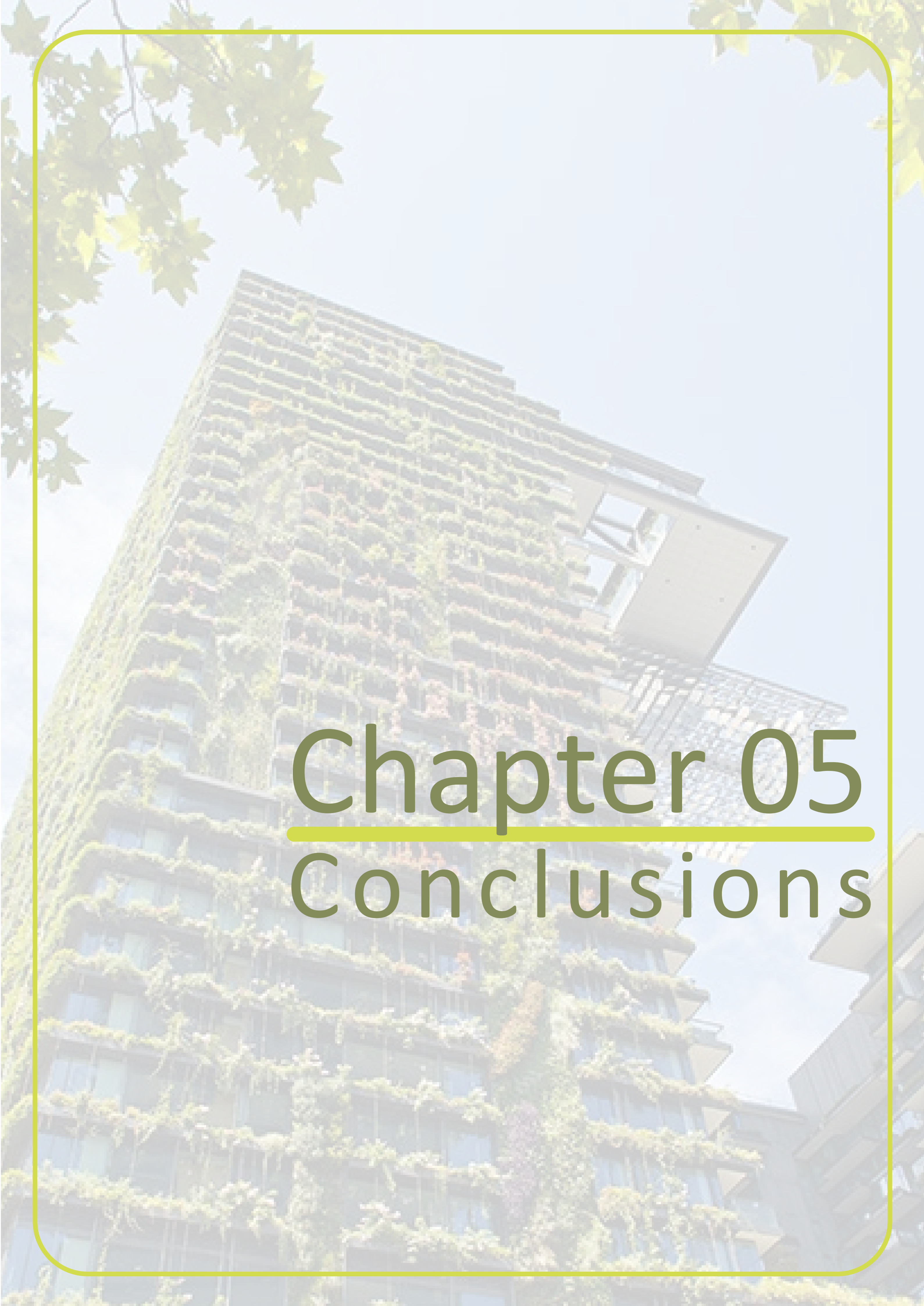
Laslty the tools could be transformed into design tools. It could be developed as a plug-in for drawing programms such as Rhino or Revit. The tool could be used as a plug-in where a drawn design could be analysed with the plug-in, so the designer would not have to manually answer the questions. It could also be that the designer would answer the questions manually and that the tool automatically generates a design based on the filled in questions. By incorporating the tool into a drawin programm, the use of the tools could bcome more integrated in the design process.

4.8 Key aspects

The development of the decision-making framework helped in identifying the relevant parameters. It was found that communicating the findings properly with designers is key. Therefore a three step framework was developed. The infographic is a quick overview with the most relevant findings which gives advise for designing with VGS. It was found that such an infograhpic is useful for many different parties involved in the design process.

The tools can be used to check if a design is of an acceptablerisk level. The tool also helps in identifying the most critical aspects of a design, where improvements could be made. It was found that architects and manufacturers would make use of such a tool in practice to check if their design ideas are safe in terms of fire safety. Specifically in more unsure situations such a tool would be benificial for designers to check their designs. It was also found that the use of such a tool increases the understanding of designes of what aspects are relevant in terms of fire safety of a design with VGS.

Furthermore some examples of safe designs were shown, which can be identified with the tools. It was also shown how the tool can help in improving a high risk design.



Chapter 05
Conclusions

5.1 Discussion and limitations

Current research is performed with a basic understanding of fire safety. Given the complexity of fire safety, typically addressed by experts with years of experience, it is important to recognize that the results presented in this study represent an initial step towards understanding rather the fire safety aspects involved in Vertical Greenery Systems (VGS) than definitive solutions. It is important to state that the outcomes of this research may be further refined by researchers with different or more specialized backgrounds in fire safety engineering.

The primary goal of this research is not to provide prescriptive solutions for designing fire-safe buildings with VGS, but rather to foster a mindset of critical thinking and awareness. By exploring various aspects of fire safety and conducting risk analyses, this study aims to contribute to a broader understanding of the challenges and considerations involved in integrating greenery into vertical structures.

Within the time-frame and with the resources available, no physical fire tests could be performed. The research was dependent on analysing existing knowledge and data. A main method during the research was contacting relevant parties and gathering information from them. It must be acknowledged that this part of the research is hard to objectify. The interviewees gave their answers in a certain role, which was also why they were contacted, to try and get the view of different parties involved together. Not every party that was tried to get in contact with responded, so certain views have not been able to be taken into account in the current research. Also it was tried to state the information given by the different parties in an objective manner, but this must always be looked at critically and answers or information could have been biased.

Furthermore it was the goal to take the sustainability and costs aspect more heavily into account in balancing the risk against them. It would be beneficial if those aspects would be linked to the fire risk analysis, so that a more comprehensive understanding of a proposed design can be developed and even better informed decisions can be made in the design process. Unfortunately it was found that in the time-frame of the research, it was too hard to be able to take this into account as well. For future research is would be interesting if a better link between the aspects of fire safety, sustainability and costs could be explored and explained.

The infographic and tools aimed to provide clear advise to design safer VGS. Certain general advises were given and the tools provide a risk level for a filled in design. An initial approach was made where parameters were analyzed and a risk factor was linked to design solutions. Yet, since different design choices are interconnected, and the risk of one choice depends not only on that choice but also on the context of other choices, a more comprehensive analysis is necessary. With the current knowledge and understanding, it was challenging to develop the tool in a way that encompasses all these underlying connections, so this can be developed further. In future research or further development of such tools, AI could be utilised to navigate the complex web of relevant links among the different aspects that influence each other. This would allow for a more sophisticated and nuanced analysis of fire safety risks in VGS designs.

During the research, certain interesting fire safety measures and suggestions were found. This included the use of fire breaks and positioning the VGS with certain distances between green patches and from openings in the façade. In terms of design, these are interesting and relative simple parameters to work with when designing with VGS. There were some numerical distances found in the literature, but they seemed to be inconsistent and most were not based on physical testing. For more precise advise in how to make us of fire breaks and vegetation free zones, it would be desirable more explorative testing would be done with these aspects to gain a better understanding of the fire behaviour in such situations. If more precise information of numerical distances can be identified, more precise advise can be given in terms of designing with these parameters. The following tests exploring different parameters are proposed to be of use to be tested in future research with physical fire tests:

- **Fire break:** Test making use of metal or concrete fire breaks protruding from the façade dividing the VGS in different patches. This should be both tested in vertical and horizontal direction. Questions to be answered: *How far does the material need to protrude from the wall/VGS to effectively prevent fire propagation?*
- **Vegetation free zones:** Tests with vegetation free zones between patches of VGS and to façade openings. This should be both tested in vertical and horizontal direction. Questions to be answered: *How much distance is necessary to prevent fire propagation from a patch of VGS to another? How much distance is necessary to prevent fire propagation from VGS to openings in the façade? How much distance is necessary to prevent fire propagation from window ejecected flame plume to VGS?*
- **Distance to façade.** Test with regards to distance of the system to a combustible façade or curtain wall. With the different systems and thus different fuel loads and heat release in case of fire. Also to determine the influence of rear façade on direct application and on air cavity. Questions to be answered: *When could a fire in the VGS be able to ignite the façade behind it or cause the glass in a curtain wall to fail? What distance would prevent this from happening? What distance would prevent a fire in the façade prevent the ignition of the VGS in front of it?*
- **Plant conditions**. Tests of different species of plants and different seasonal conditions of the plants to be able to create a database with this information. Specifically more for vegetation used in LWS, since these are not thorougly tested, whereas there is some testing done on climbing plants. Questions to be answered: *How do different vegetation types behave in fire? How do the plants behave in different seasons?*

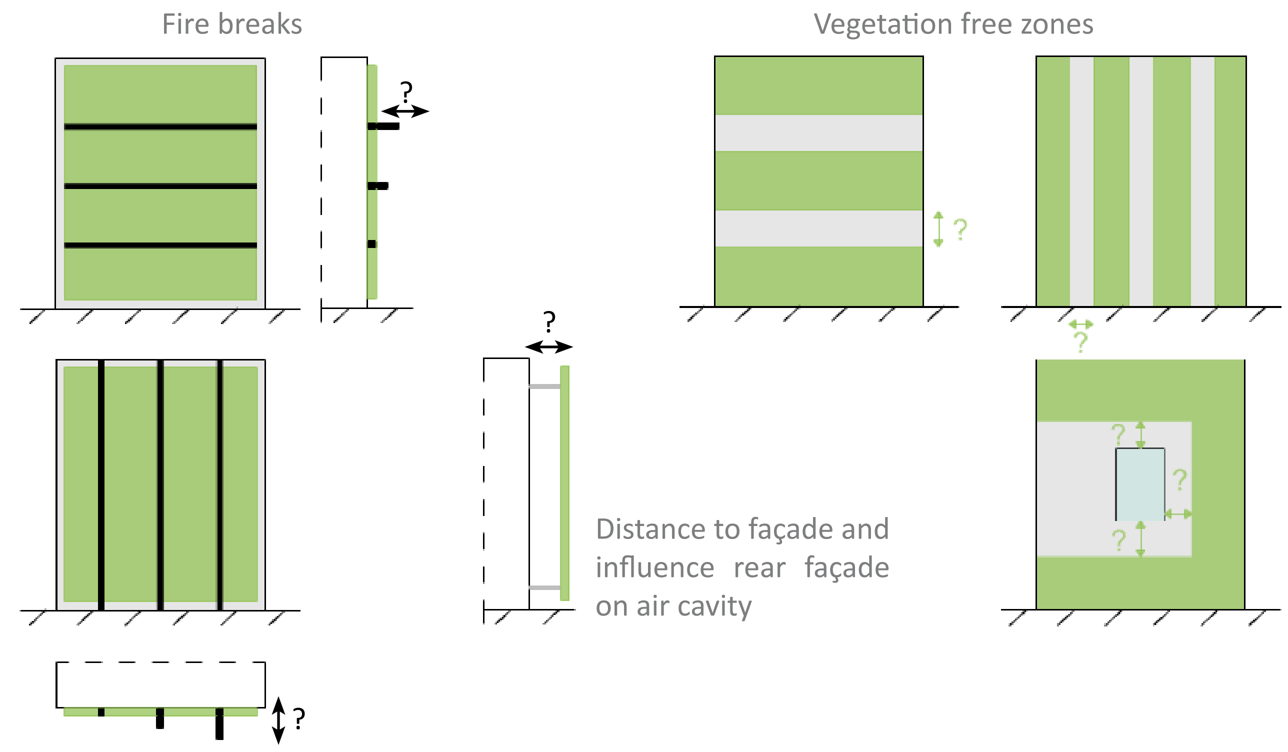


Figure 5.1: Parameters to be tested further in explorative fire testing (Own work)

Lastly the current research focused on legislation and the current climatic situation in the Netherlands. Many of the findings would still be relevant for different countries and for different climates. But when designing with VGS in different conditions, it should be acknowledged that not all the conclusions or advises in the current thesis are of the same relevance in those different situations. Also climate change can result in more extreme weather in the reverenced climate, such as longer periods of drought. This can influence the risk level of VGS, since the moisture content has great influence on the fire behaviour. This shows again the importance of robust and properly maintained irrigation systems to be used in the systems.

