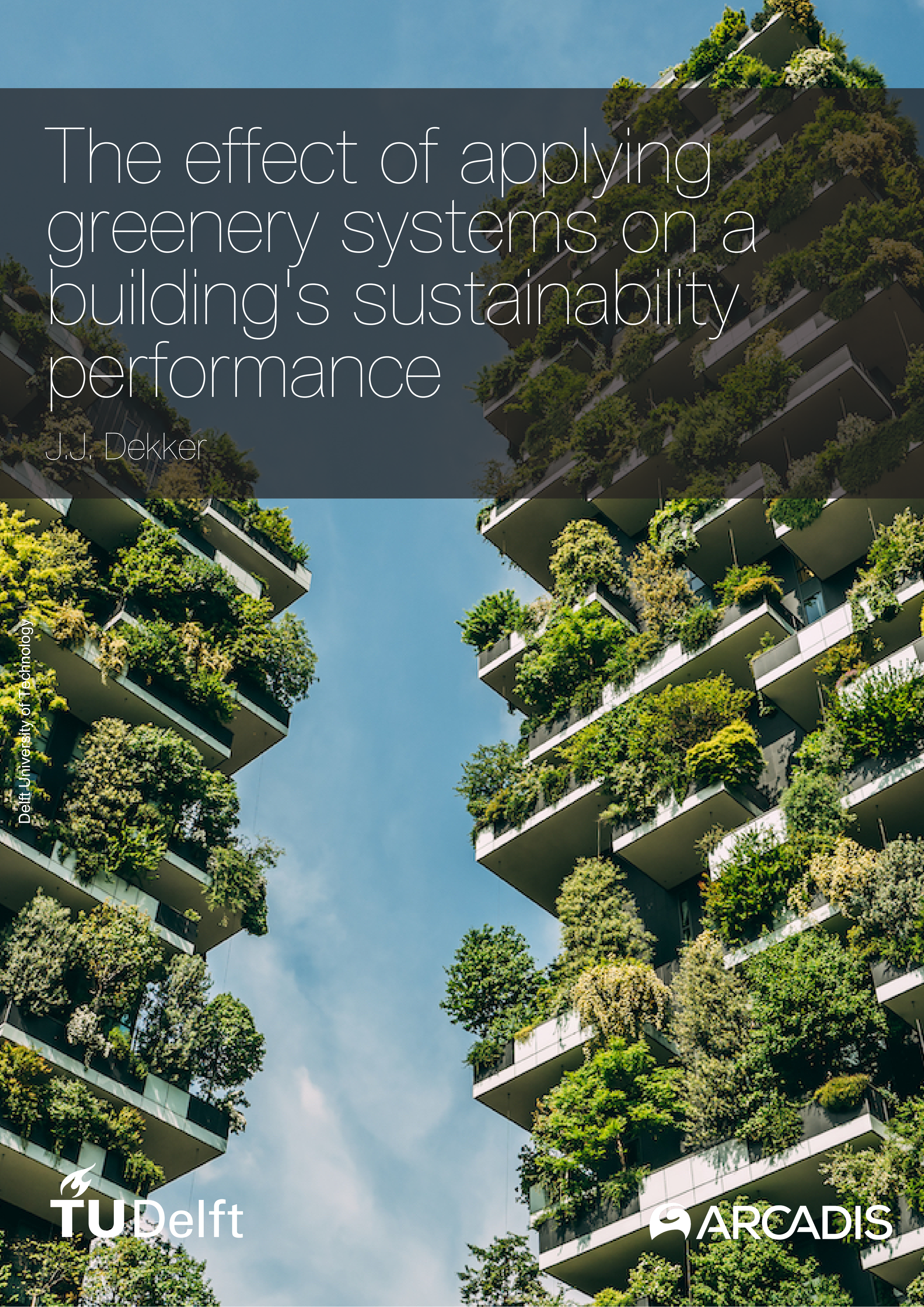

The effect of applying greenery systems on a building's sustainability performance

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ARCADIS

The effect of applying greenery systems on a building's sustainability performance

by

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Cover Image: Bosco Verticale, the innovative architecture design (Sabino Parente) [1]

Preface

When seeing large buildings with trees on the façades such as Bosco Verticale, a few questions popped into my mind: does this really make a building more sustainable and does this extra weight not have large effects on the load bearing structure of this building? Over the past few months I have worked on answering these questions focusing on the influence of greenery systems on the overall sustainability of a building. In front of you lies the result of my work: my MSc Thesis. This thesis document serves as the last part needed for the completion of my Masters in Civil Engineering at the Delft University of Technology.

This thesis could not have been completed without the support I received from the people around me. First of all I would like to thank Meint Smith, my supervisor from Arcadis, the firm at which I performed my thesis research. He gave me valuable inside into common engineering practices and was of great help when in need of a sparring partner about some decisions. In addition to this my three supervisors from TU Delft, Henk Jonkers, Marc Ottelé and Sander Pasterkamp all provided me with valuable tips and insights in completion of this research. I would like to thank them greatly for their feedback and help when needed. In addition to this I would like to thank my colleagues at Arcadis for offering me a place in their team and creating a nice working environment. The experts at Arcadis that I spoke to about various topics also deserve my gratitute. A special thank you goes out to Vanessa Schuphof-Veenstra and Wiljan Houweling.

Lastly, I would like to thank my family and friends for their support and willingness to think think with me about my thesis when I just needed a second opinion. Especially my roommates who were there to listen to the highlights and setbacks of my research or offered some good distraction when needed.

With the completion of this research I hope people will find that they have a better idea of the value of the application of greenery systems and that it might have a possible impact on the sustainability of our cities for the future.

I wish you much pleasure in reading this thesis.

J.J. Dekker
Rotterdam, June 2024

Summary

Urbanisation has increased the worlds' cities populations. This has influenced the living conditions within these cities. Temperatures rise, the air becomes more polluted and noise levels increase. It has been proven that types of vegetation such as plants and trees can reduce the negative effects of urbanisation by for instance cooling cities, filtering the air or damping out noise. A total of seven benefits provided by greenery systems can be distinguished. Due to the limited space in urban areas, placing vegetation on building façades and roofs can be a practical solution to gain the benefits of natural elements without the need for large pieces of land. The benefits of greenery systems have been researched intensively, however it is unknown how these benefits compare to the downsides of adding extra loads to a structure. The downsides come in the form of extra material use which leads to an increased environmental impact for the building. In this research these benefits and downsides were compared to determine whether the application of greenery systems actually makes the building more sustainable or not. Vegetation can be placed on buildings in various different types of systems. In this research the effect of six horizontal greenery systems (also known as green roofs) and eight vertical greenery systems (also known as green façades) on the sustainability of the building was assessed.

The effects of the benefits of the greenery systems on the sustainability of the building were determined using three different certification methods: BREEAM, LEED and WELL. In these certification methods credits related to one of the seven benefits can award the building a preset amount of points, thereby increasing the overall amount of points awarded to the building. The impact of extra material use was determined using the environmental cost indicator (ECI), after determining the needed element sizes for a steel, concrete and timber variant of a building. The percentage increase of the sustainability certification score and the ECI were compared to determine which of the two has a higher percentage increase. When the increase in the sustainability certification score is larger than the increase in ECI, the greenery system receives a 'positive score' meaning the building has become more sustainable. If this is the other way around, the greenery system has a 'negative score' meaning application of the greenery system has made the building less sustainable. When both are equal, which in this thesis is the case when both scores have an increase of 0%, the system has a 'neutral score'.

It can be concluded that the certification methods used in this research are not able to cover all of the seven benefits provided by greenery systems. Modifications and improvements are needed so they can assess all benefits. Of the three certification methods BREEAM is currently the best fit because it has the most credits that can be linked to one of the seven benefits, thereby covering the most aspects of greenery systems. Despite the certification methods not being able to cover all benefits it was found that in 52% of the tested cases the application of a greenery system will result in a positive score based on the benefits that can be taken in to account. This means the sustainability score increased more in percentage terms than the ECI value of the building. A negative score is obtained in 27% of the cases, while 21% of the cases receives a neutral score. The nature roof always receives a positive score and application of a direct green façade can result in a positive or neutral score but never a negative score. These two systems can thus always be applied to a building without having a negative effect on the building's sustainability. It is found that horizontal greenery systems more often receive a positive score than the vertical greenery systems. The horizontal greenery systems are often specifically mentioned as a means to obtain the points available for a credit. This has resulted in a higher percentage of horizontal greenery system cases receiving a positive score. As mentioned, of the thee certification methods BREEAM was determined to be the best suitable for scoring the most aspects of greenery systems. This was also translated into a higher number of positive scores using BREEAM. Using BREEAM results in a positive result 93% of the time, while LEED and WELL receive a positive score 52% and 12% of the time respectively.

This research has shown that it is currently not possible to value all aspects of greenery systems in the certification methods used. Nonetheless, greenery systems lead to an increased sustainability

of a building in 52% of the tested cases. There is potential for modification of the existing certification methods so they can score all benefits provided by the greenery systems properly, giving more insight into the impact of these greenery systems on a building's sustainability and potentially affecting the number of cases with a positive score.

Contents

Nomenclature

Abbreviations

Abbreviation	Definition
BENG	Bijna Energieneutrale Gebouwen
BRE	Building Research Establishment
BREEAM	Building Research Establishment Environmental Assessment Method
BSDT	Building Structural Design Tool
BSGR	Biosolar Green Roof
CLT	Cross Laminated Timber
DGF	Direct Green Façade
ECI	Environmental Cost Indicator
EGR	Extensive Green Roof
EGRBS	Extensive Green Roof - Bio-Solar
EGRLW	Extensive Green Roof - Light Weight
EGRN	Extensive Green Roof - Nature
EGRR	Extensive Green Roof - Retention blue
EP	Exemplary Performance
GBCI	Green Business Certifcation Inc.
GBRS	Green Building Rating System
GF	Green Façade
GST	Greenery Systems Tool
HERS	Home Energy Rating System
HGS	Horizontal Greenery System
IGF	Indirect Green Façade
IGFC	Indirect Green Façade with Continuous guides
IGFT	Indirect Green Façade with modular Trellis
IGR	Intensive Green Roof
IGRG	Intensive Green Roof - Garden
IGRR	Intensive Green Roof - Retention blue
LCA	Life Cycle Assessment
LEED	Leadership in Energy and Environmental Design
LWS	Living Wall System
LWSC	Continuous Living Wall System
LWSL	Linear Living Wall System
LWSMB	Living Wall System with Modular framed Boxes
LWSMT	Living Wall System with Modular Trays
MPG	Milieu Prestatie Gebouwen
PM	Particulate Matter
SFB	Slim Floor Beam
UHI	Urban Heat Island
USGBC	United States Green Building Council
VF	Vertical Forest
VGS	Vertical Greenery System
VO	Voorlopig Ontwerp

Symbols

Symbol	Definition	Unit
AC_D	Combined drag factor	
G	Permanent loads	
Q	Variable loads	
q	Distributed load	kN/m^2
$\boldsymbol{U}$	Time-varying wind velocity	m/s
$\dot{\boldsymbol{X}}$	Time-varying plant velocity	m/s
ϵc_D	Combined drag coefficient	
ρ	Density	kg/m^3

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1 Introduction

This chapter will discuss the current state of the art on the subject of the use of green façades and roofs in urban areas. The usefulness and current knowledge on the subject will be outlined and the relevance of the proposed research will be discussed.

1.1. Urbanisation

Over the past centuries the population of the earth has continued to grow and reached a total of 8 billion people by November 2022 [2]. It is predicted that the world population will grow even further and that in the year 2050 between 9.4 billion and 10 billion people will inhabit the earth [2], as illustrated in Figure 1.1.

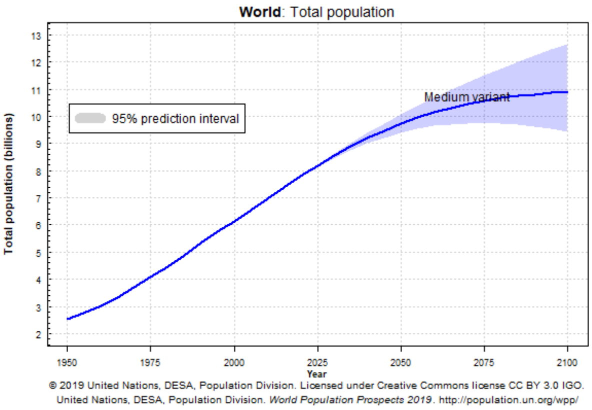


Figure 1.1: Total world population [2]

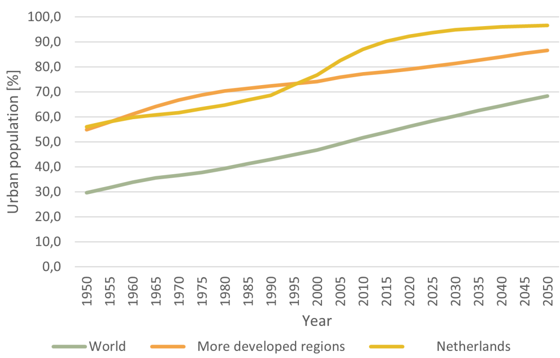


Figure 1.2: Urban population as part of the total population 1950-2050 (own work, data from [3])

In addition to the growing number of people on this planet, the percentage of the world population that lives in urban areas is increasing as well. More people choose to live in the cities and multi-million metropolises are not a rare sight. In 1950 the population of urban areas made up 29.6% of the world population. By 2018 this percentage had already risen to 55.3% and in 2050 this percentage is projected to be 68.4%, according to the United Nations Department of Economic and Social Affairs - Population Division [3]. More developed regions (Europe, Northern America, Australia, New Zealand and Japan) will have an even higher urban population in terms of percentage which will reach a projected 86.6% in 2050 [3]. In the Netherlands specifically the rate of urbanisation is even higher than that. In 2018 the percentage of the population that resides in urban areas was 91.5%, and it is predicted that in the year 2050 96.6% of the Dutch people will live in urban areas [3]. The percentage of the urban population as part of the whole population for the world, the more developed regions, and the Netherlands can be seen in Figure 1.2.

As the populations of the worlds cities grow, living conditions within the cities are subject to change [4]. Due to urbanisation, both the lay-out of and function of these areas are adjusted. Buildings will be built closer together and become higher, often at the cost of natural elements such as trees and plants [5, 6]. The construction of urban areas, which leads to radiative trapping, wind obstruction and low surface permeability, in combination with other human activities causes heat accumulation and therefore higher temperatures in these urban areas [5]. This effect where the temperature in urban areas is higher than the temperature in surrounding rural areas is also called the Urban Heat Island (UHI) effect [7]. Due to this effect, urban temperatures are on average 1 to 3°C higher than in the surrounding rural areas [8, 9], cited in [5]. Other effects of urbanisation include noise levels becoming higher and the air quality worsening [4]. Increased traffic intensity in urban areas contributes to both of these effects [10]. Air pollution in urban areas is mainly caused by traffic emissions [11, 12] as the combustion in motor vehicles produces particulate matter $PM_{2.5}$ [13], which has a negative influence on human health [14]. A worse air quality due to pollution of the air can lead to serious health issues. The life expectancy of people exposed to air pollution related to traffic for a long time may be shorter due to the pollution [15]. According to Landrigan [16] an estimated 6.4 million deaths each year have been caused by air pollution. Nature in cities, either on street levels or in building envelopes, has proved to be useful for the improvement of the living conditions within urban areas and help diminish the problems as stated in this paragraph [4].

1.2. Advantages of nature in cities

As mentioned above, nature in cities can help to reduce several negative effects of the way urban areas are currently shaped [4, 18, 19]. Vertical Greenery Systems (VGS) have shown to be able to reduce noise levels and cool down urban areas. In addition to this they can improve the quality of the air in the area and have a positive effect on happiness of people and urban biodiversity [4, 20].

Research by Scheuermann *et al.* [4] also shows that the use of greenery systems in urban areas can reduce the outside temperature. Especially in urban areas where the height to width ratio (H/W ratio) of the streets is greater than two, the influence of the UHI effect can be heavily reduced. For these type of urban areas Scheuermann *et al.* [4] modelled a reduction of the peak temperature of up to 10°C. They also found that VGS can not only reduce outside temperatures, but can also be used to cool the inside of buildings by working as a form of insulation. To obtain the largest reduction of the inside temperature, the optimal situation would be a street with an H/W ratio smaller than one, and a sunny climate [4].

In addition to this temperature decrease, noise levels can also be reduced by up to 10 dB(A) by VGS. The effect of VGS on the acoustics in an area seems to be the largest during the night according to Scheuermann *et al.* [4]. They also found that the improvement in noise level

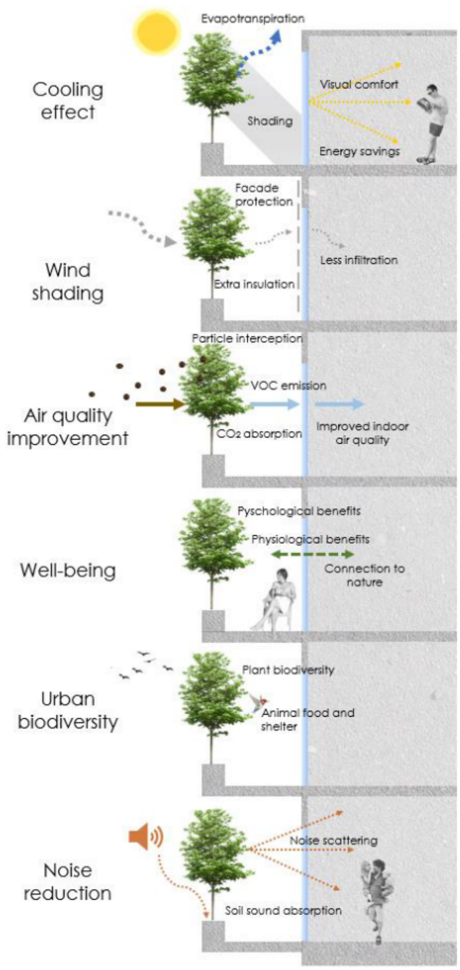


Figure 1.3: Potential benefits of green balconies [17]

reduction becomes larger when the distance from the noise source increases.

As mentioned in Section 1.1, urbanisation has caused air pollution within urban areas. It has been found that greenery systems in the building envelope can improve the air quality by reducing the amount of PM, O_3, NO_2 and SO_2 [21, 22]. In addition to this health benefit, VGS and Horizontal Greenery Systems (HGS) can also provide other benefits. Elsadek *et al.* [23] found that people that see green façades feel more relaxed and their mood improves. In addition to that their research suggests that seeing green façades releases feelings of comfort and cheerfulness. They conclude that citizens of urban areas could benefit from green façades both physiologically and psychologically.

1.3. Consequences of nature in the building envelope

Applying greenery systems in the building envelope can have consequences for the design of the structure of the building. The extra load can result in the need to change the design of the load bearing structure, for instance increasing the cross sections of certain members or changing the grid size of the design. These changes can result in an increased volume of material used for the load bearing structure. Using more material leads to a higher carbon footprint for the building in question. According to Wiedmann and Minx [24] the carbon footprint can be defined as follows: "The carbon footprint is a measure of the exclusive total amount of carbon dioxide emissions that is directly and indirectly caused by an activity or is accumulated over the life stages of a product."

1.4. Green façade and roof systems

Different types of greenery systems exist. They can be divided into two main categories, horizontal greenery systems (HGS), commonly known as green roofs, or vertical greenery systems (VGS), also known as green façades. Within these two groups many variations are possible. Green roof systems can vary from simple types with low growing vegetation like grasses to the heavier types that include trees as well [25, 26]. The same is true for green façades, which can consist of a lightweight climber plant on the one hand or a heavy system with balconies that support trees like in Bosco Verticale, Milan, on the other hand [17, 27–29].

Figure 1.4: A type of green façade with climber plants in Germany [30]

Figure 1.5: A building with a green roof with trees [31]

1.5. Research gap

As discussed in this chapter, a lot of information about the application of greenery systems is known. It is known that the greenery systems can contribute to bettering living condition in urban areas. The total effect of greenery systems on the sustainability of a building however is not always known. The research gap that this research aims to fill considers the relation between the positive effects on the sustainability value of a building provided by the greenery systems on the one hand and the need for extra supporting material on the other hand. The use of extra supporting material can lead to an increased carbon footprint. It is important to know whether or not the positive effects of the added greenery systems outweigh the negative effects of the extra material needed for the load bearing construction. Currently the insight into this so called 'tipping point' is limited. Therefore, the aim of this research is to create more insight into this situation.

2 Methodology

2.1. Goal and research questions

The goal of this thesis is to give more insight into the effect of VGS and HGS on the sustainability of a building. Part of this insight includes finding the 'turning point' for a building, where the positive effects of greenery systems are no longer of greater value than the negative effects caused by the need of extra material in the load bearing structure to support the greenery system. For this research the main research question is defined as follows:

> **When does the application of a greenery system have a positive effect on the sustainability performance of a mid rise building in an urban area?**

To answer the main research question, the following sub-questions are formulated.

1. *How can the sustainability of a building with greenery systems be determined?*
   The sustainability of buildings can be determined in different ways. Different types of rating systems for the sustainability of buildings will be investigated and compared to determine the best fit for this research.

2. *What are the differences in building characteristics for different use-purposes of buildings?*
   Different types of buildings will be assessed and the main building characteristics will be determined.

3. *Which types of horizontal greenery systems exist?*
   An inventory will be made to determine the differences between the different types of HGS.

4. *Which types of vertical greenery systems exist?*
   An inventory will be made to determine the differences between the different types of VGS.

5. *What is the positive impact on the sustainability certification score of the building caused by application of a greenery system?*
   For each greenery system it must be determined what the positive effects are and how they influence the sustainability score of the building.

6. *What is the impact of the different greenery systems in terms of added loads?*
   The goal of this research question is to find the value of the added loads due to the implementation of a greenery system. These added loads include self weight of the systems, but also possible increased values of for instance wind and snow loading.

7. *What is the influence of the added loads due to greenery systems on the amount of material needed for the load bearing construction and the sustainability score?*
   A model will be used to find the the optimal design for a building with greenery systems applied

that is both structurally safe and has the lowest volume of materials used. This design will be compared with a design without greenery systems.

2.2. Methodology

To answer the research questions, the following methodology will be applied.

Sub-questions 1 to 5 will be answered through a literature study. Information that needs to be found in literature includes the different types of greenery systems and their properties. One of the properties of the different systems considers the positive effect on the sustainability score. This positive influence is caused by the so called positive environmental effects such as heat reduction, noise reduction and air purification. These values must be quantified, and this will happen based on literature study. It is however possible that not all these effects have been quantified yet. Assumptions will have to be made for the missing values. In addition to the literature research, interviews will be scheduled with people from Arcadis and possibly other parties that have worked on this subject. Their insights might prove useful to determine which types of greenery systems are most often used in practice.

To answer sub-question 6 the added loads caused by a VGS or HGS must be determined. Included in these added loads will be the self weight of both the plants used and the supporting system of the greenery system, e.g. balconies, containers or a cable system, and if needed soil and the water providing system that are present in some types of systems. Increased variable loads such as wind and snow loading will also be taken into account. For each greenery system an average load per area will be determined. This will mostly be done by using literature and previously performed studies. The information will be stored in a database that will serve as the basis for a tool that gives more insight into the different greenery systems.

To answer sub-question 7 a structural design tool will be used, which is made by Arcadis. The tool is made in the Viktor environment. The tool will be used to test the influence of greenery systems on a mid-rise building which is constructed out of either concrete or steel. For the variant made of timber a seperate model in RFEM will be used. The different greenery systems as distinghuished in the previous part of this research will be put on the building. The tool should give as output the unity checks (U.C.) to make sure the building is structurally safe as well as volume of material used for the load bearing structure of the building. The U.C. and the material volume should be given for both the building with the greenery systems applied, as well as for the building without greenery systems. In this way the values can be compared and it can be concluded whether or not the application of greenery systems had a positive or negative impact on overall sustainability of the building. With the tools the different greenery systems will be tested. Because the tool will be used to test buildings constructed with different materials, this will also show if applying a greenery system on a building of timber gives a very different change in construction material use than applying a greenery system on a steel or concrete building. For this sub-question a case study will be performed on the building Urban Woods, which is currently being constructed in Delft. Arcadis has worked on the calculations for this project.

After the sub-questions have been answered, the main research question is answered with the information gathered from the sub-questions. This will be done by comparing the results acquired for sub-questions 5 and 7 which consider the positive and negative effects on the sustainability score respectively. This comparison will be made based on the case study of Urban Woods.

2.3. Scope

This thesis is aimed at mid rise buildings with an office or residential function in an urban environment, where environmental effects due to construction are the largest as explained in Chapter 1. For this research the lay-out and urban environment of a Dutch city will be assumed when needed. This might for instance be necessary when a H/W ratio is used to determine the effect of the greenery system on temperatures both inside and outside the building. It is assumed that the building in question covers the entirety of the plot.

This thesis will focus on new buildings. This is because when more material would be needed to support the added weight, this can easier be applied in the design phase of new building. For existing buildings reinforcement can be applied, but in such cases it would probably be easier to apply a system that does not require reinforcement due to its limited weight.

Quantifying all the positive environmental effects of greenery systems is still a big issue surrounding this subject. In this research values will be based on available literature. The positive effects that have no established quantified value will receive an assumed value based on the information that is available. Quantifying these values however is not the aim of this research, so an extensive quantification will not be performed in this thesis.

The ultimate comparison to answer the main research question will be made based on a case study. For the case study the building Urban Woods has been chosen. This is a building that is currently being constructed in Delft. The building has a residential function and is constructed out of timber elements. In addition to this, the building contains greenery systems as well. More information about Urban Woods is given in Chapter 7.

Part I
Theoretical framework

3 Defining sustainability

The sustainability of a building can be defined using a few different systems. These so called Green Building Rating System (GBRS) all have their own advantages and disadvantages. GBRS are used to evaluate and enhance the sustainability of building projects [32]. Generally, the GBRS's try to make it easier to improve the operational performance of the building, to make the environmental impact as low as possible, to estimate the impact of the building on the environment and to judge the development of the building [32, 33].