In conclusion, while this thesis lays the groundwork for exploring fire safety in vertical greenery systems, it is important to recognize its limitations and the potential for future research to build upon these findings. By fostering awareness and promoting a thoughtful approach to design, this research contributes to the ongoing dialogue surrounding fire safety of Vertical Greenery Systems.

5.2 Conclusion

This research examined the fire safety of Vertical Greenery Systems (VGS). The main conclusions found are listed below:

- Tests performed to classify VGS are inconsistent and are not representative for the in practice application;
- Further explorative testing is desired to determine when fire breaks or vegetation free zones work effectively;
- The materials used in the systems are of greater impact on the fire behavior than the vegetation;
- Green façades show significantly lower risks than Living Wall Systems (LWS);
- Irrigation does not guarantee protection from fire. Moisture slows down the fire, but does not prevent;
- Location on the façade has significant influence on the risk that occurs by applying the VGS;
- Maintenance contracts for LWS should be demanded by authorities when applying for a permit;
- A risk analysis tool can be helpful for designers to determine the risk level of a design without needing to consult a fire safety expert in the early design stages;
- Concerns about fire safety of VGS are valid but there are also plenty situations identified which pose minimal risk, as shown in Figure 5.2.

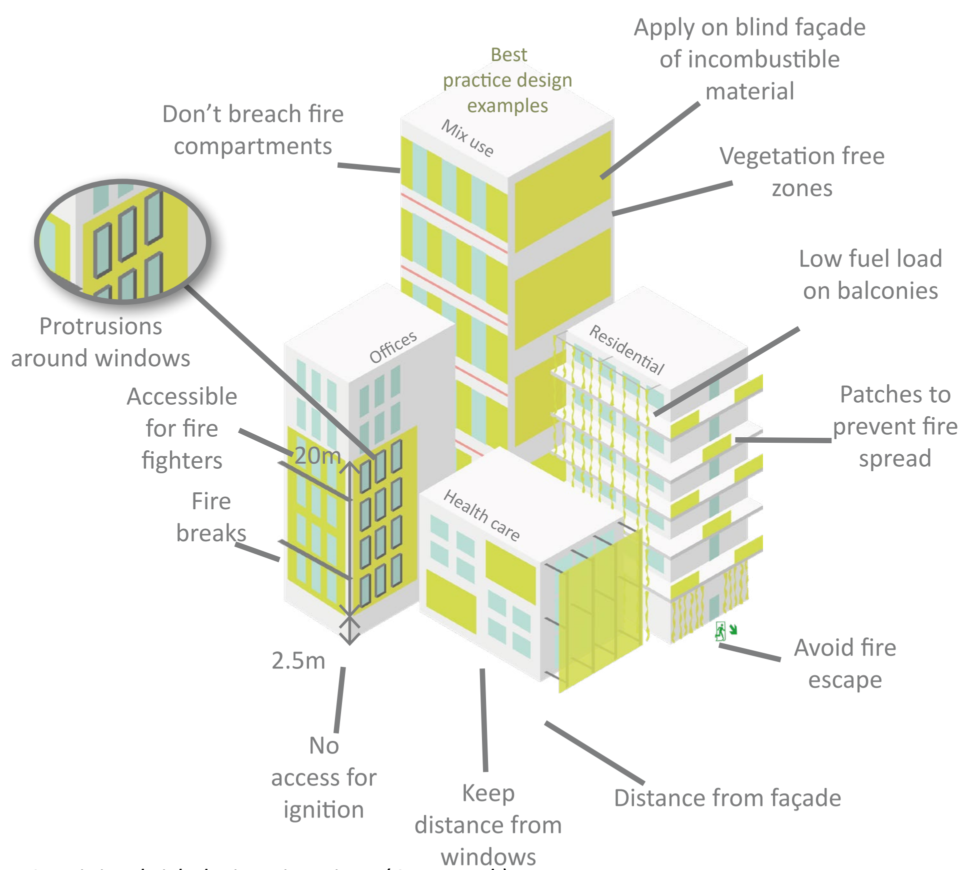


Figure 5.2: Minimal risk design situations (Own work)

The following research question was the main driver for the research:

"How can a decision-making framework help guide the design process for outdoor vertical greenery systems which provides responsible fire risk management relevant to a building's characteristics?"

To be able to answer this main question, several sub-questions were researched. These subquestions will first be answered, after which the main question will be answered. The subquestions are categorised by topic.

Vertical greenery systems

"What are the different vertical greenery systems currently in use and how do they differ in configuration and materials?"

There are 13 main different systems identified. These systems differ in terms of type of growing method, support structure and how it is integrated in the building. Main distinctions can be made between green façades, living wall systems, wall vegetation and vertical forests. The different systems score differently in terms of fire safety which is caused by type and amount of material used, whether or not irrigation is necessary and how it can be configured on the building. It was found that in general the green façades pose the least amount of risk. This is because these systems use less material than the LWS. Since it was found that not the plants but the materials used in the systems are of great influence on the fire performance of a system, it was found that LWS pose a greater risk, because more materials are used and in a more complex configuration. Ground based systems pose the least risk, because these are not dependent on irrigation, so irrigation failure cannot occur. Lastly vertical forests are complex and especially when using tress introduces high fuel loads on the building. Here the plant choice and configuration to the façade is of more significance that the system itself.

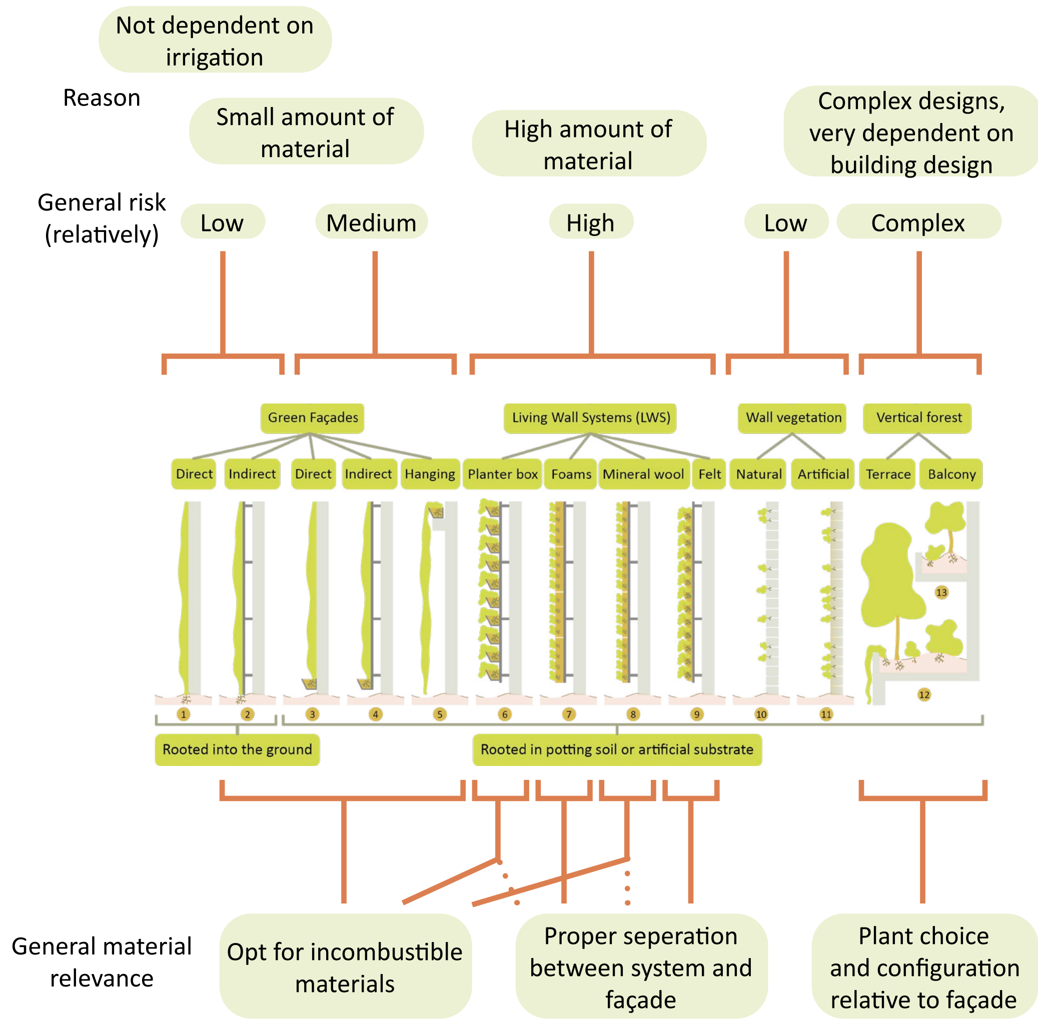


Figure 5.3: Overview of VGS and the general relevance (Own work)

"What are the advantages and disadvantages of vertical greenery systems?"

VGS were found to have a great variety of advantages. These can have influence on an urban scale but also on a building scale. Advantages found on urban scale were: mitigation of urban heat island effect, contribution to urban biodiversity, reduction of air pollution, storm water management, improvement of human health and psychological wellbeing. Advantages on building scale were: positive influence on thermal performance, reduction of noise and economical benefits. These advantages have a positive impact on the liveability of urban areas and show why these systems are increasing in popularity. VGS also show some disadvantages.

These were found to be the cost, maintenance, material use, damage to façade and fire hazards. In general it was found that the LWS score better on the advantages than the green façades. But they also score higher on the disadvantages. Which shows that there is a balance between the advantages and the disadvantages and not one system can be determined as 'the best'.

Fire safety

"What are current legislation and regulations on fire safety in buildings?"

Current legislation in the Netherlands relating to fire safety of buildings is organised in The Environment Buildings Decree ('Besluit Bouwwerken Leefomgeving' (Bbl). Here requirements are set out to which buildings need to comply. The focus of the legislation is to ensure safe escape in case of a fire and prevent the possibility of a fire to spread to other buildings. To be able to ensure this the legislation demands requirements in terms of preventing the possibility of a fire occurring, preventing the possibility of rapid fire spread and ensuring safe escape routes are present. This is done by compartmentation and demanding certain classifications to which the materials used need to comply.

Requirements can be more strict depending on the building characteristics. This is dependent on the function of use and on the height of the building. Buildings were people reside that sleep or have reduced self-reliance, need to comply to stricter requirements. The same goes for higher buildings. The higher the building, the stricter the requirements. There are certain rules that are necessary from certain heights. These increases in requirements in relation to hide are set at different heights so as not to make a large step in the requirements package at one height, which can encourage the design of a building just below a certain height.

To fulfil the requirements, a design needs to comply with the performance demanded in the Bbl or equivalence ('gelijkwaardigheid') needs to be demonstrated. If the same level of safety can be achieved by another means than what the Bbl demands and this can be demonstrated to the authorised supervision, a design can still approved even though it does not directly follow the Bbl.

"What fire safety aspects are relevant to vertical greenery systems?"