Nguyen and Altan [34] compared five different GBRS's (BREEAM, LEED, CASBEE, GREEN STAR and HK-BEAM) on various different aspects such as popularity and influence, methodology, user friendliness and accuracy and verification. From their research performed in 2011 BREEAM and LEED scored the highest. In this chapter five different rating systems will be discussed to find the system that best fits the purpose of this research. The two highest scoring GBRS's from the research by Nguyen and Altan [34], BREEAM and LEED, have been chosen and will be supplemented with two more methods, which are ECI and and WELL. GPR Gebouw was also considered as one of the GBRS's to be used. This method was however dropped because no reference certification of a building was available. A general impression of GPR Gebouw is given in Appendix A.

For each of the certifications BREEAM-NL, LEED and WELL credits have been selected that have the potential to award points by applying a greenery system. These credits were selected using the seven benefits that were introduced in Chapter 1 and are shown in Figure 3.1.

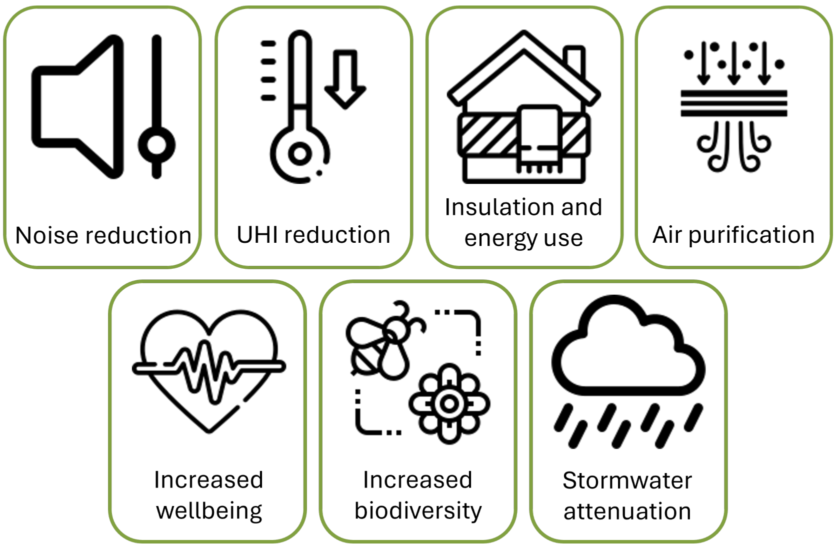


Figure 3.1: Benefits of greenery systems (own work, icons from [35])

3.1. BREEAM-NL

The first certification method that will be discussed is BREEAM (Building Research Establishment Environmental Assessment Method). The information about the BREEAM qualification method as discussed in this section was retrieved from BREEAM [36]. BREEAM is a certification method that can be used to determine the sustainability of a building. It has been in use since 2009 as the first sustainability quality mark in the world and is currently used in over 80 countries as the international standard. The tool was originally made by the BRE (Building Research Establishment). It was later made more specific to fit the Netherlands by the Dutch Green Building Council, which resulted in BREEAM-NL. BREEAM-NL has four different quality marks which can be used for different types of projects. The four quality marks are "New Construction and Renovations", "In-Use", "Area" and "Demolition & Disassembly". For this research the quality mark New Construction and Renovations is the best fitting one because this research focuses on new buildings. Within the New Construction and Renovations module a building is judged and scored on nine different categories which all contain credits. The nine different categories are shown in Table 3.1. Each category contains a number of credits making a total of 49 credits. For each credit within a category certain criteria are defined that have to be met in order to receive (part of) the predetermined number of points for this credit. A total of 163 points can be earned. In the end all category scores are summed to obtain the total BREEAM score of the construction project. Based on percentage of the points obtained, the project is given a qualification which can be Unclassified, Pass, Good, Very good, Excellent or Outstanding. The needed scores for each qualification are shown in Table 3.2.

Table 3.2: BREEAM-NL qualifications [36]

BREEAM-NL qualification	Score
Outstanding	$\geq 85\%$
Excellent	$\geq 70\%$
Very good	$\geq 55\%$
Good	$\geq 45\%$
Pass	$\geq 30\%$
Unclassified	$< 30\%$

Some credits allow for the awarding of additional points for an Exemplary Performance (EP). These extra points are also called innovation points. These points are kept separately from the normal points and when the percentage of points obtained is calculated 1% may be added to the total percentage score for each innovation point obtained, up to a total of 10%. For some qualification levels specific credits are mandatory to earn in order to receive that qualification level. For instance, if a project manager aims to receive the classification 'Excellent', the environmental impact of the used of the energy and water usage for this project must be monitored. To obtain an 'Outstanding' classification, it is mandatory to monitor the environmental impact of the building materials, ground work and waste as well. Apart from these mandatory points, project managers can choose which credits they want to earn in order to receive enough points for the wanted qualification. When the project fails to obtain more than 30% of the points, the project falls into the category unclassified. The minimum requirements are thus not met and therefore the project does not receive a sufficient BREEAM-NL classification.

As can be seen from the different categories and the credits that can be earned, there are some credits for which a more positive score could be obtained when implementing a vertical or horizontal greenery system because greenery systems help improving certain aspects of the building and its environment. Points could be earned for instance the credits acoustic performance or energy efficiency. Categories where greenery systems could potentially lead to an increased number of points earned are highlighted in green in Table 3.1. A few credits must be mentioned as the name might sound like they can award points for greenery systems, but this is actually not the case, which is why they are not highlighted in Table 3.1. This is the case for the following credits:

- HEA01: Visual comfort
  This credit offers points for the daylight entering the living unit and a free view on either landscape or city environments. Greenery systems do not influence whether or not a free view is present.

Table 3.1: BREEAM categories and credits [36], credits with potential for a higher score because of the application of a greenery system highlighted in green

Category	Credits		Available points
Management	MAN 01	Projectdesign	5
	MAN 02	Lifecycle costs	4
	MAN 03	Responsible construction practices	5
	MAN 04	Commissioning and handover	3
	MAN 05	Aftercare	2 + 1 EP
	MAN 06	Social risks and decisions	2 + 1 EP
Health	HEA 01	Visual comfort	4 + 1 EP
	HEA 02	Ventilation	5
	HEA 03	Internal air quality	4 + 1 EP
	HEA 04	Thermal comfort	2
	HEA 05	Acoustic performance	3
	HEA 06	Accessibility	2
	HEA 08	Outdoor space	3
	HEA 10	Biophilic design	2
	HEA 11	Safety	2
	HEA 12	Smart home	2
Energy	ENE 01	Energy efficiency	15
	ENE 02	Energy use monitoring	3
	ENE 03	Energy efficient outdoor lighting	2
	ENE 04	Passive design and environmental impact of energy use	5 + 1 EP
	ENE 06	Energy efficient elevators	2
	ENE 08	Energy efficient household equipment	3
	ENE 10	Coordinate demand and supply of energy	4
Transport	TRA 01	Proximity of public transport	4
	TRA 02	Proximity of basic facilities	2
	TRA 03	Availability of alternative transport	5
	TRA 04	Traffic safety in the residential area	3
	TRA 06	Home office	2
Water	WAT 01	Reduce water use	5
	WAT 03	Water leakage detection and prevention	4
	WAT 04	Water efficiency and reuse	4 + 2 EP
Materials	MAT 01	Environmental impact of building materials	6 + 1 EP
	MAT 02	Embodied and whole life carbon	5 + 2 EP
	MAT 05	Robust design	1
	MAT 07	Demountability	2 + 1 EP
Waste	WST 01	Waste management at the building cite	3 + 1 EP
	WST 03	Storage space for recyclable waste material	2
	WST 04	Design and finish	2
	WST 05	Climate adaptation	2 + 1 EP
	WST 06	Building flexibility	4
Land-use and ecology	LE 01	Location choice and healthy soil	4
	LE 02	Protection of ecological values	2
	LE 04	Nature inclusive location	2
	LE 05	Long term use ecological value	3
Pollution	POL 01	Environmental effects of refrigerants	3
	POL 02	Reduce air pollution	2
	POL 03	Run off rain water	5 + 1 EP
	POL 04	Reduce light pollution	1
	POL 05	Reduce noise disturbance	1
Total			**163 + 14 EP**

- HEA03: Internal air quality
  This credit awards points for the use of building materials that have low emission levels, but not for the reducing particles that are emitted already.
- HEA04: Thermal comfort
  This credit awards points for being able to manage the temperature inside. The credit is thus not about insulation value but rather about how the inside temperature is managed, for instance with a thermostat or being able to open a window.
- POL02: Reduce air pollution
  This credits awards points for reducing the pollution of the air by for instance installing heating systems that do not use fossil fuels and have low NO_x emissions. Points are not awarded for reducing the pollution levels in the air once the air is already polluted, for which greenery systems could be of use.

It must be noted that some positive effects of greenery systems can be scored with the BREEAM credits, but not all positive effects. For instance, the reduction of the UHI effect can not directly be taken into account in the current categories as provided by BREEAM. BREEAM can take into account four of the seven defined benefits.

On the other hand negative effects like the environmental impact of the building materials can be taken into account to a certain level. Points can be earned for the use of a more sustainable material that has a lower impact on the environment or the use of less material, however no points are subtracted when increasing the amount of material used. Thus only the positive effects of material choice are taken into account. BREEAM is thus not able to give a sustainability rating based on both the positive and negative effects, but can only be used to score the positive effects caused by greenery systems.

3.2. ECI

For each building a Environmental Cost Indicator (ECI) can be determined. The value of this ECI depends on multiple different aspects and expresses the impact of a building on the environment in the form of a sum of money, depending on the kilograms of material used in the building. To find the ECI value, a Life Cycle Assessment (LCA) is used. An LCA cover the four life cycle stages of the building, which are the construction stage, use stage, end-of-life stage and recycle/reuse stage. The environmental impact of a structure is found using nineteen Environmental Impact Categories. The categories are listed in Table 3.3. Previously the number of impact categories was eleven, but in 2020 this number was increased to nineteen [37].

Since this method is based on the weight or volume of material that are used in the building, the addition of extra material to support the greenery systems can easily be taken into account and will lead to a higher ECI value. However, the positive effects on the environment and the sustainability of the building due to addition of greenery systems can not be taken into account in the existing form of the ECI. The method is easy to use, since the only input required is the amount of material in either weight or volume.

Table 3.3: Environmental impact categories [37]

Environmental Impact Categories	
GWP-t	Global Warming Potential - Total
GWP-f	Global Warming Potential - Fossil fuels
GWP-b	Global Warming Potential - Biogenic
GWP-luluc	Global Warming Potential - Land Use and Land Use Change
ODP	Ozone Layer Depletion
HTP	Human Toxicity Potential
FAETP	Freshwater Aquatic Eco-Toxicity Potential
MAETP	Marine Aquatic Eco-Toxicity Potential
TETP	Terrestrial Eco-Toxicity Potential
POCP	Photochemical Oxidation Potential
AP	Acidification Potential
EP-sw	Eutrophication Potential - Sweet water
EP-sa	Eutrophication Potential - Salt water
EP-l	Eutrophication Potential - Land
ADP-f	Abiotic Depletion Potential - fossil fuel
ADP-nf	Abiotic Depletion Potential - non-fuel compounds
WDP	Water Depletion Potential
PM	Particulate Matter emissions
IR	Ionising Radiation

BREEAM-NL credit MAT01 uses the MPG (Milieu Prestatie Gebouwen) which is similar to the ECI. While the ECI gives a value for the complete project, the MPG gives a value per square meter of area. These values can however easily be converted from one to another. The mentioned credit however only awards points when the MPG value is improved. A possible deterioration of the MPG score can not be taken into account. The LEED credit ”Building life cycle impact reduction” requires a life cycle assessment, which is also part of the ECI, and requires a reduction of the at least three of six given aspects. Examples include the global warming potential in kilograms CO_2 or the acidification of land and water sources in kilograms SO_2 or moles H^+. Just as in BREEAM-NL no points can be awarded for an increase of these aspects. Therefore it is useful to calculate the ECI value separately to observe how this value may change due to the implementation of greenery systems in the building envelope.

3.3. LEED

LEED (Leadership in Energy and Environmental Design) is a method of defining sustainability by the United States Green Building Council (USGBC) [38]. The LEED system focuses on creating projects that have an overall more sustainable performance, instead of performing well on just one or a few aspects [38]. This means that the LEED certification method looks at more than just the construction, but also for instance the location of a project and the access to public transport [38]. LEED v4.1 applies different certification programs for different types of projects. The different programs they offer are ”Building Design and Construction”, ”Interior Design and Construction”, ”Building Operations and Maintenance”, ”Residential”, and ”Cities and Communities”. The LEED program Building Design and Construction would be the most suitable for a non-residential building. However if the building has a residential function, the program Residential should be chosen [38]. The Residential program has three variants: ”Multifamily”, ”Multifamily Core and Shell” and ”Single Family Homes”. In this case the ”Multifamily Core and Shell” program is the best fit for this thesis, since this program focuses on multifamily projects with any number of stores that do not include a complete fit out of the inside of the building and this thesis focuses on the addition of greenery system on the outside of the building. The Multifamily Core and Shell program focuses mainly on the construction. Each project that wants to receive a LEED certification is subjected to a review process by Green Business Certification

Table 3.4: LEED certification categories [38]

Certification level	Points
No Certification	< 40
Certified	40-49
Silver	50-59
Gold	60-79
Platinum	$\geq$ 80

Inc. (GBCI) and is assessed on various aspects [38].

The following aspects are to be improved according to the LEED certification:

- Reduce contribution to climate change
- Enhance individual human health
- Protect and restore water resources
- Protect and enhance biodiversity and ecosystem services
- Promote sustainable and regenerative material classes
- Enhance community quality of life

The project can thus receive credits for a number of different aspects. Table 3.5 shows all categories and the credits that make up the categories. The available points are shown as well. The credits that could be earned by implementing a greenery system are highlighted in green. There are three credits that have names that can suggest that greenery systems could earn points in those categories, but this is not the case. This goes for the following credits.

- Thermal comfort
  This credit awards points for installing systems that control the thermal comfort in a dwelling unit, such as air conditioning, heating and ventilation.
- Acoustic performance
  The available points in this credit are awarded for using quiet installations for heating, cooling and ventilation. Points are not awarded for damping the created noise afterwards.

A total of 131 points can be achieved. Of these credits the largest part relates to climate change and the impact on human health, however also the impact on water resources, the effect on biodiversity, the green economy and the impact on community and natural resources are taken into account [38]. Based on the total amount of credits, a building project receives the according LEED certification. The different certifications are shown in Table 3.4. Most categories contain one or more credits that are required to obtain. They are marked with the letters 'Req' in Table 3.5. They do not provide any points, but a building must comply to the requirements of these credits in order to receive a LEED certification. Just like the BREEAM-NL certification, the LEED certification is not able to take into account the negative effects of the application of greenery systems such as an increased volume of material needed for the load bearing structure. LEED has credits relating to four of the seven defined benefits.

Table 3.5: LEED categories and credits [38], credits with potential for a higher score because of the application of a greenery system highlighted in green

Category	Credits	Points
Minimum program requirements	Must be in a permanent location on existing land	Req
	Must use reasonable LEED boundaries	Req
	Must comply with project size requirements	Req
Integrative process	Integrative process	2
Location and transportation	LEED for neighbourhood development location	20
	Sensitive land protection	2
	High-priority site	2
	Surrounding density and diverse uses	7
	Access to quality transit	5
	Bicycle facilities	1
	Reduced parking footprint	1
	Electric vehicles	2
Sustainable sites	Construction activity pollution prevention	Req
	Site assessment	1
	Protect or restore habitat	1
	Open space	1
	Rainwater management	4
	Heat island reduction	2
	Light pollution reduction	1
	Tenant design and construction guidelines	1
Water efficiency	Building level water meter	Req
	Water use reduction	Req
	Water use reduction	10
	Water metering	2
Energy and atmosphere	Fundamental systems testing and verification	Req
	Minimum energy performance	Req
	Energy metering	Req
	Fundamental refrigerant management	Req
	Enhanced commissioning	2
	Optimize energy performance	18
	Whole building energy monitoring and reporting	1
	Grid harmonization	1
	Renewable energy	5
Materials and resources	Storage and collection of recyclables	Req
	Construction and demolition waste management planning	Req
	Building life cycle impact reduction	7
	Environmentally preferable products	6
	Construction and demolition waste management	2
Indoor environmental quality	Minimum indoor air quality performance	Req
	Combustion venting	Req
	Garage pollutant protection	Req
	Radon-resistant construction	Req
	Interior moisture management	Req
	Environmental tobacco smoke control	Req
	Compartmentalization	Req
	Enhanced indoor air quality strategies	4
	Enhanced compartmentalization	1
	No environmental tobacco smoke	1
	Low-emitting materials	4
	Thermal comfort	1
	Daylight and quality views	1
	Acoustic performance	2
Innovation	Innovation	5
	LEED accredited professional	1
Regional priority	Regional priority	4
Total		**131**

3.4. WELL

WELL is a building standard that is used to improve human health by implementing design interventions and policies [39]. The following information about the WELL system was all retrieved from the WELL website [39]. WELL is mainly focused on buildings that have a large shared area accessible to all tenants, such as offices and school buildings. WELL can also be applied to multifamily residential buildings, but the project must contain a minimum of five dwelling units. WELL distinguishes two types of projects: WELL Certification and WELL Core certification. In the case of a multifamily residential building such as Urban Woods the WELL Certification should be pursued. The WELL rating system is based on ten concepts that are listed in Table 3.7. In addition to the ten standard concepts an eleventh concept called 'Innovation' is added. Each concept consists of multiple features for which points can be achieved.

The features can either be preconditions or optimizations. Preconditions in the WELL system are mandatory components that must be met in order to receive a certification. They are presented by a P instead of a number of points available in Table 3.7. The optimization features on the other hand are optional and while working on a project choices can be made on whether or not an optimization will be pursued. Not all optimization features are worth the same amount of points. The summation of the different parts make up the total point value of a feature. For each concept a maximum of 12 points can be achieved and in addition to this a total of 100 points may be achieved for all ten concepts combined. If a concept earns more than the maximum 12 points, the additional points may be used in feature I01 if the maximum of 10 points for the additional concept Innovation has not been obtained yet. Based on the amount of points earned a certain certification is awarded, ranging from WELL Bronze (40 ore more points) to WELL Platinum (80 or more points). All certification levels are shown in Table 3.6.

Table 3.6: WELL certification categories [39]

Certification level	Points	Minimum points per concept
Bronze	≥ 40	0
Silver	≥ 50	1
Gold	≥ 60	2
Platinum	≥ 80	3

Important to note is that the WELL system is performance-based. This means that the amount of points gained by the building and the attached classification are based on on-site testing of the buildings performances after the building has been completed. Features that have points with the potential to be earned due to the implementation of a greenery system are highlighted in green in Table 3.7. Some of the preconditions can also be obtained by the use of greenery systems. Examples of these include A01: Air quality and M02: Nature and place. However, since the preconditions do not award any points they will not be elaborated on as much as the optimization features. Some optimization features might on the first hand seem to be able to be earned by the implementation of greenery systems, however a closer look leads to the conclusion that this is not the case. This is true for the following features:

- T02: Verified thermal comfort
  In this WELL credit points are awarded for thermal comfort. To determine whether the thermal comfort is good enough surveys have to be taken among the occupants at least twice a year. This makes this credit very subjective and it is not possible to take this credit into account.
- S03: Sound barriers
  This credit awards points for sound insulation of interior walls. Since the greenery systems are placed at the outside of the building they will not help towards earning these points.
- S05: Sound reducing surfaces
  Even though VGS do create a sound reducing surface, this feature is specifically about sound reducing surfaces inside the building, which is why VGS will not lead to obtaining the points available for this feature.

Just like the BREEAM-NL and LEED certifications, the WELL certification is not able to take into account the negative effects of the application of greenery systems such as an increased volume of material needed for the load bearing structure. WELL can cover four of the seven defined benefits.

Table 3.7: WELL concepts and features [39], features with potential for a higher score because of the application of a greenery system highlighted in green

Concept	Features		Available points
Air	A01	Air quality	P
	A02	Smoke-free environment	P
	A03	Ventilation design	P
	A04	Construction pollution management	P
	A05	Enhanced air quality	4
	A06	Enhanced ventilation design	3
	A07	Operable windows	2
	A08	Air quality monitoring and awareness	2
	A09	Pollution infiltration management	2
	A10	Combustion minimzation	1
	A11	Source separation	1
	A12	Air filtration	1
	A13	Enhanced supply air	1
	A14	Microbe and mold control	1
Water	W01	Water quality indicators	P
	W02	Drinking water quality	P
	W03	Basic water management	P
	W04	Enhanced water quality	1
	W05	Drinking water quality management	3
	W06	Drinking water promotion	1
	W07	Moisture management	3
	W08	Hygiene support	4
	W09	β Onsite non-potable water reuse	2
Nourishment	N01	Fruits and vegetables	P
	N02	Nutritional transparency	P
	N03	Refined ingredients	2
	N04	Food advertising	1
	N05	Artificial ingredients	1
	N06	Portion sizes	1
	N07	Nutrition education	1
	N08	Mindful eating	2
	N09	Special diets	2
	N10	Food preparation	1
	N11	Responsible food sourcing	1
	N12	Food production	2
	N13	Local food environment	1
	N14	β Red and processed meats	1
Light	L01	Light exposure	P
	L02	Visual lighting design	P
	L03	Circadian lighting design	3
	L04	Electric light glare control	2
	L05	Daylight design strategies	4
	L06	Daylight simulation	2
	L07	Visual balance	1
	L08	Electric light quality	3
	L09	Occupant lighting control	3
Movement	V01	Active buildings and communities	P
	V02	Ergonomic workstation design	P
	V03	Circulation network	3
	V04	Facilities for active occupants	3
	V05	Site planning and selection	4

Continued on next page

Table 3.7 – continued from previous page

Concept	Features		Available points
	V06	Physical activity opportunities	2
	V07	Active furnishings	2
	V08	Physical activity spaces and equipment	2
	V09	Physical activity promotion	1
	V10	Self-monitoring	1
	V11	β Ergonomics programming	3
Thermal comfort	T01	Thermal performance	P
	T02	Verified thermal comfort	3
	T03	Thermal zoning	2
	T04	Individual thermal control	3
	T05	Radiant thermal comfort	2
	T06	Thermal comfort monitoring	1
	T07	Humidity control	1
	T08	β Enhanced operable windows	1
	T09	β Outdoor thermal comfort	3
Sound	S01	Sound mapping	P
	S02	Maximum noise levels	3
	S03	Sound barriers	3
	S04	Reverberation time	2
	S05	Sound reducing surfaces	2
	S06	Minimum background sound	2
	S07	β Impact noise management	3
	S08	β Enhanced audio devices	2
	S09	β Hearing health conservation	1
Materials	X01	Material restriction	P
	X02	Interior hazardous materials management	P
	X03	CCA and lead management	P
	X04	Site remediation	1
	X05	Enhanced material restrictions	2
	X06	VOC restrictions	4
	X07	Materials transparency	3
	X08	Materials optimizations	2
	X09	Waste management	1
	X10	Pest management and pesticide use	1
	X11	Cleaning products and protocols	2
	X12	β Contact reduction	2
Mind	M01	Mental health promotion	P
	M02	Nature and place	P
	M03	Mental health services	4
	M04	Mental health education	2
	M05	Stress management	2
	M06	Restorative opportunities	2
	M07	Restorative spaces	1
	M08	Restorative programming	1
	M09	Enhanced access to nature	2
	M10	Tobacco cessation	3
	M11	Substance use services	2
Community	C01	Health and well-being promotion	P
	C02	Integrative Design	P
	C03	Emergency preparedness	P
	C04	Occupant survey	P
	C05	Enhanced occupant survey	4
	C06	Health services and benefits	5

Continued on next page

Table 3.7 – continued from previous page

Concept	Features		Available points
	C07	Enhanced health and well-being promotion	2
	C08	New parent support	3
	C09	New mother support	3
	C10	Family support	3
	C11	Civic engagement	2
	C12	Diversity and inclusion	3
	C13	Accessibility and universal design	2
	C14	Emergency resources	2
	C15	β Emergency resilience and recovery	4
	C16	β Housing equity	2
	C17	β Responsible labor practices	3
	C18	β Support for victims of domestic violence	2
	C19	β Education and support	2
	C20	β Historical acknowledgement	1
Additional: Innovation	I01	Innovate WELL	10
	I02	WELL accredited professional (WELL AP)	1
	I03	Experience WELL certification	1
	I04	Gateways to well-being	1
	I05	Green building rating systems	5
	I06	β Carbon disclosure and reduction	10
Total			110 / 229

3.5. Conclusion

As described in the paragraphs above multiple Green Building Rating Systems (BREEAM-NL, LEED and WELL) are available to give the increased sustainability caused by the implementation of greenery systems in the building envelope a value. Effects such as increased thermal insulation, the reduction of noise and the improved quality of the air can all be taken into account and award the building points. In addition to this the reduced storm water runoff can also be scored (BREEAM-NL and LEED only) and the access to nature provided by these greenery systems is also worth points (BREEAM-NL, LEED and WELL). One of the methods, the Environmental Cost Indicator (ECI), shows the effect of the implemented greenery systems in terms of the amount of material used for the construction. None of the certification methods assessed is able to take both the positive effects of the greenery systems and increased material use for the load bearing structure into account. A comparison between the ECI on the one hand and one or more of the other certification methods on the other hand is therefore needed.

The GBRS's that are able to take into account the positive effects of the greenery systems (BREEAM-NL, LEED and WELL) all award points based on slightly different aspects of the building. None of the three certifications is able to cover all seven benefits. They all cover four of the seven benefits, but not all of them cover the same benefits. BREEAM does not cover UHI reduction and air purification. LEED does not score noise reduction and WELL cannot award points for insulation and energy use, increased biodiversity or stormwater attenuation. Each certification method has its own requirements to earn a differing number of points. For instance, applying an accessible green outdoor space for residents can earn a building 3 of the total 163 points in BREEAM-NL. In LEED this could grant the building 1 of the total 131 points and in WELL 2 of the total 229 points. Therefore, each of these methods will be used to quantify the positive effect of the implemented greenery systems. The increased impact on the environment caused by the use of extra material will be determined by using the ECI. These methods can not directly be compared with each other. The comparison will therefore be made between the percentage change of BREEAM-NL, LEED and WELL on the one hand and ECI on the other hand.