Vertical greenery systems are part of the façade and therefore need to comply with the legislation regarding the façade. This means that VGS need to adhere to the Euro classifications. It was found that there is a discussion going on about this. Since the Euro classification is determined using an SBI test, where the product needs to be conditioned and tested in the situation it is applied in practice, it is questioned if this is an appropriate way of determining the classification for VGS. VGS are dynamic systems, where the plants are not always in the same condition. Furthermore the systems usually have an irrigation system, which makes the system wet. But if the irrigation fails, the system becomes dry, and then the testing performed is not in accordance anymore with the applied situation in practice.

For the classification and tests performed on the VGS to be relevant, it should be more consistently performed. It is not very useful to be testing soaking wet walls. It should be determined what the worst acceptable condition in practice would be and test in that condition. These conditions then need to be thoroughly documented in the test report. So mention the moisture content and state and health of the plants used. This way the test is performed in a condition which would be the expected condition the wall would perform in the worst case. It would be advised to take this up in the norms describing the tests and what needs to be reported in the test reports.

Furthermore, it is advised that when applying for a permit with VGS, a maintenance contract is demanded as part of this permit. Since the health of the plants and the proper functioning of the irrigation system is of great impact on the fire safety of the VGS, it can be demanded by authorised supervision that the a maintenance contract has to be concluded as part of the fire safety management of the building.

Furthermore it was found that one of the main ignition sources of VGS are human behaviour or ignition by a nearby fire. The systems are not easily self-igniting, unless there is a monitoring system or lighting in the system. Monitoring system are usually low voltage systems, and do not pose a high risk of causing ignition of the system. Lighting in the systems can cause the system to dry out on top of being an ignition source. So when using lighting in the system, careful considerations are needed.

"What is the current approach of fire safety of vertical greenery systems in practice?" (2.3)

Since VGS are part of the façade, they should comply with legislation for façades and façade products. It was found that a number of systems, mainly LWS, have been tested and classified according to the European fire classification. But there is a discussion on how reliable these tests performed on VGS are.

It was also found that in terms of fire safety the reliance is often laid on the irrigation system. It is often stated that 'as long as the system is wet, there is no risk', but it was found that that is not true. First of all, an irrigation system can fail and dry out, so then there is a risk. And furthermore, with big enough fires, the flames can dry out the system as well, still setting aflame the system. Proper irrigation is very important for the health of the plans and of course moisture in the system slows down a fire, but it is not enough to prevent it completely. Solely trusting on 'the system being wet' as a fire safety measure is not enough.

It has been found that measures are sometimes taken in the form of vegetation free zones or fire stops in the system or around transparent parts in the façade. There was also a mention of a 'fire mode' in the irrigation system to provide additional water when flames would be detected in the system.

Risk assessment

"How can the fire risks of vertical greenery systems be assessed?"

There are numerous risk analysis methods in existence which analyse the risks of a certain situation. Most of them require the involvement of experts or work best when assessing a very specific case. Since for the current research a more holistic analysis of different VGS in different settings were to be assessed, a more general aproach in risk analysis was necessary. For this a qualitative 'What-If' anlaysis performed on multiple case-studies proved to be of value in assessing the fire risks of vertical greenery systems and identifying the relevant parameters and their design options which influence the risks.

Then this information was translated into a tool, which can automatically assess a VGS design. The design options of the different parameters were coupled to risk factors and the tool gives feedback on the filled in information on the different parameters. Effectively the tool can perform a 'What-If' analysis for a design, determining the overall risk of the combination of the risk factors and giving back information on how the filled in design options effect the fire safety of the design.

"What are relevant and credible scenarios in terms of fire in vertical greenery systems?"

Relevant scenarios involved those where it would be logical to make use of these systems. To look at the many different scenarios, differentiation in the case studies was made between building functions, building height and façade build-up. Not every situation would be relevant for every type of system. Mainly LWS are relevant on closed façade parts, whereas green façades could also stretch in front of transparent parts of a building.

"Which parameters influence the fire risk of using vertical greenery systems?"

After performing the risk analyses on the case-studies, a comprehensive list of 28 relevant parameters was found. These parameters mainly revolved around the following aspects:

- What type of building is it?
- Where on the façade is the system applied?
- What is the material built-up of the system?
- How is the system integrated in the building structure?
- How is the irrigation carried out?

It was found that placement on the façade is of great significance in the fire risk. If the system is next to façade openings, chance of fire spread becomes very relevant. If the system covers the whole façade, fire spread is more easily. If the system is placed where it can threaten escape routes, there is greater risk. If the system is placed where the fire fighters have no easy access, a fire can become incontrollable.

Furthermore the material choice was found to be of great influence on the fire performance, even more so than the plant choice. When using plastics in the system a VGS can create a big fire, even when the system started out wet. Opting for incombustible materials seems to greatly lower the risks.

In literature and practice, it is often stated, that as long as the system is wet, there is no fire risk. But it was found that this is not true. Moisture content does have a great influence on the fire behaviour, but it merely slows down the fire propagation or lowers chance of ignition, it does not completely rule out the possibility of a fire occurring and spreading. Relying solely on the idea of 'as long as the system is wet, the façade is safe' is therefore a naive and potentially dangerous way of treating VGS.

Design solutions

"Which design solutions can be utilised regarding the found risk scenarios?"

Several relatively simply to implenent design solutions were identified and explained. This mainly included how to implement the system on the building. By avoiding high risk situations, such as near escape routes or near façade openings, easy safe situations can be designed.

Also some measures for in the system were identified which could help with the fire performance of a VGS design. For this further testing would be recommended to get a better understanding of when these measures acutally work. It is found that design solutions could be using fire breaks in the systems. This can be done with adding incombustible barriers or by leaving vegetation free zones. Further testing should be done in how much distance is needed for such fire breaks to work effectively with different VGS. Since different VGS have different fuel loads, it could well be that the same distance would not work for the different systems. To gain a better understanding of this it is advised further explorative testing to be done on these topics.

"How can a decision-making framework be developed regarding the found parameters?"

When working on the risk analysis it was found that this analysis can be used as part of the decision-making framework. A rather comprehensive tool was developed to analyse designs and show how different design choices influence the risk level of a design. By linking the found parameters to a risk factor, an assessment of the design can be made and visualised for the user. By using colour coding and graphs it can be visualised for the user where the critical risks are present and where potential improvements can be made.

It was found after talking with experts, that a quick and simple overview of the main considerations would be more approachable and usable in practice than the comprehensive tool on its own. So a simple tool was developed which provides a quick analysis of a design. Also an infographic was designed to show in one overview what the

Further development of the tool can include more crosslinked parameters. Including the mitigating measures. Weighing against the sustainability gains. Provinding a cost overview.

Main research question

"How can a decision-making framework help guide the design process for outdoor vertical greenery systems which provides responsible fire risk management relevant to a building's characteristics?"

The developed framework works threefold. First an infographic can be used by designers to get a quick overview of best practices when designing with VGS. By following these guidelines, risky situations can be easily avoided. The design can then be quickly checked in the simple tool, which can provide a quick analysis in the risk level of the design. When necessary the comprehensive tool can be consulted to get a more in depth analysis on the design. The tool and infographic most importantly provide information and communicate knowledge with designers, which they can use in discussions in the design process to convince other parties why certain design options are important in terms of fire safety.

By testing the tools with and showing the infographic to several parties involved in the design process of a building, it was found that such products can be helpful in designing saver designs with VGS. It was found that the tools can help architects and other designers in the early stages of the design process in making informed design decisions related to fire risks. It was found that the tool can help identify where problems may occur and can help in raising awareness and understanding on the topic, which ultimately leads to safer decisions. Specifically in more dubious situations, the tool can guide in understanding the relevant risks involved in a design and advises in how to mitigate them.

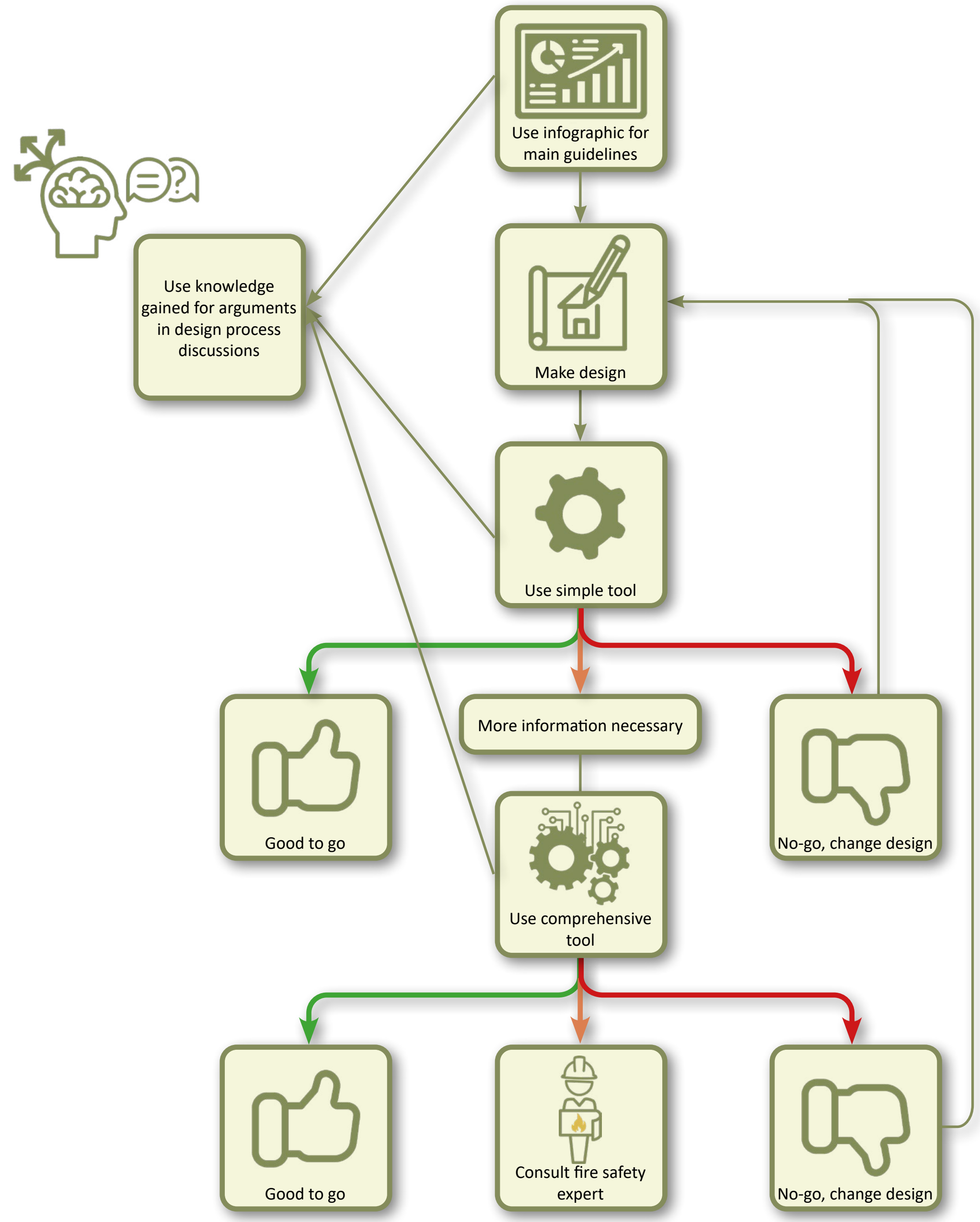


Figure 4.28: Decision-making framework with infographic, a simple tool and a comprehensive tool (Own work)

5.3 Future recommendations

Current research is performed with a basic understanding of fire safety. Given the complexity of fire safety, typically addressed by experts with years of experience, it is important to recognize that the results presented in this study represent an initial step towards understanding rather the fire safety aspects involved in Vertical Greenery Systems (VGS) than definitive solutions. It is important to state that the outcomes of this research may be further refined by researchers with different or more specialized backgrounds in fire safety engineering.

The primary goal of this research is not to provide prescriptive solutions for designing fire-safe buildings with VGS, but rather to foster a mindset of critical thinking and awareness. By exploring various aspects of fire safety and conducting risk analyses, this study aims to contribute to a broader understanding of the challenges and considerations involved in integrating greenery into vertical structures.

Within the time-frame and with the resources available, no physical fire tests could be performed. The research was dependent on analysing existing knowledge and data. A main method during the research was contacting relevant parties and gathering information from them. It must be acknowledged that this part of the research is hard to objectify. The interviewees gave their answers in a certain role, which was also why they were contacted, to try and get the view of different parties involved together. Not every party that was tried to get in contact with responded, so certain views have not been able to be taken into account in the current research. Also it was tried to state the information given by the different parties in an objective manner, but this must always be looked at critically and answers or information could have been biased.

Furthermore it was the goal to take the sustainability and costs aspect more heavily into account in balancing the risk against them. It would be beneficial if those aspects would be linked to the fire risk analysis, so that a more comprehensive understanding of a proposed design can be developed and even better informed decisions can be made in the design process. Unfortunately it was found that in the time-frame of the research, it was too hard to be able to take this into account as well. For future research is would be interesting if a better link between the aspects of fire safety, sustainability and costs could be explored and explained.

The infographic and tools aimed to provide clear advise to design safer VGS. Certain general advises were given and the tools provide a risk level for a filled in design. An initial approach was made where parameters were analyzed and a risk factor was linked to design solutions. Yet, since different design choices are interconnected, and the risk of one choice depends not only on that choice but also on the context of other choices, a more comprehensive analysis is necessary. With the current knowledge and understanding, it was challenging to develop the tool in a way that encompasses all these underlying connections, so this can be developed further. In future research or further development of such tools, AI could be utilised to navigate the complex web of relevant links among the different aspects that influence each other. This would allow for a more sophisticated and nuanced analysis of fire safety risks in VGS designs.

During the research, certain interesting fire safety measures and suggestions were found. This included the use of fire breaks and positioning the VGS with certain distances between green patches and from openings in the façade. In terms of design, these are interesting and relative simple parameters to work with when designing with VGS. There were some numerical distances found in the literature, but they seemed to be inconsistent and most were not based on physical testing. For more precise advise in how to make us of fire breaks and vegetation free zones, it would be desirable more explorative testing would be done with these aspects to gain a better understanding of the fire behaviour in such situations. If more precise information of numerical distances can be identified, more precise advise can be given in terms of designing with these parameters. The following tests exploring different parameters are proposed to be of use to be tested in future research with physical fire tests:

5.4 Relevance

With the growing emphasis on sustainability in the built environment, new and less understood challenges are emerging in our cities. While sustainable innovations are on the rise, it is crucial that our understanding of fire safety keeps up with these innovations. Buildings need to be sustainable, but they also need to be fire safe. Therefore, ongoing research into these aspects is essential to ensure that our buildings remain both environmentally friendly and safe.

The current research is therefore of great relevance due to the increasing use of Vertical Greenery Systems (VGS) in the built environment and the expressed concerns in lack of knowledge of the fire safety aspects of these systems. This research collected the current knowledge on the topic and introduced and overview of relevant aspects. Advises were proposed and a means to communicate this knowledge to people not focused on fire safety engineering was developed. By raising awareness and spreading knowledge on this topic, the aim is to prevent fire safety from falling behind in the innovations of the built environment.

Neglecting fire safety in design impacts the sustainability. A burned-down building is not very sustainable, and the need to dismantle systems, as seen with aluminum sandwich panels in England, is also rather unsustainable. To prevent such operations to be necessary in the future, fire safety should be taken seriously into account from the beginning of these new developments. Designs with VGS should be designed fire safe now, to prevent the necessity of having to take down these systems in the future because they would be found to be unsafe then.

Designers and engineers have a responsibility to the society to create safe and healthy living spaces. This research was performed to contribute to the fulfilment of this responsibility.

5.5 Reflection

Methodology

The literature research fueled the process, but it was important to stay critical in the things read. It was noted that sometimes the way people talk about fire safety aspects of vertical greenery involves personal opinions or other interests. When reading always think ‘why would a person think or say this?’, is it subjective or objective?, what would be the reasoning of someone saying a certain thing?

Interviews were a tremendous resource. It was a little difficult sometimes to get in contact with people and it sometimes took quite a while before people would respond or would be able to make an appointment. I was glad I started to get into contact with different parties early on in the process. If I would’ve waited too long, it would maybe have been too late or I would’ve been stuck, as the interviews helped me in taking next steps.

Unfortunately not all the parties that wanted to be spoken to, were reached. The method of taking interviews, does make it that you are dependent on other parties for the success of your research, which can be tricky. Overall it is my opinion that with the parties that were reached, a comprehensive understanding was gained on the topic, and relevant information was gathered which would not have been able to be collected by merely looking at literature available. If I could start over with the research, I would probably try and contact more parties. I found it rather scary to do this, and often felt like I was bothering people. But the people that responded were all very enthusiastic and interested in the project. This showed me that I shouldn’t be worried about contacting parties and later on in the process this became easier.

Furthermore it was found rather difficult to get the appropriate information sometimes from the interviewees. It can be really hard to phrase your questions in such a way that you get the information you are looking for. I found that I struggled with this sometimes. To try and overcome this it was important to keep in mind what 'my problem' was. What was the information I am lacking to overcome the problem. It was therefore found that conversations generally worked better for the interviews than sending out a survey with questions (written interview). To be able to hold a dialogue and be able to elaborate on questions or ask follow up questions guided the interviews in the right direction.

Looking at case-studies helped a lot in developing scenarios and understanding that in different situations, different aspects come forward. Something I had trouble with during the research was setting this step into looking at cases and just try to green building and see what problems I encountered. I realised I kept gathering information and had difficulty translating that into design situations. My mentors reminded me that this step was important to take. The case-studies helped very well in determining scenarios.

Furthermore it was hard to determine the proper cases. Since there are so many different types of buildings, I struggled with making decisions in this regard.

The "What-If" analysis approach helped in thinking about the topic, but is wasn't the most effective way in systematically analysing the risks. A "What-If' analysis works best in a properly defined case. Since this research was looking at many different cases, it would've been nearly impossible to perform a complete and thorough "What-If" analysis for all the cases. It was found that the way of thinking for a "What-If" analysis did help in looking at the cases.

First it was expected that a risk analysis would be performed after which a design process would be performed. But during the research it was found that these two go hand in hand, and the risk analysis became incorporated into the design guide. Even when the tool became more of an end product of the research, the development of the tool was also a great driver of the research itself. By designing the tool, I learned much better what the influence of the different parameters on the risk was and how these parameters are interconnected. The development of the tool worked as research by design, where the tool was the design.

On thing that was found difficult in the risk analysis was determining the proper weight on the different parameters and also providing the proper thresholds for the risk levels. Normally in determining fire safety experienced experts would have a look at it and can make an informed decision due to expertise and experience. Since I am still relatively novel in the field and only just started to get acquainted with all the aspects involved in fire safety, my judgement is limited. My judgement is still based on sources and help from experts, but it is not achievable for me to reach a perfect result, I can only strive to approach proper results as best as possible.

When working with the case-studies, research by design was a helpful way of assessing the different design options. By trying out all sorts of different design options on different cases and in different contexts, a broad understanding of the relevant parameters which can be used in a design process were identified. I think that the result of the advise on design options can be very helpful for designers with minimal knowledge on fire safety to use simple strategies to prevent unnecessary fire risks.

Lastly, documentation was not per se considered a method. But it is now found that proper documenting from the beginning actually helps in guiding the next steps and organizing the information in one's head. It was found difficult to properly document and categorise all the information found and evaluate what information was more important than others. By putting in more effort in to properly documenting the information found, a better understanding of the whole research approach would've been developed more early on in the process. Now I sometimes worked without really knowing what the goal was, working in vagueness, which prevented me from making decisions and make progress. A tremendous help in this were my mentors. They helped me in taking steps and making sure I kept clear goals throughout the process.

The chosen methods were made due to time limitations and limitations in access to data and testing. Of course it would've been super informative if real life tests could've been performed on different set-ups of vertical greenery systems and/or vegetation. But I realised early on in the process, that this would be very difficult to set up. So the focus was made to make use of information of other experts in the field to fuel my research. The chosen methods have proven to be useful and for the purpose of the research are found to be sufficient.

Relevant support

First of all, my mentors had proper knowledge on the topic of vertical greenery systems, which helped a lot to be able to ask certain questions when in doubt from the literature research. It was found that support in expertise of fire safety was needed. Unfortunately in the beginning of the process, this support was lost, so in the beginning it was found that there was a lack in support on this field and I was mostly dependent on literature research. I would've been helpful if in this stage, I could've talked more with a fire safety expert, which could've helped speed up the process in the beginning. Luckily by talking to other experts later on, this gap was filled rather sufficiently. Later on in the process a connection was made with fire experts from DGMR, which helped tremendously and it is found that without their guidance, the current research would not have reached all the conclusions and findings it did now.

My mentors helped me in staying focused on the topic and trying to frame the research properly. Since the topic of fire safety is so broad, it is easy to lose oneself, and my mentors helped me stay on track. They especially helped in trying to stay focused on what I was working toward. What is the result you want to show? Also my mentors and DGMR asked critical questions on my work, which helped me to think about what I was doing and why. Making sure I was working argumentative and wrote down why I made certain decisions. Lastly my mentors pushed me in documenting my research, which I found very difficult. Without their persistence I would've probably postponed proper documentation too long, which would've slowed down the whole research process and would've made me lose track of the final product.

Personal growth

At the beginning of this research I had minimal knowledge on Vertical Greenery Systems and Fire safety regulations and design considerations. I knew it would be a challenge to teach myself in these topics in such a short amount of time, but I am glad I did. I learned so much during this research and I would not have been able to gain this knowledge in another way. Furthermore I learned about risk analysis, which was a rather complex field, but interesting to touch upon. This learned about scenario thinking and to identify risks and relevant parameters in different situations. I now look with a completely different view at the buildings around me. Lastly I pushed myself into contacting different parties and having conversations with them. This is a great skill to have, since communication is, in my opinion, a key factor in design satisfying building designs. Overall I am satisfied with my achievements of the research and I am grateful I was able to learn so much about such an overlooked topic.

References

Chapter page images: Tensile. (n.d.). *3 Popular Types of Vertical Gardening Systems.* Tensile Design & Construct. Retrieved March 25th, 2024 from https://www.tensile.com.au/3-popular-types-of-vertical-gardening-systems/

ACS Institute. (n.d.). *What-if Analysis.* Retrieved March 7th, 2024 from https://institute.acs.org/acs-center/lab-safety/hazard-assessment/ways-to-conduct/what-if-analysis.html#samples

Al-Kodmany, K. (2023). Greenery-Covered Tall Buildings: A Review. *Buildings 13,* 2362. https://doi.org/10.3390/buildings13092362

Alalouff, R. (2023). *Living walls guidance and fire testing is "inconsistent and inappropriate" says leading fire engineering academic*. IFSEC Global. Retrieved on November 9th, 2023 from https://www.ifsecglobal.com/fire-prevention/living-walls-guidance-and-fire-testing-is-inconsistent-and-inappropriate-says-leading-fire-engineering-academic/

Ascione, F., De Masi, R.F., Mastellone, M., Ruggiero, S., & Vanoli, G.P. (2020). GreenWalls, a Critical Review: Knowledge Gaps, Design Parameters, Thermal Performances and Multi-Criteria Design Approaches. *Energies, 13*(9), 2296. https://doi.org/10.3390/en13092296

Bachmeier, P. (2020). *Brandschutz großflächig begrünter Fassaden.* AGBF bund. Retrieved April 11th, 2024 from https://www.agbf.de/downloads-fachausschuss-vorbeugender-brand-und-gefahrenschutz/category/28-fa-vbg-oeffentlich-empfehlungen?download=335:2020-03-fachempfehlung-fassadenbegruenung

Bielawski, J., Papis, B.K., Krajewski, G., & Węgrzyński, W. (2024). An exploratory investigation into moisture content and wind impact on the fire behaviour of modular living walls. *Fire Safety Journal 142*, 104024. https://doi.org/10.1016/j.firesaf.2023.104024

Biotecture. (n.d.a). *PlantBox.* Retrieved January 21st, 2024 from https://www.biotecture.uk.com/bioextra/plantbox/

Biotecture. (n.d.b). *Specifications and Drawings.* Retrieved March 20th, 2024 from https://www.biotecture.uk.com/design-and-specify/specifications-and-compliance/specifications-and-drawings/

Bowe, P. (2004). *Gardens of the Roman world* (1st ed.). J. Paul Getty Museum Getty Publications.