4 Structural aspects

This chapter will discuss several structural aspects of buildings types in urban areas. The implications of placing trees on buildings will also be discussed in this chapter.

4.1. Structural characteristics of different building types

Structural differences exist between office buildings and buildings with a residential function. This section will briefly outline the characteristics of each type of building and mention the differences. To do this, two different buildings will be assessed. The first one is The Joan, an office building in Amsterdam. Secondly the Spakler building will be assessed, which is a residential building located in Amsterdam as well. When the load bearing structure is set up differently, the application of greenery systems might have a different effect because the elements that have to carry the load differ. It is interesting to know what different types of load-bearing structures exist because the increased loads could have different effects on each type of structure. In addition to this all of the three certification methods offer different variants of their certification for different use-purposes of a building. This means that the credits themselves and the points available for a credit can be different.

4.1.1. Office buildings

The Joan is an office building located in Amsterdam [40]. All information about this building was taken from the VO (Voorlopig Ontwerp) document by Smith and Houweling [40]. The building actually consists of two buildings, The Joan I and The Joan II. The Joan I consists of nine floors containing office spaces. The ground floor has space for cafe and restaurant spaces. The Joan II serves as a parking space building of four levels. The focus of this section will be on The Joan I since that is the part of the complex that has an office function. The top floors of The Joan I has floors with a length of 105 meters and a

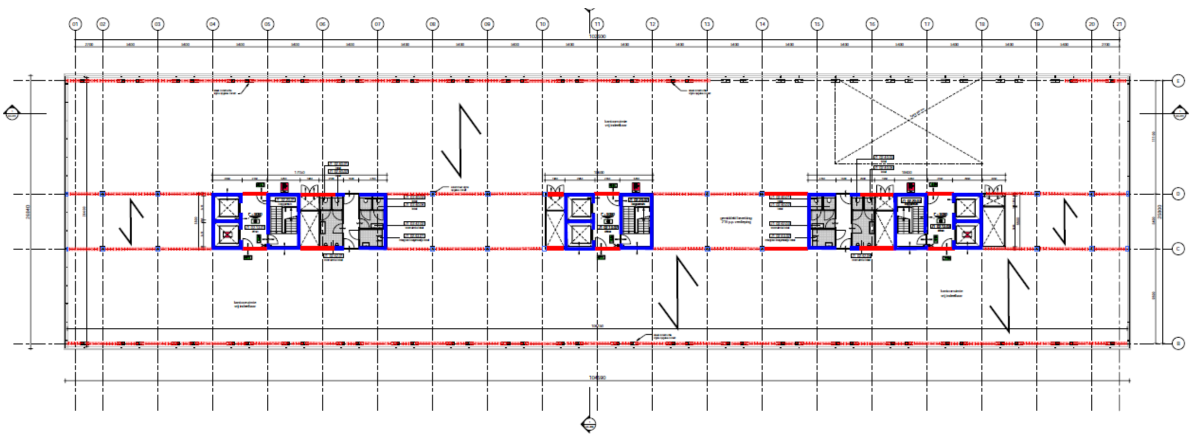


Figure 4.1: Floor plan of the top floors of The Joan I [40]

width of 27 meters. Only the ground floor has a larger area. For this floor the width differs between 30 and 40 meters and has a nod on one side. This building has a height of 38 meters. The Joan I has multiple concrete cores. Along the cores run beams in the longitudinal direction of the building on top of two rows of columns thus making a beam-column structure. The first floor has prefabricated concrete beams, while the floors above that have beam of the SFB type (Slim Floor Beam) in order to save space. An SFB type of beam is a composite that is comprised of a rolled cross section with a plate welded to one of the flanges. The columns are all made of prefabricated concrete. The columns along the facades however are made of steel.The two rows of columns split the width of the building into three pieces with widths of 9,3, 5,4 and 11,1 meters respectively. Since there are only concrete cores and columns with beams on top of them, the rest of the space is very open. Apart from the concrete cores, there are no load-bearing wall elements. A floor plan of the Joan I floors 2 to 8 can be seen in Figure 4.1.

4.1.2. Residential buildings

An example of a typical residential building is the Spakler building, located in the Amstelkwartier in the city of Amsterdam [41]. Information about this project was taken from the VO document written by Smith and Minartz [41]. The building has a total of 23 floors The lower two floors contain a combination of commercial spaces and storage or parking space. The second and third floors contain apartments and parking or storage space. The fourth to twenty third floors contain apartments only. The total number of apartments is 160. The floor area decreases in two steps along the height of the building, as shown in Figure 4.2.

In the high rise parts of the building the longitudinal facades are made of load bearing prefab elements. The floors span between the load-bearing elements. The bottom floors do not have load bearing walls but instead have columns to carry the load. This was done to make it possible to use the floors for parking space. Important to note is thus that there are load bearing walls in the upper levels of this structure that can not easily be removed. This makes the space less flexible to change [42]. However, it also has advantages. The walls that carry load often have a greater thickness which helps with reducing noise transfer between different spaces. Specifically between different apartments this is a great advantage because there will be requirements for noise transfer in place. Part of the walls form a core to provide stability to the structure.

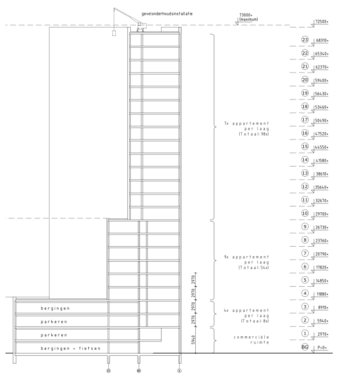


Figure 4.2: Side view of the Spakler building [41]

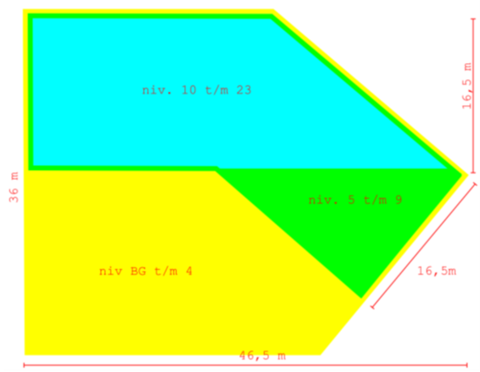


Figure 4.3: Top view of the Spakler building [41]

4.1.3. Comparison

The main difference between the two types is the type of load bearing structure that is applied. This all has to do with the purpose of the space and the demands that are attached to this purpose. Offices tend to have large open spaces and thus require large spans between columns. Often a beam-column structure is used so walls do not have to be load-bearing and can therefore be added in or removed easily later on, increasing the flexibility in use of the space.

Residential buildings on the other hand do not require to be as open or flexible as office spaces and often have load bearing walls. Walls between different dwelling units must be thick enough to reduce the noise transfer from one unit to another. Using load bearing walls also has some disadvantages. For

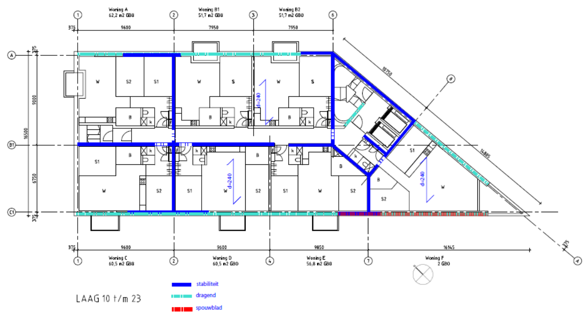


Figure 4.4: Spakler building construction of floors 10-23 [41]

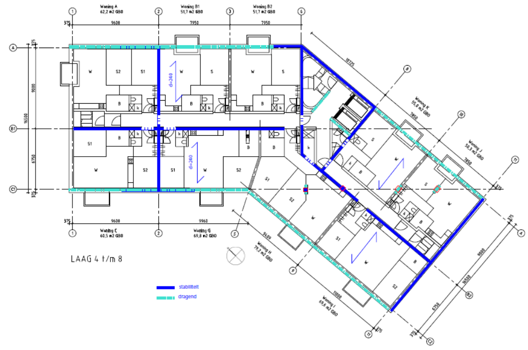


Figure 4.5: Spakler building construction of floors 4-9 [41]

instance, the spans of the floor can not be as large as in a beam-column structure.

It must be noted that these different types are not always applied as described in this chapter. Even though the use of load bearing wall elements may have advantages for residential buildings, the use of beam-column structures might be more fitting as the height of a building increases.

4.2. Wind forces on trees

The addition of trees on a building might have consequences for the wind loads the building is exposed to because the trees increase the area that is exposed to wind forces. Under these wind loads the tree tends to rock back and forth. The wind load F_{wind} will cause a bending moment M_{wind} and when this bending moment becomes larger than the maximum resisting bending moment M_{res}, it is possible that the tree will fall [20, 43]. This has been schematized by Wang *et al.* [20] in Figure 4.6. The resistance M_{res} is provided by the stem of the tree in combination with the root-soil system, which are all dependent on the growth conditions and type of tree [44]. Wang *et al.* [45] states that it might be good to have a substrate layer as thin as possible in order to reduce the added weight. In addition to this it could give an advantage to use lower growing plants instead of trees at the higher elevations since the wind speeds will be higher there, leading to a higher distortion of the trees. Dorrenboom *et al.* [46] investigated

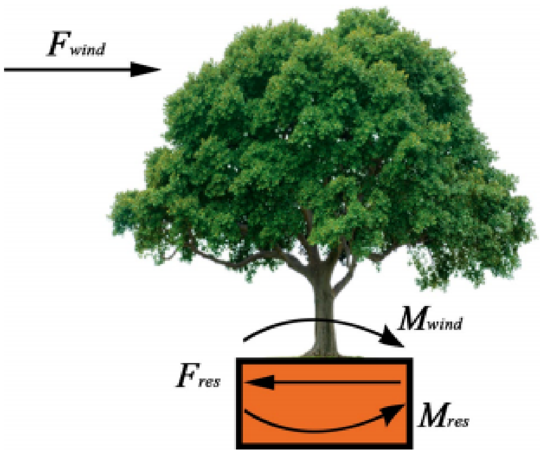


Figure 4.6: Loading conditions of a tree in a container [20]

wind forces working on the Anne Frank tree in Amsterdam. They stated that the leaves have a big influence on the C_w factor that is used for calculation of the wind force. This coefficient considers the friction caused by the leafs. This value differs between different seasons when the trees are deciduous (non-evergreen) [47], because deciduous trees drop their leaves during winter, thereby decreasing the area that is exposed to wind. However, storms in the Netherlands are often heavier during winter. In addition to this Rudnicki *et al.* [48] states that the movement of the leaves has influence on the wind force working on the trees as well. Due to possible movement of the leaves relative to the tree itself it is possible for the leaves to move to a position parallel to the direction of the wind, an effect which is also called streamlining. This reduces the area of the leaves exposed to wind with about 50% [48]. The C_w thus decreases for higher wind forces and is dependent on tree species as well [47]. Vollsinger *et al.* [49] specified these values even further for various types of trees and found for instance that at a wind speed of 20 m/s the area of a tree exposed to wind decreased with 28% for black cottonwood, 37% for red alder and 20% for paper birch. These relations between the wind speed and the leaf area exposed to the wind were combined into two separate formulas to calculate the wind force on the tree by [50]. Equation 4.1 can be used to derive a time-varying point load $\boldsymbol{F}$ when the tree is seen as a bluff body surrounded by air flow. An example of this is an individual leave. When the complete tree crown is considered as a porous body through which wind can flow, Equation 4.2 can be applied to find the time-varying distributed load $\boldsymbol{f}$.

$$\boldsymbol{F} = \frac{1}{2}\rho AC_D|\boldsymbol{U} - \dot{\boldsymbol{X}}|(\boldsymbol{U} - \dot{\boldsymbol{X}}) \tag{4.1}$$

where: ρ = leaf area density
AC_D = combined drag factor
$\boldsymbol{U}$ = time-varying wind velocity
$\dot{\boldsymbol{X}}$ = time-varying plant velocity

$$\boldsymbol{f} = \frac{1}{2}\rho\epsilon c_D|\boldsymbol{U} - \dot{\boldsymbol{X}}|(\boldsymbol{U} - \dot{\boldsymbol{X}}) \tag{4.2}$$

where: ρ = leaf area density
ϵc_D = combined drag coefficient
$\boldsymbol{U}$ = time-varying wind velocity
$\dot{\boldsymbol{X}}$ = time-varying plant velocity

In these formulas the combined drag factor AC_D and the combined drag coefficient ϵc_D are only mentioned as combined factors since only their combined effect is of influence [50]. AC_D is dependent on the Reynolds number and the geometry of the tree, while ϵc_D is derived from the Reynolds stress [51]. In this case there are too many unknowns to solve these equations.