Brandweer Nederland en Verbond van Verzekeraars. (2021). *Duurzaam Veilig.* (Position paper). https://www.verzekeraars.nl/media/8579/paper-duurzaam-veilig.pdf

Business gov. (n.a.). *The Environment and Planning Act (Omgevingswet): what does it mean for you?* Retrieved February 21st, 2024 from https://business.gov.nl/running-your-business/business-location/establishing-or-relocating-a-business/the-environment-and-planning-act-omgevingswet-what-does-it-mean-for-you/

Bustami, R.A., Belusko, M., Ward, J., & Beecham., S. (2018). Vertical greenery systems: A systematic review of research trends. *Building and Evironment 146*, 226-237. https://doi.org/10.1016/J.BUILDENV.2018.09.045

Calvo, J.A.S. (2021). *Green-Cities, How to Combine Fire Safety and The Fight Against Global Warming.* [Master thesis]. ETH Zurich, Switzerland. Retrieved February 25th, from https://imfse.be/theses

Carpenter. (n.d.). *Green Walls – Vertical Gardening Systems for Naturally Beautiful Rooms*. Retrieved January 21st, 2024 from https://www.foampartner.com/en/foam/industrial-foam/greening-systems/vertical-gardening-systems/

COIMA. (2020). *How Milan's Bosco Verticale Has Changed the Way Designers Think About Sustainable Design.* ADPRO. Retrieved March 20th, 2024 from https://www.architecturaldigest.com/story/how-milans-bosco-verticale-has-changed-the-way-designers-think-about-sustainable-design

Dahanayake, K.C., & Chow, C.L. (2018). Moisture Content, Ignitability, and Fire Risk of Vegetation in Vertical Greenery Systems. *Fire Ecology 14*(1), 125–142. https://doi.org/10.4996/fireecology.140112514

Dahanayake, K.C., Yang, Y., Wan, Y., Han, S., & Chow, C.L. (2020). Study on the fire growth in underground green corridors. *Building Simulation 13,* 627-635. https://doi.org/10.1007/s12273-019-0595-4

DGMR. (2019). *Handreiking Beoordeling brandveiligheid gevels.* Rijksoverheid. Retrieved from https://www.rijksoverheid.nl/documenten/brieven/2018/11/30/onderzoek-brandveiligheid-gevels

Dictionary. (n.d.). *Fire.* Retrieved February 24th, 2024 from https://www.dictionary.com/browse/fire

Dienst Justitiële Inrichtingen. (n.d.). *PI Rotterdam locatie De Schie*. Retrieved April 26th, 2024 from https://www.dji.nl/locaties/r/pi-rotterdam-locatie-de-schie

Dijkstra, R. (2021). *Drone blijkt populair middel om drugs in gevangenis De Schie te krijgen.* AD. Retrieved April 26th, 2024 from https://www.ad.nl/rotterdam/drone-blijkt-populair-middel-om-drugs-in-gevangenis-de-schie-te-krijgen~a94dc01b/

EFB. (2022). *Fire regulations for green walls.* [Video]. Retrieved April 11th, 2024 from https://www.youtube.com/watch?v=E24euj4UTSI

Efectis. (n.d.). *Brandveilige gevels* Retrieved February 24th, 2024 from https://efectis.com/nl/brandveilige-gevels/

Eneco. (n.d.). *Over Eneco.* Retrieved May 25th, 2024 from https://www.eneco.nl/over-ons/wie-we-zijn/over-eneco/

Engel, T. (2023, Oktober 10). Green façades fire tests. Retrieved April 26th, 2024 from https://www.linkedin.com/posts/thomas-engel-aab413114_%3F%3F%3F%3F%3F-%3F%3F%C3%A7%3F%3F%3F%3F-%3F%3F%3F%3F-%3F%3F%3F%3F%3F-activity-7117469557887221760-_cir/?utm_source=share&utm_medium=member_desktop

Engel, T., & Noder, J. (2020). Begrünte Fassaden aus brandschutztechnischer Sicht. *Bautechnik 97*(8), 549-557. Retrieved December 8th, 2023, from https://doi.org/10.1002/bate.202000041

Engel, T., & Werther, N. (2024). Fire Safety for Green Façades: Part 1: Basics, State-of-the-Art Research and Experimental Investigation of Plant Flammability. *Fire Technology.* https://doi.org/10.1007/s10694-024-01566-0

Fire Protection Association. (2022, February 7th). *Green Walls as a Maintained Rainscreen Cladding* [Video]. Retrieved from https://www.thefpa.co.uk/advice-and-guidance/public-webinar-archive?sort=date

Florafelt. (2015). *Florafelt Living Wall Guide.* Retrieved March 20th, 2024 from https://florafelt.com/florafelt-living-wall-guide

Freie und Hansestadt Hamburg. (2022). *Bauordnungsrechtliche Anforderungen an Fassadenbegrünungen.* Retrieved May 7th, 2024 from https://ap.lc/GmCDM

Geoplast. (2019). *Green facades make a big difference.* Retrieved January 21st, 2024 from https://www.geoplastglobal.com/en/blog/green-facades-make-a-big-difference/

Google, Airbus, & Maxar Technologies. (n.d.). [Google Maps location of Visstraat Delft]. Retrieved April 22nd, 2024 from https://www.google.com/maps/@52.0139607,4.3568301,125a,35y,326.02h,45.32t/data=!3m1!1e3?authuser=0&entry=ttu

Green Guide. (n.d.). *Groene muur.* Retrieved April 26th, 2024 from https://greenguide-groenegevelbegroeiing.nl/groene-muur/

Greenarea. (n.d.). *Preserved ornamental plant.* Archi Expo. Retrieved April 26th, 2024 from https://www.archiexpo.com/prod/greenarea/product-158447-1946068.html

Greenroofs. (n.d.) *Caixa Forum Museum Vertical Garden.* Retrieved June 18th, 2024 from http://www.greenroofs.com/projects/caixa-forum-museum-vertical-garden/

Gunawardena, K., & Steemers, K. (2020). Urban living walls: reporting on maintenance challenges from a review of European installantions. *Architectural Science Review 63*(6), 526-535. http://doi.org/10.1080/00038628.2020.1738209

Hakkarainen, T. (2002). Studies on fire safety assessment of construction products /. *VTT Publications.* Retrieved April 26th, 2024 from https://www.researchgate.net/publication/35218077_Studies_on_fire_safety_assessment_of_construction_products

Hoondert, P., & van Mierlo, R. (2024). *Ontwikkeling NPR 6999: aanscherping eisen aan hoogbouwgevels.* BWTinfo. Retrieved May 10th, 2024 from https://www.bwtinfo.nl/nieuws/2024/3/ontwikkeling-npr-6999

Instituut Fysieke Veiligheid. (2017). *Basis voor brandveiligheid*. Retrieved January 21st, 2024 from https://nipv.nl/basis-voor-brandveiligheid/

Jiffy group. (n.d.). *ABC of culture media, find out how to choose the right substrate for your culture.* Retrieved February 22nd, 2024 from https://jiffygroup.com/news/abc-of-growing-media-find-out-how-to-choose-the-right-substrate-for-your-culture/

Karunaratne, T.L.W., & Chow, C.L. (2022). Fire spread along vertical greenery systems from window ejected flame: A study based on a fire dynamic simulator model. *Journal of Building Engineering 62,* 105359. https://doi.org/10.1016/j.jobe.2022.105359

Koninklijk Nederlands Normalisatie-instituut. (2010). *Reaction to fire tests for building products - Conditioning procedures and general rules for selection of substrates* (NEN-EN 13238). Retrieved from https://connect.nen.nl/Standard/Detail/143903?compId=10037&collectionId=0

Koninklijk Nederlands Normalisatie-instituut. (2019). *Fire classification of construction products and building elements - Part 1: Classification using data from reaction to fire tests* (NEN-EN 13501-1). Retrieved from https://connect.nen.nl/Standard/Detail/3574589?compId=10037&collectionId=0

Koninklijk Nederlands Normalisatie-instituut. (2020). *Determination of the resistance to fire movement between spaces* (NEN 6068). Retrieved from https://connect.nen.nl/Standard/Detail/3635890?compId=10037&collectionId=0

Koninklijk Nederlands Normalisatie-instituut. (2022a). *Determination and classification of resistance to fire of building elements and building products* (NEN 6069). Retrieved from https://connect.nen.nl/Standard/Detail/3675466?compId=10037&collectionId=0

Koninklijk Nederlands Normalisatie-instituut. (2022b). *Reaction to fire tests for building products - Building products excluding floorings exposed to the thermal attack by a single burning items* (NEN 13823-1+A1). Retrieved from https://connect.nen.nl/Standard/Detail/3668855?compId=10037&collectionId=0

Kotzen, B., Galea, E.R., Mosco, S., Wang, Z., Ewer, J. & Jia, F. (2023). Fire safety risks of external living walls and implications for regulatory guidance in England. *Fire Safety Journal 139,* 103816. https://doi.org/10.1016/j.firesaf.2023.103816

Kraaijvanger Architects. (2018). *City Hall Venlo.* Retrieved May 25th, 2024 from https://arqa.com/en/architecture/city-hall-venlo.html

Lawn & Garden. (n.d.). *Sagegreenlife (Smart Biotiles).* Retrieved January 21st, 2024 from https://www.lawnandgardenmarketing.org/store/m/11410-Sage-Vertical-Garden-Systems.aspx

van Liempd, R., Ebus, J., Reinders, J., & van der Graaf, J. (2022). *De invloed van duurzaam, energiezuinig en circulair bouwen op de brandveiligheid van gebouwen.* Nederlands Instituut Publieke Veiligheid. https://nipv.nl/wp-content/uploads/2022/10/20220926-NIPV-Invloed-duurzaam-energiezuinig-circulair-bouwen-brandveiligheid-gebouwen.pdf

Lim, Y., & Ismail, M.R. (2022). Aptitudes of Double Skin Façade Toward Green Building within Built Environment. *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences 100*(3), 146-170. https://doi.org/10.37934/arfmts.100.3.146170

van der Linden, A.C., Kuijpers-Van Gaalen, I.M., & Zeegers, A. (2018). *Building Physics.* (2nd ed.) ThiemeMeulenhoff.