As mentioned Dorrenboom *et al.* [46] investigated the Anne Frank tree in Amsterdam. This tree is a chestnut tree [47]. For this tree the value of the drag coefficient C_w was found to be 0,8 and the maximum value of the thrust P_w was found to be 0,97 kN/m^2 [47]. In winter, when most storms occur but the trees do not have leaves, the C_w value is decreased and found to be 0,15. The value of P_w remains 0,97 kN/m^2. During summer, the value of C_w was found to be 0,8, but the value of P_w had to be reduced by 50% because the wind speeds during summer are lower. Because of the stream lining effect, the value of C_w is also reduced by 50%, as was explained earlier. The wind forces per area of the tree crown during summer and winter can thus be calculated as follows [47].

$$f_{winter} = P_w \cdot C_w = 0{,}97 \cdot 0{,}15 = 0{,}15kN/m^2 \tag{4.3}$$

$$f_{summer} = 0{,}5P_w \cdot 0{,}5C_w = 0{,}5 \cdot 0{,}97 \cdot 0{,}5 \cdot 0{,}8 = 0{,}2kN/m^2 \tag{4.4}$$

When trees are placed along the facade of a building, wind forces do not always have to be taken into account. When wind blows directly onto a façade where the tree is in front of, the tree does take wind loading, however the part of the façade behind the tree in turn is shielded from the wind. However when the wind is coming from the other direction, blowing along the facade, the tree would result in a higher area exposed to wind. Trees on roofs of buildings will always result in a higher area exposed to horizontal wind forces.

In Urban Woods a more simple approach was followed. In order to take the wind forces on the balconies and trees into account the façade perpendicular to the wind direction was assumed to be wider [52]. The increased surface would thus be subjected to a larger wind load.

5
Horizontal greenery systems

Horizontal greenery systems in the form of green roofs have been present for a long time and were one of the first types of greenery systems that were used [20]. Green roof systems can be subdivided into two main categories, Extensive Green Roofs (EGR) and Intensive Green Roofs (IGR) [25, 26]. IGR have deeper substrate layers than EGR and this means the possibilities for the use of different types of vegetation are different [25, 26]. The purpose of the two classes of green roofs differs as well. Both EGR and IGR have a functional purpose, for instance serving as insulation or helping with storm water management, however in addition to this IGR systems typically also have an aesthetic purpose. IGR systems often serve as an extension of the living space [25]. Within the two categories multiple variants exist, which will all be touched upon in this chapter. The International Green Roofs Association also distinguishes a third type of green roof, the Semi- Intensive Green Roof [53], which has a substrate layer not as thick as an IGR, but thicker than that of an EGR, however most literature studies do not make that distinction [25, 26]. In this report only the distinction between EGR and IGR will be made. Green roofs face living conditions that greenery at ground level would not experience. Examples of this include higher wind speeds, high light intensities and extreme temperatures [54], cited in [25]. According to Dunnett and Kingsbury [54] these conditions cause a higher risk of drying out of the soil and could damage the components of the green roof system. This has to be taken into account when designing a green roof system.

5.1. Extensive green roofs

EGR are a more modern type of green roof than IGR and have a substrate layer that is more shallow than in IGR. Due to the shallower substrate layer (< 300 mm), EGR contain low-growing plants such as herbs, mosses and grasses [25, 26, 55]. Extensive green roofs have a natural appearance that changes over the seasons [53]. Due to the low growing plants it is possible that this type of green roof is invisible for people on the street [26]. Extensive green roofs often have a more functional purpose like insulation and are mostly inaccessible to people [25, 26]. In contrast to IGR, EGR can also be applied on sloped surfaces [26]. Because the EGR systems are less costly, require less maintenance and have a lower weight, this is the most chosen type of green roof system [56]. The system consists of multiple layers, including a waterproof layer, an insulation layer and growing medium [25, 57]. The most simple form of an extensive roof system is a light weight green roof [57]. Extensive roof systems can however also be combined with solar panels, in the form of a biosolar green roof, or with a water retention system in the form of a retention blue roof.

5.1.1. Lightweight green roof

A lightweight green roof (EGRLW) is the most simple form of an EGR system [57]. The thickness of the substrate layer is somewhere between 60 and 150 millimeters and a lightweight green roof contains mostly sedums, herbs and grasses [57]. Due to the type of coverage used this type of green roof system has a low ecological value and requires little maintenance, in addition to this the installation costs and weight are low as well [57]. The dead load has been determined by Boon and Veugelers [57] to be at least 0,55 kN/m^2, depending on the thickness of the substrate layer. This type of green roof system

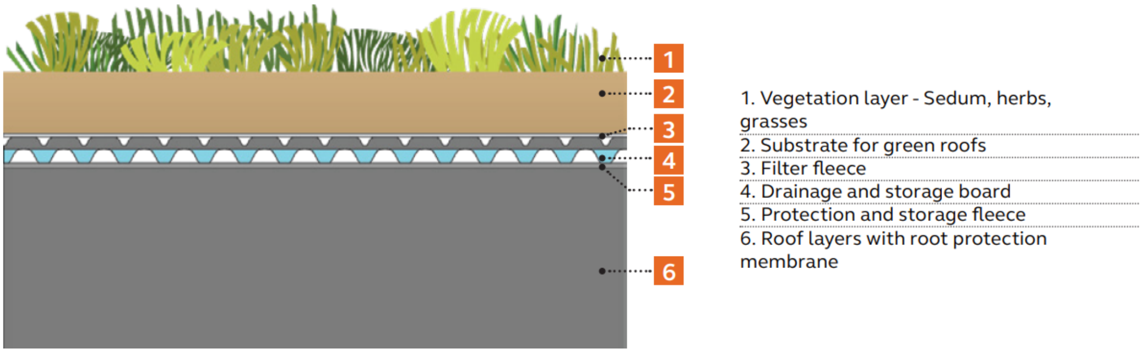


Figure 5.1: Lightweight green roof [57]

is inaccessible for humans except for maintenance work. The live load can therefore be taken as 1,0 kN/m^2 [58, 59]. All properties of the lightweight green roof are shown in Table 5.1.

Table 5.1: Lightweight green roof properties, data from [57–60]

General properties	
Coverage	Sedum, herbs, grasses
Build up depth	from 100 mm
Water storage	18 L/m^2
Slope	0-5°
Ecological value	Low
Installation costs	from 95 €/m^2
Maintenance costs	Low
Loads	
Dead load, fully saturated	from 0,55 kN/m^2
Dead load, dry	from 0,3 kN/m^2
Live load	1 kN/m^2
Snow load	No increased value, 0,56 kN/m^2
Wind load	No increased value

5.1.2. Biosolar green roof

A biosolar green roof (EGRBS), or a solar green roof is a roof that contains both solar panels and vegetation [61]. Specifically on flat roofs this is a useful method [57]. In the Netherlands, roofs of new buildings with a roof area of 250 m^2 or more must be covered with solar panels starting in the year 2025 [62], making this a type of green roof an interesting option for the future. Combining vegetation and solar panels has a positive effect on the energy generation of the solar panels because a green roof is generally cooler than a normal, gravelly roof. Due to the lower temperature and the lower solar reflection of the roof, the solar panels will have a lower temperature as well which leads to an increase in the efficiency of the solar cells [57, 63]. In a biosolar green roof system it is important to make sure that the plants do not block the sunlight from the solar panels. Therefore, the lower end of the (tilted) solar panels should be at least 20 centimeters above the substrate layer [57]. The solar panels can be placed in the same direction (facing south) or in two directions (facing east and west). Distance between the rows of solar panels, the height of the modules and other spatial factors must be based on the vegetation on the roof and location of the building [57]. Both options are shown in Figures 5.2 and 5.3. All properties of the biosolar green roof are shown in Table 5.2. By adding solar panels to the green roof system the weight increases. Additional weight has been added for both the mounting system and the solar panels themselves. The total weight of the system then comes to 1,1 kN/m^2 [60]. For this type of HGS the accumulation of snow also has to be taken into account because the solar panels can form an obstacle that blocks the movement of the snow resulting in a pile of snow next to the solar panel. To take this snow accumulation into account the following formula from Eurocode NEN-EN

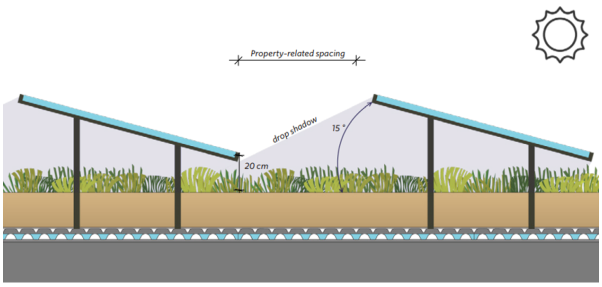


Figure 5.2: South facing biosolar green roof [57]

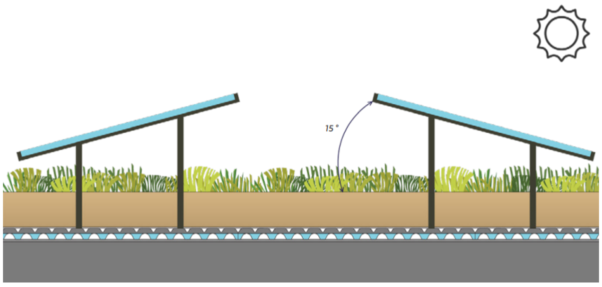


Figure 5.3: East-west facing biosolar green roof [57]

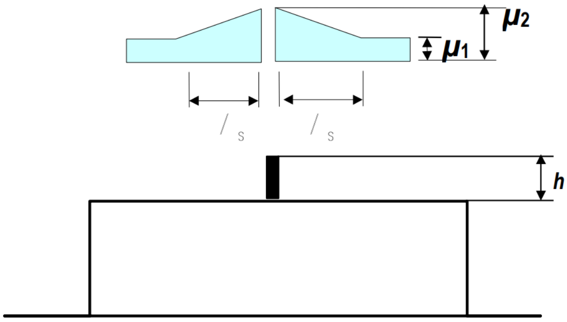


Figure 5.4: Snow accumulation coefficients at obstacles [64]

1991-1-3 [64, 65] is used to calculate the snow load form coefficient μ_2 at the obstacle.

$$\mu_2 = \frac{\gamma h}{s_k} = \frac{2 \cdot 0.6}{0.7} = 1.71 \tag{5.1}$$

The snow load decreases over distance l_s from the obstacle. l_s must have a value between 5 and 15 meters. Since the distance between the solar panels is less than five meters, the increased snow load due to accumulation is taken over the whole area of the roof. The accumulated snow load s_{acc} is calculated as follows.

$$s_{acc} = \mu_2 \cdot C_e C_t s_k = 1.71 \cdot 1 \cdot 1 \cdot 0.7 = 1.2kN/m^2 \tag{5.2}$$

Table 5.2: Biosolar green roof properties, data from [57–60]

General properties	
Coverage	Sedum, herbs, grasses
Build up depth	from 100 mm
Water storage	18 L/m^2
Slope	0-5°
Ecological value	Low
Maintenance costs	Medium
Loads	
Dead load, fully saturated	from 1,2 kN/m^2
Dead load, dry	from 0,95 kN/m^2
Live load	1 kN/m^2
Snow load	1,2 kN/m^2
Wind load	No increased value

5.1.3. Nature roof

A nature roof (EGRN) can be scaled between a lightweight roof and a garden roof. The system has a substrate layer with a thickness ranging from 100 to 300 mm [57] and can therefore be classified as an

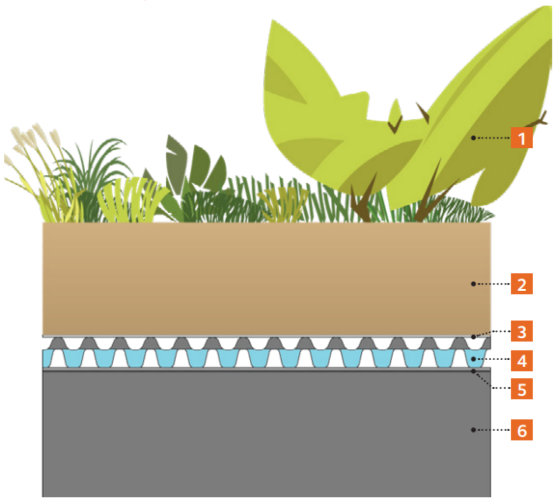


Figure 5.5: Nature roof [57]

EGR system. In comparison to the light weight green roof, a higher diversity in plants can be applied [57], as a nature roof house herbs, grasses and small bushes and they have a high evaporation capacity. The installation costs of a nature roof are higher than those of a lightweight roof and they also require a bit more maintenance [57]. They are however still less expensive and require less maintenance than the IGR systems [57]. The dead load has been determined by Boon and Veugelers [57] to be at least 0,95 kN/m^2, depending on the thickness of the substrate layer. Unlike the other extensive green roof systems, this type of green roof system is accessible to people. The live load can therefore be taken as 3 kN/m^2 for a surface of loading category C [58]. All properties of the nature roof are shown in Table 5.3.