Ma, A. (2018). *The 5-star Mandarin Oriental Hotel in London is on fire.* Business Insider. Retrieved January 21st, 2024 from https://www.businessinsider.nl/mandarin-oriental-massive-fire-at-knightsbridge-london-5-star-hotel-2018-6?international=true&r=US

Maas, J., Verheij, R.A., Groenewegen, P.P., de Vries, S., & Spreeuwenberg, P. (2006). Green space, urbanity, and health: how strong is the relation? *Journal of Epidemiology & Community Health 60*(7), 587-592. https://doi.org/10.1136/jech.2005.043125

Manso, M., & Castro-Gomes, J. (2015). Green wall systems: A review of their characteristics. *Renewable and Sustainable Energy Reviews 41,* 863-871. https://doi.org/10.1016/j.rser.2014.07.203

Martin, Y. (2021). Brandveiligheid: een belemmering voor de ontwikkeling van groene gevels? *WTCB-Contact 2021/3,* p.10-11. Retrieved from https://www.wtcb.be/media/wb4aoalu/contact_nl_03_2021.pdf

Meacham, B.J., Charters, D., Johnson, P., & Salisbury, M. (2016). Building Fire Risk Analysis. *SFPE Handbook of Fire Protection Engineering*, 2941–2991. https://doi.org/10.1007/978-1-4939-2565-0_75

Meacham, B.J., & McNamee, M. (2020). *Fire Safety Challenges of 'Green' Buildings and Attributes*. (Report nr. FPRF-2020-13). Fire Protection Research Foundation. https://content.nfpa.org/-/media/Project/Storefront/Catalog/Files/Research/Research-Foundation/Reports/Building-and-life-safety/RFGreenBuildings2020.pdf?rev=78d79e0c26df4363a7e7261071c5b3dd

Mobilane. (n.d.a). *Architectenmap - MobiPanel.* Retrieved February 23rd, 2024 from https://mobilane.com/nl/producten/mobipanel-groene-gevel/

Mobilane. (n.d.b). *Groene gevels voor nieuw hoofdkantoor LC Packaging met BREEAM Outstanding certificering.* Retrieved February 22nd, 2024 from https://mobilane.com/nl/projecten/groene-gevels-voor-nieuw-hoofdkantoor-lc-packaging-met-breeam-outstanding-certificering/

Mostert De Winter bv. (n.d.). *Stadskantoor Venlo.* Retrieved May 25th, 2024 from https://www.mostertdewinter.nl/nl/onze-projecten/groene-gevels/stadskantoor-venlo/

Nieman & DGMR. (2022). *Borgingsprotocol brandveilige gevels.* Rijksoverheid. Retrieved from https://www.rijksoverheid.nl/documenten/rapporten/2022/01/17/borgingsprotocol-brandveiligheid-gevels

Notcot. (2011). *Ortofabbrica living wall pouches.* Retrieved January 21st, 2024 from http://www.notcot.com/archives/2011/04/ortofabbrica-living-wall-pouch.php

Oak Leaf Gardening. (n.d.). *Inorganic growing media.* Retrieved February 22nd, 2024 from https://www.oakleafgardening.com/glossary-terms/inorganic-growing-media/

van Onna, N. (n.d.). *De Trudo Toren.* Trudo. Retrieved March 20th, 2024 from https://www.trudo.nl/trudo-toren

Onshore Safety Alliance. (2021). *How to Conduct a Risk Assessment Using the What-If Methodology.* Retrieved March 7th, 2024 from https://www.onshoresafetyalliance.org/-/media/BrightfindOSA/Resource-Library/What-If%20Methodology.pdf

Ottawa Fire Services. (n.d.). *Enclosure Fire Development.* The Guides Project. Retrieved February 24th, 2024 from https://guides.firedynamicstraining.ca/g/fd203-enclosure-fires-sd/118181

Ottelé, M. (2011). *The Green Building Envelope: Vertical Greening*. TU Delft. ISBN: 978-90-9026217-8. Retrieved from http://resolver.tudelft.nl/uuid:1e38e393-ca5c-45af-a4fe-31496195b88d

Ottelé, M., Perini, K., Fraaij, A.L.A., Haas, E.M., & Raiteri, R. (2011). Comparative life cycle analysis for green façades and living wall systems. *Energy and Buildings 43*(12), 3419-3429. https://doi.org/10.1016/j.enbuild.2011.09.010

Paison, K. (2022). *Exterior unidentify modern building facade with green vertical garden on corridor sustainability architecture business design concept. - Stockbeeld.* iStock. Retrieved January 21st, 2024 from https://www.istockphoto.com/nl/foto/exterior-unidentify-modern-building-facade-with-green-vertical-garden-on-corridor-gm1415016496-463537251

Perini, K., Ottelé, M., Haas, E.M., & Raiteri, R.(2011). Greening the building envelope, façade greening and living wall systems. *Open Journal of Ecology 1*(1), 1-8. http://dx.doi.org/10.4236/oje.2011.11001

Perini, K., & Rosasco, P. (2013). Cost–benefit analysis for green façades and living wall systems. *Building and Environment 70*, 110-121. https://doi.org/10.1016/j.buildenv.2013.08.012

Primatech Inc. (n.d). *Process hazard analysis.* Retrieved March 7th, 2024 from https://www.primatech.com/technical/process-hazard-analysis

Pritchard & Pritchard. (2023). *Happy 133rd Birthday Stanley Hart White, the inventor of the living wall.* Retrieved February 22nd, 2024 from https://green-roofs.co.uk/stanley-hart-white-greenwallday-inventor-of-the-living-wall-february-15th/

PT Horticulture. (2016). *Fundamentals of growing media.* Hortidaily. Retrieved February, 22nd, 2024 from https://www.hortidaily.com/article/6026715/fundamentals-of-growing-media/

Radic, M., Brković Dodig, M., & Auer, T. (2019). Green Facades and Living Walls—A Review Establishing the Classification of Construction Types and Mapping the Benefits. *Sustainability 11*(17), 4579. https://doi.org/10.3390/su11174579

Range. (n.d.). *Breaking down the 5 decision-making models.* Retrieved March 20th, 2024 from https://www.range.co/blog/decision-making-models

Rijksoverheid. (2024). *Besluit bouwwerken leefomgeving.* BRIS. Retrieved February 21, 2024, from https://www.bouwbesluitonline.nl/docs/wet/bbl

Roehr, D., & Laurenz, J. (2008). Living Skins: Environmental Benefits of Green Envelopes in the City Context. *WIT Transactions on Ecology and the Environment, 113*, 149–158. https://doi.org/10.2495/ARC080151

Sempergreen. (n.d.a). *Certificeringen & Awards.* Retrieved April 26th, 2024 from https://ap.lc/tulIY

Sempergreen. (n.d.b). *Hotel Gilbert.* Retrieved February 25th, 2024 from https://sempergreenwall.com/nl/projecten/hotel-gilbert/

Sempergreen and Mastop Totaaltechniek BV. (n.d.). *Parking garage hospital.* Retrieved February 25th, 2024 from https://sempergreenwall.com/projects/sempergreenwall-parking-garage-hospital-denmark/

Tromp, A.J., & Mierlo, R.J.M. (2014). *Fire Safety Engineering Handboek voor de bouw* (2nd ed.). Eburon.

Ulrich, R.S. (1984). View Through a Window May Influence Recovery from Surgery. *Science, 224*(4647), 420-421. https://doi.org/10.1126/science.6143402

UNFPA. (2016). *Urbanization*. Retrieved on January 7th, 2024 from https://www.unfpa.org/urbanization#readmore-expand

Utanner. (2023). *Delft Quay Wall Garden.* facadeworld. Retrieved March 20th, 2024 from https://facadeworld.com/2023/03/27/delft-quay-wall-garden/

van der Veek, J.H., & Janse, E.W. (2005a). *Brandveiligheid: Ontwerpen en Toetsen. Deel A: Brandveiligheid en gebouwontwerp* (3rd ed.). SBR.

van der Veek, J.H., & Janse, E.W. (2005b). *Brandveiligheid: Ontwerpen en Toetsen. Deel B: Ontwerprichtlijnen voor woningen en woongebouwen* (3rd ed.). SBR.

van der Veek, J.H., & Janse, E.W. (2005c). *Brandveiligheid: Ontwerpen en Toetsen. Deel C: Ontwerprichtlijnen utiliteitsbouw* (3rd ed.). SBR.

van der Veek, J.H., & Janse, E.W. (2005d). *Brandveiligheid: Ontwerpen en Toetsen. Deel D: Bouwdeel- en materiaalgedrag* (3rd ed.). SBR.

Vero Digital. (n.d.). *Wonderwoods.* MVSA architects. Retrieved March 20th, 2024 from https://mvsa-architects.com/en/projects/wonderwoods/

Vertical Meadow. (n.d.). *Bringing biodiversity back into our cities.* Retrieved June 18th, 2024 from https://www.verticalmeadow.com/

VIDOK. (2019). *Bladeren van het onkruid gekiemd op de bakstenen muur. - Stockbeeld.* iStock. Retrieved March 20th, 2024 from https://www.istockphoto.com/nl/foto/bladeren-van-het-onkruid-gekiemd-op-de-bakstenen-muur-gm1151954245-312346646

Vorenkamp, J., Leijendeckers, P.H.H., & van Herpen, R.A.P. (2005). *B-1; Fire Safety Engineering: Het verschijnsel brand*. Klimapedia. Retrieved October 26th, 2023 from https://klimapedia.nl/module/het-verschijnsel-brand/

Wagemans, J.H.M. (2016). *Modularity of Living Wall Systems.* [Master thesis]. TU Delft, Netherlands. Retrieved February 25th, 2024 from https://repository.tudelft.nl/islandora/object/uuid%3Adf5817a8-8425-4835-aff0-1476e479dace?collection=education

Watts, J.M., & Hall, J.R. (2016). Introduction to Fire Risk Analysis. *SFPE Handbook of Fire Protection Engineering*, 2817–2826. https://doi.org/10.1007/978-1-4939-2565-0_72

Węgrzyński, W. (Host). (2023, September). How we have designed a fire safe green wall. (No. 120) [Audio podcast episode]. In *Fire Science SHow.* OFR. Retrieved February 26, 2024 from https://open.spotify.com/episode/2FVXPj87XToljL8GzI70G5

Węgrzyński, W. (Host). (2024, February 21). Development and implementation of the SBI test with Rudolf van Mierlo. (No. 140) [Audio podcast episode]. In *Fire Science SHow.* OFR. Retrieved February 26, 2024 from https://open.spotify.com/episode/6bGC2qNAr8BeWQ96GddWK4

Zioandsons. (2015). Instsagram. Retrieved January 21st, 2024 from https://www.instagram.com/p/391ue2GBgu/

Apendix

Apendix A: interviews

In this apendix a short summary of the most important information gained from the different interviews is shown. For every interview the date when the correspondence occured, how it occured and with whom is mentioned. The interviews are grouped by expertice of the interviewee. As these interviews are all personal communication, they are therfor not incorporated in the reference list.

Risk experts

Genserik Reniers. Risk expert TU Delft. 21/12/23 Physical talk.

Speeking with the risk expert helped in getting an understanding of how risk analyses are performed. They recomended that for the current research a “What-if” analysis was sufficient. They also explained how scenario thinking worked. Differentiation between prevention and mitigation.

Philip Potasse. Manager insurance company Univé. 29/01/24 Physical talk.

As an insurance company you look at potential damage. Insuring against fire risk -> chance of fire and damage. Normally we look at data, but for new developments that data is not there. If you then make an estimate, it can sometimes be wrong.
Look at:
- use of flammable materials
- use of electricity
- nature of business activity
May require compartments.

Fire safety experts

Bauke Knottnerus. Project leader reaction to fire at Efectis. 11/01/24 Physical talk.

A lot of information on legislation and how and why tests are performed the way they are. Focus may be more on inspections of the proper implementation of systems. Already mentioned that there are developments towards larger-scale testing. You should test a product as it is applied, as stated in the standard.

Emily Pearson. Graduate Fire Engineer at ARUP. 15/03/24 Video call.

Important aspects they look at when determining fire risks: evacuation strategy; If there is a fire, is it a problem?; Access for fire brigade; Minimize ignition sources, then look that when ignited what is the possible spread and damage?.
Easy go’s: story 2-5 super chill. Short buildings and bottom of buildings.
Testing: test in the worst case state that is ever present in a forseeable situation. For example, if an irrigation system fails, how long does it take to fix it and how dry becomes the wall in such a situation? Test in this situation. Or if the plants are subject to seasonal changes, test in worst condition. But this is rather complex and is hard to quentivy/make repeatable. Same for when determining how much distance in fire break gaps is needed to work. Depends on plant species, density and moisture content.

Fire safety experts

Rudolf van Mierlo. Fire expert DGMR. 18/03/24 physical talk.

Information on testing methods. How developed and why. What is looked at when determining fire risks of façade systems and products.

LWS manufacturers

Max de Vos. Research and Development Sempergreen. 12/12/23 & 22/02/24 email. 07/06/24 physical talk.

Helped in understanding how their fire classifications were achieved and how the systems were tested. Mentioned that design details are not their responsibility but that of the client. Tested the developed tool and gave relevant feedback on how such a tool could help them as manufacturers in providing better advisc when selling their products to clients. A better understanding on the topic with such a tool can be a benefit for the sector as a whole.

Reinald van Ommeren. Director Virtoria. Loohorst. 23/02/24 email.

Infromation on their product and how they treat fire safety. Their product is being prepared for testing and classification according to the European classification.

GF manufacturers

Foamglas. Eric Linnenbank. Manager Techincal Service. 27/02/24 email.

Information on how they treat fire safety in their company. Tests with foam glass alone are performed but not with the vegation.

Palentis. Leon Heesen. Director. 07/03/24 phone call.

Often ground-based system with metal climbing aid. Does not receive any questions from customers about fire safety, but they have looked into it themselves. Take plant choice into account. Expect the architect to take fire compartmentalization into account.

Designers

Jesse Plas. Specialist in Sustainability and Health. 02/04/23 & 22/02/24 physical talk.

Designers can benefit from a simple tool to quickly determine if a design is on the safe side in terms of fire safety without needing to consult a fire safety expert. This way it can be prevented that later on in the design, changes are necessary to comply with the fire safety requirements.

Eva Stache. Architect with experience in VGS. 17/04/24 video call. 05/06/24 physical talk.

Designers usually avoid fire safety. It is not a topic happily embraced in the design process. It can help designers to have a quick overview of design options that can be used to make sure designs with VGS are fire safe. Tested the developed tool. Found it clear to fill in and that it provides relevant information for a designer. Such a tool can be helpful in the design process.

Juan Carlos. Architect. 04/06/24 physical talk.

Tested the developed tool. Would use the tool as a reference to check design on fire safety aspects. Would prefer a more visual representation of a design, when filling in the tool. Thinks would help in mitigating risks in designs. Tool provides the situation where people can learn from their design.

Ramona. Landscape architect at Felixx. 11/06/24 video call.

Tested the developed tools. Found the information interesting and relevant. Tool was relatively hard to fill in. In her roll as landscape architect could not answer all the façade related questions properly. Tool more relevant for façade designer or architect.

Project developers

Maud en Sebastiaan. Project Developers. 02/04/23 & 22/02/24 video call.

Designers can benefit from a simple tool to quickly determine if a design is on the safe side in terms of fire safety without needing to consult a fire safety expert. This way it can be prevented that later on in the design, changes are necessary to comply with the fire safety requirements.

Apendix B: case-studies risk analysis

In this apendix an overview of the looked at buildings for the risk analysis is shown. The cases are grouped according to the functions found in The Environment Buildings Decree ('Besluit Bouwwerken Leefomgeving' (Bbl)). For every case the specific location for the greening of the façade which was looked at is shown. Furthermore the most relevant characteristics which influences the fire behaviour per case are stated.

The green façade images used are from (Green Guide, n.d.) and the hanging green are from (Greenarea, n.d.).

Residential

Terraced house. No vertical fire compartments. Brickwork façade without transparent parts and light wooden façade with transparent parts.

Gallery apartments. Vertical fire compartments. Brickwork façade without transparent parts. Light wooden façade with transparent parts and concrete protrusions (balconies).

Residential

'Portiekwoning'. Single escape route for upper floors. Vertical fire compartments. Brickwork façade with transparent parts.

Row house. Incombustibe blind façade. Simple escape situation.

Residential

Residential. High rise. Appartments have single escape route (one staircase). Blind icombustible façade. Transparent parts but incombustible cladding.

Residential. High rise. Multiple escape routes. Transparent parts and combustible cladding.

Assembly

Hospitality. Wooden cladding. Steel frame construction. Underground area.

Childcare. Curtain wall façade. Low rise.

Offices

Office. Low rise. Multistory double-skin façade.

Office. High rise (above 20 meters). Curtain wall. Not easy accessible.

Healthcare

Healthcare building with several functions including sleeping area for people with reduced self reliance. Brickwork and transparent parts.

Hospital. Medium rise. Protrusions along the façade between the floors. Cladding unkown. Transparent parts.

Detention

Penitentiaire Inrichting Rotterdam (PI Rotterdam) locatie De Schie. Medium rise building. Transparent parts. Not easily accessible.

(Dijkstra, 2021)

(DJI, n.d.)

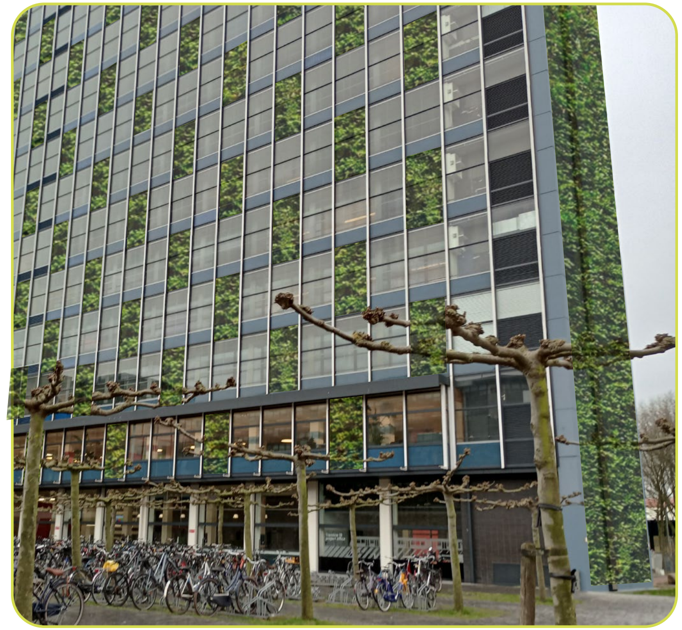
Sports

Sports building. Curtain wall.

Educational

Secondry school. Not easily accessible.

University building. High rise. Curtain wall.



Retail

Multiple retail functions. Low rise. Wooden façade.

Retail. Low rise. Curtain wall. Easy accessible.

Apendix C: weighting with case-studies

Here a few examples of the used case-studies for weighting the detailed tool are shown.

	Low risk
	Medium risk
	High risk

2	(2) Opaque façade with air cavity
1.0	(1) No double skin façade
1	(1) No
1.0	(1) No
2.0	(2) No
2	(2) Yes
1	(1) Yes
1	(1) No
8	Facade overview

Colour coding per parameter factor

	Low risk
	Medium risk
	High risk

Thresholds	<25	25-55	>55
Risk level	Low	Medium	High

Colour coding per category level based on thresholds

1	(1) Other building functions	4	(4) Residential in a residential building, accomodation in an accomodation building
1	(1) Building height <15m	1	(1) Building height <15m
1	(1) One staircase in residential or acc	1	(1) Two staircases on distance >H/2
-	(-) Four façades	-	(-) Four façades
1		4	

Crossing fire compartments not an issue on incombustible blind façade

2	(2) Opaque façade with air cavity	2	(2) Opaque façade with air cavity	2	(2) Opaque façade with air cavity	2	(2) Curtain wall
1.0	(1) No double skin façade	1.0	(1) No double skin façade	1.0	(1) No double skin façade	1.0	(1) No double skin façade
1	(1) No	1	(4) Yes, vertically	4	(4) Yes, vertically	4	(4) Yes, vertically
1.0	(1) No	1.5	(1.5) Yes	1.0	(1) No	1.0	(1) No
2.0	(2) No	2	(2) No	1	(1) Yes, horizontal protrusion >0.5m	2	(2) No
2	(2) Yes	1	(1) No	2	(2) Yes	2	(2) Yes
1	(1) Yes	1	(1) Yes	1	(1) Yes	1	(1) Yes
2	(2) Yes	2	(2) Yes	2	(2) Yes	2	(2) Yes
16	Facade overview	12	Facade overview	32	Facade overview	64	Facade overview

2	(2) System 6: LWSPB	2	(2) System 9: LWSFE	1	(1) System 4: IGFP	1	(1) System 4: IGFP
1.5	(1.5) Horizontal strips	3	(3) Whole façade	2	(2) Vertical strips	2	(2) Vertical strips
2	(2) Yes, <1m distance	1	(1) No	1	(1) No	1	(1) No
2	(2) Yes, <1.5m distance	1	(1) No	1	(1) No	1	(1) No
1	(1) Yes, >1m distance	1	(1) No	1	(1) Yes, >1m distance	1.25	(1.25) Yes, 0.4m<x<1m distance
2	(2) Integrated in the façade	1.5	(1.5) On top of the façade	1	(1) At a distance from the façade >0.5	1	(1) At a distance from the façade >0.5
1	(1) No	1	(1) No	1	(1) No	1	(1) No
2	(2) Yes	1	(1) No	1	(1) No	1	(1) No
1	(1) No	2	(2) Yes	2	(2) Yes	1	(1) No
48	Facade overview	18	Facade overview	4	Facade overview	2.50	Facade overview

2	(2) Combustible; class B	4	(4) Combustible; class C-F	2	(2) Combustible; class B	1	(1) Incombustible; class A1-A2
2	(2 VGS is the cladding	1	(1) Incombustible; class A1-A2	4	(4) Combustible; class C-F	1	(1) Incombustible; class A1-A2
1	(1) No	1	(1) No	1	(1) No	1	(1) No
1.5	(1.5) Wood	1	(1) Steel or aluminium	1	(1) Steel or aluminium	1	(1) Steel or aluminium
6	Facade overview	4	Facade overview	8	Facade overview	1	Facade overview

An orange or red category not necessary unsafe situation

1	(1) Incombustable materials	4	(4) Most material is combustible	1	(1) Incombustable materials	1	(1) Incombustable materials
1.25	(1.25) Yes, every row of modules	1.25	(1.25) Yes, every row of modules	1	(1) Yes, every row of plants	1.25	(1.25) Yes, every row of modules
2	(2) Perennials	2	(2) Perennials	2	(2) Perennials	2	(2) Perennials
1	(1) No	4	(4) Yes, in the system	1	(1) No	1	(1) No
2.50	Facade overview	40.00	Facade overview	2	Facade overview	2.5	Facade overview

Facade 1	Facade 2	Facade 3	Facade 4
1	4	4	4
16.0	12.0	32.0	64.0
48	18	4	2.5
6	4	8	1
2.5	40	2	2.5
Reset all input of facade	Reset all input of facade	Reset all input of facade	Reset all input of facade
2	2	2	2
Good to go	Good to go	Good to go	Good to go




4	(4) Residential in a residential buildin	4	(4) Residential in a residential building,				
1	(1) Building height <15m	2	(2) Building height 15m-40m				
1	(1) Two staircases on distance >H/2	8	(8) One staircase				
-	(-) Four façades	-	(-) Four façades				
4		64					

2	(2) Opaque façade with air cavity	2	(2) Opaque façade with air cavity	2	(2) Opaque façade with air cavity	2	(2) Opaque façade with air cavity
1.0	(1) No double skin façade	1.0	(1) No double skin façade	1.0	(1) No double skin façade	1.0	(1) No double skin façade
4	(4) Yes, vertically	4	(4) Yes, vertically	4	(4) Yes, vertically	4	(4) Yes, vertically
1.0	(1) No	1.0	(1) No	1.0	(1) No	1.0	(1) No
1.0	(1) Yes, horizontal protrusion >0.5m	2	(2) No	2	(2) No	2	(1.5) Yes, horizontal protrusion <0.5r
2	(2) Yes	2	(2) Yes	2	(2) Yes	2	(2) Yes
1	(1) Yes	1	(1) Yes	1	(1) Yes	1	(1) Yes
2	(2) Yes	1	(1) No	2	(2) Yes	2	(2) Yes
32	Facade overview	32	Facade overview	64	Facade overview	48	Facade overview

2	(2) System 6: LWSPB	2	(2) System 8: LWSMW	2	(2) System 9: LWSFE	1	(1) System 5: HGF
1	(1) Patches	1	(1) Patches	1	(1) Patches	1.5	(1.5) Horizontal strips
1	(1) No	2	(2) Yes, <1m distance	2	(2) Yes, <1m distance	2	(2) Yes, <1m distance
1	(1) No	2	(2) Yes, <1.5m distance	2	(2) Yes, <1.5m distance	2	(2) Yes, <1.5m distance
1	(1) Yes, >1m distance	1	(1) No	1	(1) No	1.5	(1.5) Yes, <0.4m distance
1	(1) At a distance from the façade >0.5	1.5	(1.5) On top of the façade	2	(2) Integrated in the façade	1.5	(1.5) On top of the façade
2	(2) Yes, but other escape route	1	(1) No	1	(1) No	1	(1) No
2	(2) Yes	1	(1) No	1	(1) No	1	(1) No
2	(2) Yes	1	(1) No	1	(1) No	1	(1) No
16	Facade overview	12	Facade overview	16	Facade overview	13.50	Facade overview