Table 5.3: Nature roof properties, data from [57–60]

General properties	
Coverage	Sedum, herbs, grasses, possibly woody plants
Build up depth	from 130 mm
Water storage	30-80 L/m^2
Slope	0-5°
Ecological value	High
Installation costs	from 130 €/m^2
Maintenance costs	Medium
Loads	
Dead load, fully saturated	from 0,95 kN/m^2
Dead load, dry	from 0,65 kN/m^2
Live load	3 kN/m^2
Snow load	No increased value, 0,56 kN/m^2
Wind load	No increased value

5.2. Intensive green roofs

IGR have deep substrate layers ($\geq$ 300 mm) [55] and are therefore able to house a larger variety in plant species than EGR [25, 26]. Even the placement of trees is a possibility in intensive green roof systems [25, 26]. This means that IGR often also require a strong load-bearing construction [66]. Because the IGR are a more elaborate green roof system, they require more maintenance than EGR like large investments in plant care, which also leads to higher costs [25, 56]. This also explains the name. IGR require more intense maintenance and that why they are called intensive green roofs [26]. In comparison to EGR, IGR often have a secondary purpose like extension of the living space in addition to the functional purposes that EGR also have [25]. The trees that are placed on this type of roof will be subject to wind forces. More information about this can be found in Section 4.2.

5.2.1. Garden roof

Garden Roofs are a form of intensive roof that aims at using the roof as a park like area, with room for terraces, trees, pergola's and bushes [57]. A lot of variation is possible with this type of green roof system. The goal of a garden roof is to create a green space that looks like a green space that could have been at the ground level, like a park [57]. The garden roof is therefore accessible to humans and thus a live load of 3 kN/m^2 is used [58]. Garden roofs typically have two substrate layers (an intensive layer and an aeration layer) which together have a thickness of 600 mm or more [57]. Due to the thick substrate layers the dead load is relatively high compared to the other roof systems, starting at 6 kN/m^2 [57]. The Intensive Green Roof - Garden Roof will be indicated with the abbreviation IGRG. All properties of the garden roof are shown in Table 5.4.

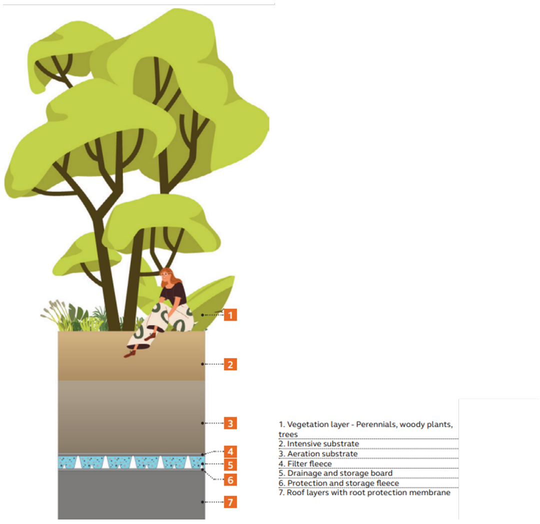


Figure 5.6: Garden roof [57]

Table 5.4: Garden roof properties, data from [57–60]

General properties	
Coverage	Perennials, woody plants, trees
Build up depth	from 600 mm
Water storage	180-320 L/m^2
Slope	0-5°
Ecological value	High
Installation costs	from 600 €/m^2
Maintenance costs	High
Loads	
Dead load, fully saturated	from 6 kN/m^2
Dead load, dry	from 5 kN/m^2
Live load	3 kN/m^2
Snow load	No increased value, 0,56 kN/m^2
Wind load	No increased value

5.2.2. Public roof

Boon and Veugelers [57] define a public roof as a roof located at ground level. This can for instance be on top of an underground parking garage. An important aspect of this type of roof is that these roofs provide access pedestrians and sometimes even to cars or fire engines [57]. These loads must therefore be taken into account. This thesis focuses on roofs on top of buildings and therefore the roofs of these buildings will not give access to vehicles of any type. This type of roof will thus not be used on top of a building and is therefore not taken into consideration in the continuation of this thesis.

5.3. Retention blue roof

Green roofs have a function in the management of the storm-water. On normal roofs without vegetation water flows from the building into the sewage system. In combined sewage systems, this can lead to an overflow of the sewage water onto natural bodies of water which can then become contaminated [25, 67]. To store rainwater, water reservoirs and ponds are a useful technique, however in urban areas there is often a lack of space areas preventing a superfluous runoff [25]. Green roofs can be used to store water in their substrate layer [25]. Factors that influence the amount of water that can be stored are the slope of the roof, the depth of the substrate and the type of plants that are used [54, 68]. In a retention blue roof there is room to store rainwater after it has landed on the roof in water retention boxes [57]. The retention boxes can store up to 160 liters of water per square meter [57]. This makes the amount of water that can be stored in the HGS even larger compared to a green roof which does not have water retention boxes. The stored water can be used to water the vegetation on the roof [57]. A retention blue roof can be applied in combination with both extensive (EGRR) and intensive green roof systems (IGRR) [57].

Since the 11th of May 2021, the so called ”Hemelwaterverordening” (Rainwater regulation) has come into effect in the city of Amsterdam [69]. This regulation applies to new buildings or existing buildings that are being renovated extensively, are being expanded with extra floors or for which the built up area is being expanded [69]. The regulation states that these buildings must be able to store up to 60 liters of water per square meter of built up area [69]. The stored water can than be released into the sewage system over the next 60 hours, which comes down to the release of 1 liter of water per hour [69]. This regulation makes the application of blue retention roofs a more interesting option to apply on roofs.

Table 5.5: Retention blue roof properties, data from [57–59]

	Extensive	**Intensive**
	General properties	
Coverage	Sedum, herbs, grasses, possibly woody plants	Perennials, shrubs, lawns, trees
Build up depth	from 80 mm	from 330 mm
Water storage	95-150 L/m^2	150-370 L/m^2
Slope	0°	0°
Ecological value	Medium	High
Installation costs	from 130 €/m^2	from 500 €/m^2
Maintenance costs	Low	High
	Loads	
Dead load, fully saturated	from 1 kN/m^2	from 3,1 kN/m^2
Retained water load	1,5 kN/m^2	3,7 kN/m^2
Live load	1 kN/m^2	3 kN/m^2
Snow load	No increased value, 0,56 kN/m^2	No increased value, 0,56 kN/m^2
Wind load	No increased value	No increased value

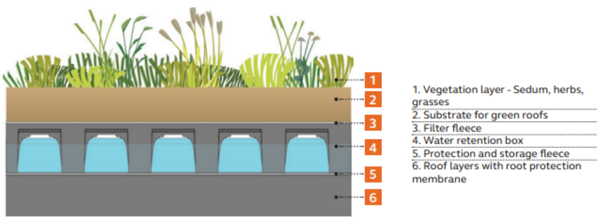


Figure 5.7: Extensive retention blue roof [57]

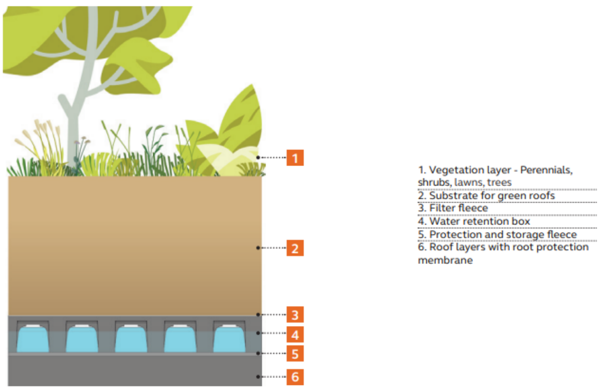


Figure 5.8: Intensive retention blue roof [57]

5.4. Overview

In conclusion, a few horizontal greenery systems have been selected to be taken into account. The public roof is left out because it does not match the subject of the thesis. The systems that are taken into account in the continuation of this analysis can be seen in Figure 5.9. This chart also shows the relation between the systems and in which category of green roof system (EGR or IGR) they belong. It is noteworthy that a retention blue roof can be applied in combination with both an extensive system and an intensive system. This is also clearly visible in the chart.

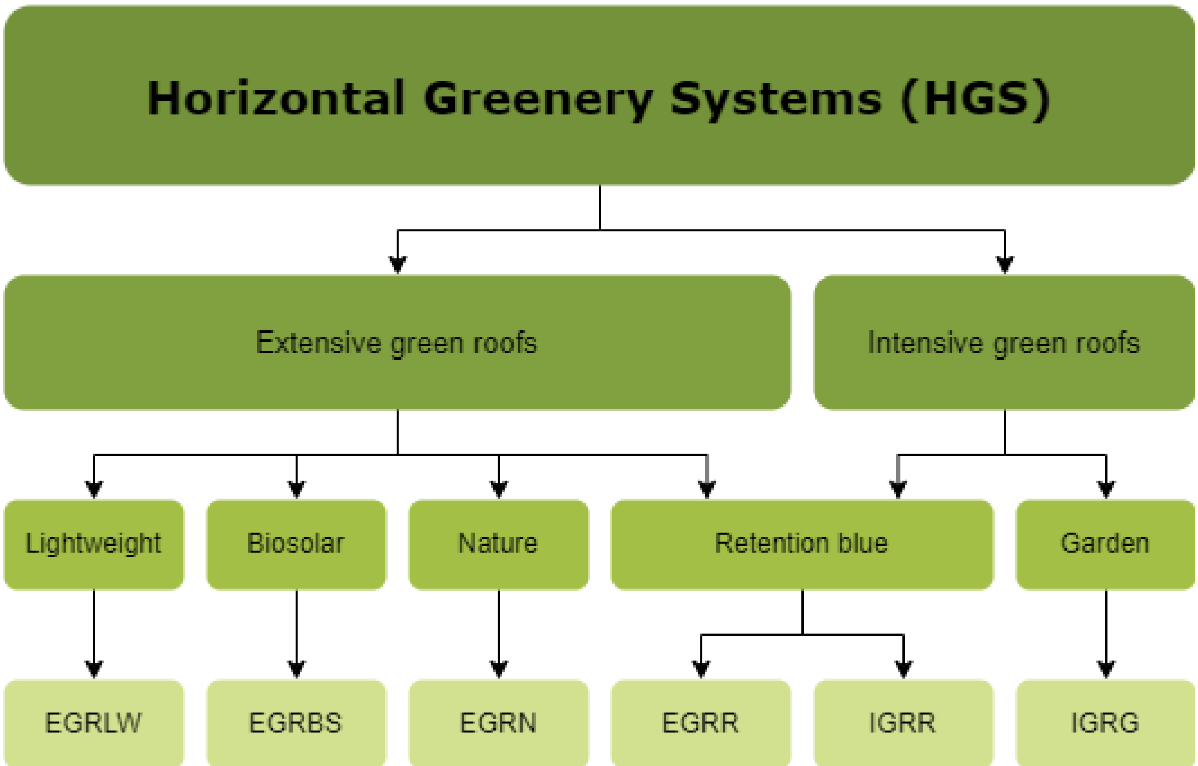


Figure 5.9: Overview of the Horizontal Greenery Systems that are considered in this thesis (own work)

6

Vertical greenery systems

In literature a broad range of terms is used when referring to vertical greenery systems [27]. Examples include the term ”vertical garden” as used by Peck *et al.* [70], ”vertical greening system” [71], ”vertical greenery system” [72] and ”green vertical system” [73]. In this report the term vertical greenery system (VGS) will be used. Vertical greenery systems are mostly divided into two categories, green façades (GF) and living wall systems (LWS) [27–29]. Some sources consider two more categories, vertical forests and green terraces [17, 74–76]. The difference between the categories is in the growing method of the plants and the supporting structure of the plants in the VGS [74, 77].

6.1. Green façades

Green façade (GF) systems contain plants that are rooted in the ground soil or in a plant container, mainly at the bottom of the façade [28, 78]. Kontoleon and Eumorfopoulou [28] further write that the plants used for a green façade system are mostly climbing plants, which climb from their rooting point to cover a specific structure. The plants can grow either upward or downward along the vertical surface according to Dunnett and Kingsbury [54], as cited in [27]. A subdivision in green façades is made between direct and indirect green façades [27]. Manso and Castro-Gomes [27] explain that the classification is made based on the basis of which type of structure is used for the plants to grow up. In direct green façades the plants grow directly on the façade of the building. Indirect green façade systems on the other hand have a separate system, for instance steel cables, which the plants grow on [74, 79]. Compared to other VGS, green façades are a relatively cost effective type [71, 74, 77, 79]. The choice of plants can influence both the aesthetical and functional properties of the VGS according to Perini *et al.* [79]. They elaborate that evergreen plants can be more useful for buildings in areas with a temperate climate, since these plants protect the façade from snow, wind and rain during winter. On the other hand, for instance in areas with a Mediterranean climate a deciduous climber might me more useful since during winter this type of plant will lose its leaves which in a Mediterranean climate or not needed to protect from intense weather effects such as snow. Instead, an exposed façade allows the building to be heated up by the sun during the colder winter season [79].