System with less fuel load

2	(2) Combustible; class B	4	(4) Combustible; class C-F	4	(4) Combustible; class C-F	2	(2) Combustible; class B
4	(4) Combustible; class C-F	1	(1) Incombustible; class A1-A2	2	(2 VGS is the cladding	2	(2) Combustible; class B
1	(1) No	1.25	(1.25) Yes, < half thickness spouwbl	1.25	(1.25) Yes, < half thickness spouwbl	2	(2) Yes, > half thickness spouwblad
1	(1) Steel or aluminium	1	(1) Steel or aluminium	1	(1) Steel or aluminium	1	(1) Steel or aluminium
8	Facade overview	5	Facade overview	10	Facade overview	8	Facade overview

1	(1) Incombustable materials	1	(1) Incombustable materials	1	(1) Incombustable materials	1	(1) Incombustable materials
1.25	(1.25) Yes, every row of modules	1.25	(1.25) Yes, every row of modules	1.25	(1.25) Yes, every row of modules	1.25	(1.25) Yes, every row of modules
1	(1) Evergreens	1	(1) Evergreens	1.5	(1.5) A mixture of evergreens and pere	2	(2) Perennials
1	(1) No	1	(1) No	1.5	(1.5) Yes, not in the system	1	(1) No
1.25	Facade overview	1.25	Facade overview	2.8125	Facade overview	2.5	Facade overview

Change material choice of system

Facade 1	Facade 2	Facade 3	Facade 4
4	64	1	16
32.0	32.0	64.0	48.0
16	12	16	13.5
8	5	10	8
1.25	1.25	2.8125	2.5
Reset all input of facade	Reset all input of facade	Reset all input of facade	Reset all input of facade
2	4	4	3
	Consult fire safety expert or change design	Consult fire safety expert or change design	Consult fire safety expert or change design




4	(4) Residential in a residential buildir	4	(4) Residential in a residential building,			8	(8) Healthcare with sleeping area, he
1	(1) Building height <15m	2	(2) Building height 15m-40m			2	(2) Building height 15m-40m
1	(1) Two staircases on distance >H/2	8	(8) One staircase			1	(1) Two staircases on distance >H/2
-	(-) Four façades	-	(-) Four façades			-	(-) Four façades
4		64				16	

2	(2) Opaque façade with air cavity	2	(2) Opaque façade with air cavity	2	(2) Opaque façade with air cavity	2	(2) Opaque façade with air cavity
1.0	(1) No double skin façade	1.0	(1) No double skin façade	1.0	(1) No double skin façade	1.0	(1) No double skin façade
4	(4) Yes, vertically	4	(4) Yes, vertically	4	(4) Yes, vertically	4	(4) Yes, vertically
1.0	(1) No	1.0	(1) No	1.0	(1) No	1.0	(1) No
1.0	(1) Yes, horizontal protrusion >0.5m	2	(2) No	2	(2) No	2	(1.5) Yes, horizontal protrusion <0.5r
2	(2) Yes	2	(2) Yes	2	(2) Yes	2	(2) Yes
1	(1) Yes	4	(4) No	1	(1) Yes	1	(1) Yes
2	(2) Yes	1	(1) No	2	(2) Yes	2	(2) Yes
32	Facade overview	128	Facade overview	64	Facade overview	48	Facade overview

No-go with ∞

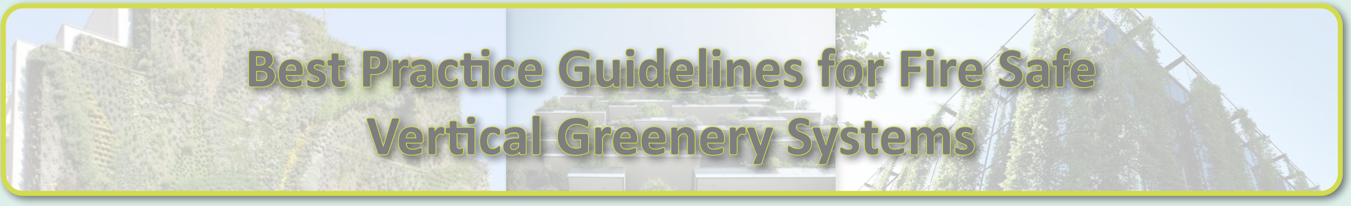
2	(2) System 6: LWSPB	2	(2) System 8: LWSMW	2	(2) System 9: LWSFE	2	(2) System 8: LWSMW
1.5	(1.5) Horizontal strips	1	(1) Patches	3	(3) Whole façade	1.5	(1.5) Horizontal strips
1	(1) No	2	(2) Yes, <1m distance	2	(2) Yes, <1m distance	2	(2) Yes, <1m distance
1	(1) No	2	(2) Yes, <1.5m distance	2	(2) Yes, <1.5m distance	2	(2) Yes, <1.5m distance
1	(1) Yes, >1m distance	1	(1) No	1.5	(1.5) Yes, <0.4m distance	1.5	(1.5) Yes, <0.4m distance
1	(1) At a distance from the façade >0.5	1.5	(1.5) On top of the façade	2	(2) Integrated in the façade	1.5	(1.5) On top of the façade
∞	(∞) Yes, no other escape route	1	(1) No	1	(1) No	1	(1) No
2	(2) Yes	1	(1) No	1	(1) No	1	(1) No
2	(2) Yes	1	(1) No	1	(1) No	1	(1) No
∞	Facade overview	12	Facade overview	72	Facade overview	27.00	Facade overview

2	(2) Combustible; class B	4	(4) Combustible; class C-F	4	(4) Combustible; class C-F	2	(2) Combustible; class B
4	(4) Combustible; class C-F	1	(1) Incombustible; class A1-A2	2	(2 VGS is the cladding	2	(2) Combustible; class B
1	(1) No	1.25	(1.25) Yes, < half thickness spouwbl	1.25	(1.25) Yes, < half thickness spouwbl	2	(2) Yes, > half thickness spouwblad
1	(1) Steel or aluminium	1	(1) Steel or aluminium	1	(1) Steel or aluminium	1	(1) Steel or aluminium
8	Facade overview	5	Facade overview	10	Facade overview	8	Facade overview

4	(4) Most material is combustible	4	(4) Most material is combustible	2	(2) Incombustible support structure	2	(2) Incombustible support structure t
1.25	(1.25) Yes, every row of modules	1.25	(1.25) Yes, every row of modules	1.25	(1.25) Yes, every row of modules	1.25	(1.25) Yes, every row of modules
1	(1) Evergreens	1	(1) Evergreens	1.5	(1.5) A mixture of evergreens and pere	2	(2) Perennials
1	(1) No	1	(1) No	1.5	(1.5) Yes, not in the system	1	(1) No
5.00	Facade overview	5.00	Facade overview	5.625	Facade overview	5	Facade overview

Facade 1	Facade 2	Facade 3	Facade 4
4	64	1	16
32.0	128.0	64.0	48.0
∞	12	72	27
8	5	10	8
5	5	5.625	5
Reset all input of facade	Reset all input of facade	Reset all input of facade	Reset all input of facade
∞	6	6	5
NO-GO, change the design	NO-GO, change the design	NO-GO, change the design	NO-GO, change the design

Apendix D: infographic



Best Practice Guidelines for Fire Safe Vertical Greenery Systems

With the increasing interest and use of vertical greenery systems (VGS), it is important to keep up with these inovations in terms of fire safety. The current infographic is developed to give a quick overview of best practices to make sure designs with VGS are designed in fire safe ways.

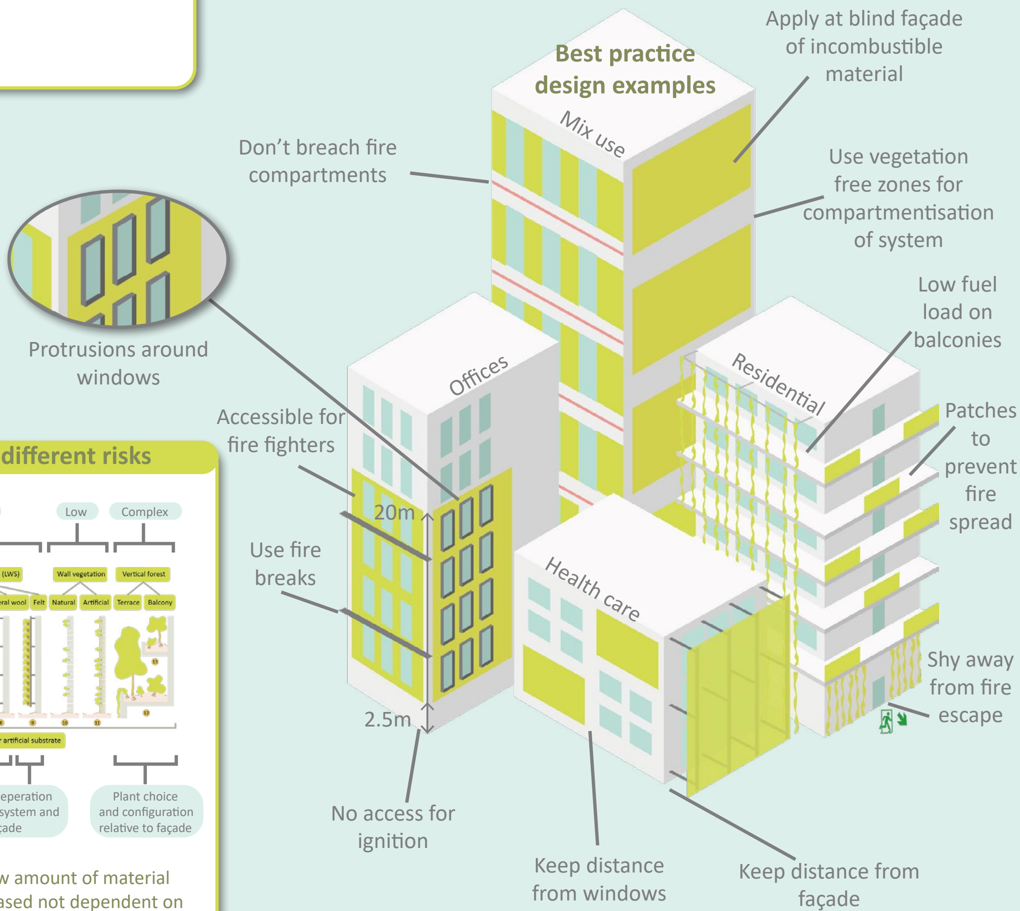
Key design considerations

Do's

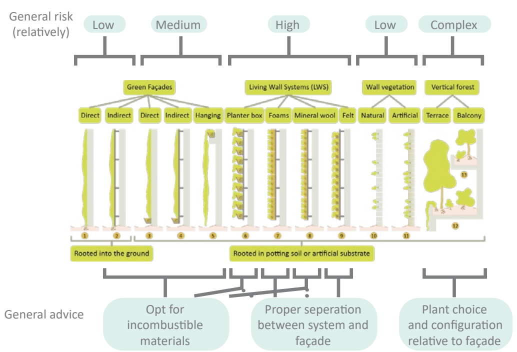
- Use automatic irrigation system
- Have a maintenance contract in place
- Use incombustible materials in the system
- Keep a distance from windows
- Façade accesssible to fire fighters
- Shy away from escape routes
- Use 'patches' in riskier situations
- Use low fuel load on balconies
- Keep a distance to the façade

Extra measures

- Fire breaks at borders of fire compartments
- Fire breaks around windows
- Vegetation free zones
- Monitoring system of VGS



Different systems pose different risks



- Green façades: low risk because low amount of material is used, so low fuel load. Ground based not dependent on extra irrigation.
- LWS creates air cavity and uses a lot of material. Air cavity is especially in combiation with plastic high risk. Proper protection from a fire reaching the air cavity necessary, for example with fibre cement board. Make use of incombustible materials when possible.
- Wall vegetation has low fuel load so low risk.
- Vertical forests are complex and especially when using trees introduces high fuel loads on the building.

Don'ts

- Don't cut back on maintenance
- Don't use plastic on combustible façade or near windows
- Don't breach borders of fire compartments
- Don't threaten all possible escape routes