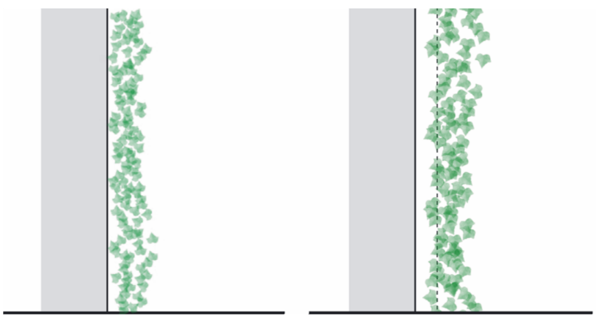


Figure 6.1: Green façade systems, from left to right: Direct Green Façade (DGF), Indirect Green Façade (IGF) [79]

6.1.1. Direct green façades

Direct green façades (DGF) are the most traditional type of green façades [27]. Since they do not need a special structure to climb on but use the façade that is already present, they might me deemed the most simple form of green façade systems as well. The self-clinging plants are planted directly into the soil and climb up from there [27]. Direct green façades were the most common used form of a VGS in the past, however the plants used in for this type of VGS could cause damage to the façade of the building there were climbing on [80]. This problem lead to new innovations and the development of different systems like the indirect green façade and LWS [28]. Properties of direct green façade systems are shown in Table 6.1.

Table 6.1: Direct Green Façade properties, data from [81]

General properties	
Coverage	Self-clinging climbers, hanging plants
Growing method	Soil based
Cultivation	Ground soil
Irrigation	Manually
Supporting structure	-
Installation costs	Low, 22-39 €/m^2
Maintenance costs	Low, 205 €/m^2/year
Loads	
Dead load	from 0,05 kN/m^2
Live load	0

6.1.2. Indirect green façades

When the green façade has a vertical support structure to support the plants which is separate from the façade of the building, the green façade it is called an indirect green façade (IGF) [27, 74, 79] or double-skin green façade [30, 82]. The plants grow from the soil at the bottom of the façade [27]. Kontoleon and Eumorfopoulou [28] describe two indirect façade systems that are used frequently. The first one uses modular trellis panels which are made from a welded steel wire. These steel wires form a panel with a width and depth to support the climber plants. The second frequently used system is a cable and wire-rope net system. In these type of systems cables are used to support the plants. The wire-nets and cable grids made have smaller holes which is useful for plants that require more support. Wire-nets have a higher flexibility than cables, and can thus be used for designs with various sorts of shapes. The systems are often relatively light weight [77]. Application of indirect green façades creates a layer of air between the green façade and the actual façade of the building, which has a positive effect on the energy benefits provided by the green façade since its serves as an extra layer of insulation [82]. Of the indirect green façade systems, about 75% is categorized as a system with modular trellis [83].

Indirect Green Facades with modular Trellis

Indirect Green Façades with modular Trellis (IGFT) are a lightweight system [83]. In this system it is possible to apply planting boxes at increased heights as well, which allows for the covering of tall façades [83]. In comparison to IGFC systems, the IGFT requires less maintenance because the chances of having to replace plants are smaller than with IGFC systems. These chances are smaller because in IGFT systems the plants are placed at several heights, meaning they can more easily replace unsuccessful plants [27].

Table 6.2: Indirect Green Facade with modular Trellis properties, data from [81]

General properties	
Coverage	Self-clinging climbers, hanging plants
Growing method	Soil based
Cultivation	Ground soil
Irrigation	Manually
Supporting structure	Lightweight nets, trellis or meshes
Installation costs	Medium, 127-270 €/m^2
Maintenance costs	Low, 205 €/m^2/year
Loads	
Dead load	from 0,25 kN/m^2
Live load	0

Indirect Green Facades with Continuous guides
Indirect Green Facades with Continuous guides (IGFC), also called indirect green façades with cables or ropes, are a system with vertical cables, horizontal calbes, rods grids or nets in a 2D system [83]. IGFC also exist in 3D systems, which also have a depth. These 3D systems as described by Ogut *et al.* [83] were created to make it easier to perform maintenance to the system and improve the growth of the plants in the system.

Table 6.3: Indirect Green Facade with Continuous guides properties, data from [81]

General properties	
Coverage	Self-clinging climbers, hanging plants
Growing method	Soil based
Cultivation	Ground soil
Irrigation	Manually
Supporting structure	Lightweight cables, ropes or rods
Installation costs	Medium, 127-270 €/m^2
Maintenance costs	Low, 205 €/m^2/year
Loads	
Dead load	from 0,25 kN/m^2
Live load	0

6.2. Living wall systems

Living Wall Systems (LWS) are known by a few different names [29], such as vertical gardens [77]. In a LWS not all plants are rooted in the ground soil, instead this system uses a different structure that involves the use of modular panels made of for example foam, felt or perline, which are filled with soil or other artificial growing mediums as described by Dunnett and Kingsbury [54], cited in [79]. In LWS a greater number of types of plants can be used, including plants that are not climber plants such as grasses and herbs, since the modular system also allows plants that would normally not grow in the vertical direction to grow at greater heights [79, 83]. Because the plants are not all rooted in the soil, the plants should be provided with water and nutrients from a separate irrigation system in the structure [84]. The irrigation system is often automated, which means the system provides a certain amount of water over a fixed amount of time, the exact amount of water can be provided on seasonal conditions at the location of the LWS [83]. According to Ogut *et al.* [83] the provision of water to the plants is one of the biggest challenges in LWS since the plants often demand a lot of water. Since the plants do not have to climb up, LWS allow for a faster covering of the facade in comparison to GF systems [85]. LWS are a modern type of VGS and due to the modular structure they are more complex than green façades [77], the costs are therefore usually higher as well, compared to green façades [79]. The aforementioned irrigation system is one of the elements that makes the design more complex [79], while the maintenance becomes harder as well due to the lay-out of the system [83]. In addition to this LWS are a heavier system, which means the structural support is more complex as well compared to a GF [83]. The LWS can installed with pre-planted modules or the planting can be performed on the building site [77]. LWS can be categorized into Continuous Living Wall Systems, Modular Living Wall Systems and Linear Living Wall Systems [27, 85].

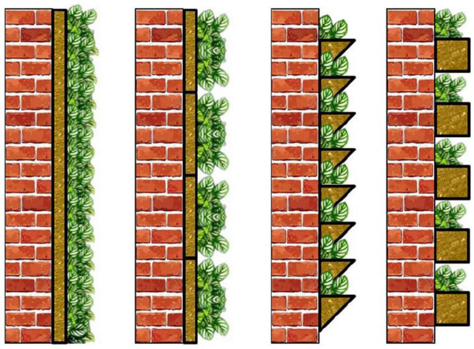


Figure 6.2: Living Wall Systems, from left to right: Continuous LWS (LWSC), LWS with Modular Boxes (LWSMB), LWS with Modular Trays (LWSMT), Linear LWS (LWSL) [86]

6.2.1. Continuous Living Wall Systems

Continuous Living Wall Systems (LWSC) have pockets made of a permeable fabric layer of for instance felt or cloth [84]. The plants are placed into the pockets individually [27, 84]. The pockets are lightweight and absorbent, which means no substrate or soil is needed [27, 85, 87]. The system is thus hydroponic, meaning no soil is needed since nutrients are included in the water given to the plants [87]. The plants do therefore need to be supplied with water constantly, which makes the maintenance of such a system more costly [27]. The permeable pockets are connected to a base panel attached to a frame which is fixed to the wall which forms a void between the frame and the facade [27, 78]. To supply nutrients and water to the plants, an irrigation system is placed at the top, allowing water to distribute downwards through the permeable layers [27, 85]. Continuous LWS are generally more lightweight than modular LWS and are able to house a larger variety of plants [27].

Table 6.4: Continuous Living Wall System properties, data from [81]

General properties	
Coverage	Wide range of species
Growing method	Hydroponic structures
Cultivation	Geo-textile layers
Irrigation	Computerized, from top of the wall
Supporting structure	Felt with pockets
Installation costs	High, 210-590 €/m^2
Maintenance costs	High, 40-100 €/m^2/year
Loads	
Dead load	from 0,49 kN/m^2
Live load	0

6.2.2. Modular Living Wall Systems

Modular LWS are panels which are composed of elements with a fixed dimension which serve as planter boxes where the plants grow in [84, 85]. Each of the elements include growing media [27, 84, 87]. Because of the presence of for instance soil as a growing media there the planting depth is greater. In addition to this replacing dead plants is easier in a modular LWS system as compared to a continuous LWS [87]. Examples of supporting elements are planter tiles, vessels, flexible bags or trays [27, 85]. Each of the elements is either connected to the facade directly or connected to a secondary supporting structure [27]. Manso and Castro-Gomes [27] further elaborate on these four types of elements and based on this a sub categorization can be made. The subcategories LWS with modular framed boxes and LWS with modular trays differ in terms of the composition and elements used in the system [81].

Living Wall Systems with Modular framed Boxes

The first category is called Living Wall Systems with Modular framed Boxes (LWSMB). The modular LWS with planter tiles, vessels and flexible bags fall within this category. Manso and Castro-Gomes [27] describe that planter tiles have multiple uses. They can serve as modular cladding where plants can be inserted, while simultaneously serving as a layer of vegetation themselves. Vessels can be connected to each other vertically, or can be connected to a vertical structure. Flexible bags contain a growing media and are made of lightweight material, this makes this system useful for application on different surface shapes. LWSMB are often used for horizontally growing types of plants [81].

Table 6.5: Living Wall System with Modular framed Boxes properties, data from [81]

General properties	
Coverage	Wide range of species
Growing method	Hydroponic cultures or soil-based
Cultivation	Modules with substrate
Irrigation	Computerized, from top of each module
Supporting structure	Panels made of galvanized steel, plastic or polyethylene
Installation costs	High, 210-590 €/m^2
Maintenance costs	High, 40-100 €/m^2/year
Loads	
Dead load	from 0,49 kN/m^2
Live load	0

Living Wall Systems with Modular Trays

The second category is called Living Wall Systems with Modular Trays (LWSMT). Trays often consist of rigid containers, which can be connected to each other and are able to support the full weight the plants and the substrate [27]. Instead of only applying the irrigation system at the top of the LWS as customary in LWSC, for modular LWS irrigation must be applied throughout the system in the form of dripping lines at the top of each module [85]. LWSMT are mostly used for vertically growing types of plants [81].

Table 6.6: Living Wall System with Modular Trays properties, data from [81]

General properties	
Coverage	Wide range of species
Growing method	Hydroponic cultures or soil-based
Cultivation	Containers with substrate
Irrigation	Computerized, from top of each module
Supporting structure	Container elements made of galvanized steel, plastic or polyethylene
Installation costs	High, 210-590 €/m^2
Maintenance costs	High, 40-100 €/m^2/year
Loads	
Dead load	from 0,49 kN/m^2
Live load	0

6.2.3. Linear Living Wall Systems

Linear Living Wall Systems (LWSL) are the last subcategory of living wall systems. In this system planter boxes are combined with a support structure for climber plants to grow on [81]. Van Reeuwijk [81] further mentions that some studies, like Perini *et al.* [79] and Manso and Castro-Gomes [27] would classify this type of VGS as an indirect green façade with planter boxes. However Van Reeuwijk [81] states that this type of VGS is actually a type of LWS since the plants are not rooted in the soil, but at height. In this report the classification as assumed by Van Reeuwijk [81] will be followed.

Table 6.7: Linear Living Wall System properties [81]

General properties	
Coverage	Climbers, hanging plant and shrubs
Growing method	Soil-based
Cultivation	Planter boxes with soil or substrate
Irrigation	Periodically
Supporting structure	Planter boxes at different heights and lightweight climbing aid
Installation costs	Medium, 190-365 €/m^2
Maintenance costs	Low-medium, 5-7,50 €/m^2/year
Loads	
Dead load	from 0,39 kN/m^2
Live load	0

6.3. Vertical Forests

A third category of vertical greenery system are Vertical Forests (VF). According to Wang *et al.* [20] Vertical Forests consist of cantilevered balconies that are attached to the building. These balconies support larger types of plants and especially trees [20]. An example of a building where vertical forests were used is Bosco Verticale in Milan, Italy. In the construction of a vertical forest differentiation can be made on a number of properties, for instance the height of the trees, the type of tree and the density of the canopy formed by the trees [20]. In addition to this the location of the trees and the free space around the three in the horizontal as well as the vertical direction can be changed in the design. The depth of the cantilevering balconies can also differ per design. In the case of Bosco Verticale these balconies have a depth of about 3,3 meters, and a width up to 14 meters [88]. Wang *et al.* [20] also state that it is important to take external factors such as the height of the specific balcony, weather conditions and the amount of exposure to the sun into account. They further observed some of the attention points in the construction of Bosco Verticale. Trees react to horizontal forces such as wind which can lead to leaf flutter and can even result in the trees growing in a bent shape [20, 50, 89]. Giacomello [90] states that a major part of the design of Bosco Verticale was defining the dynamic loads that would work on the trees. In addition to this the stability of the trees is a very important point of attention in constructing a VF [20]. The trees will grow and it was observed that this growth is affected by its placement relatively close to the building facade. This results in disproportionate distribution of the branches and also leads to differing density of the foliage between the different sides of the trees [20]. Figure 6.3 clearly shows that in Bosco Verticale the trees tend to grow away from the building and that the foliage is less dense at the building side of the tree. The plant containers

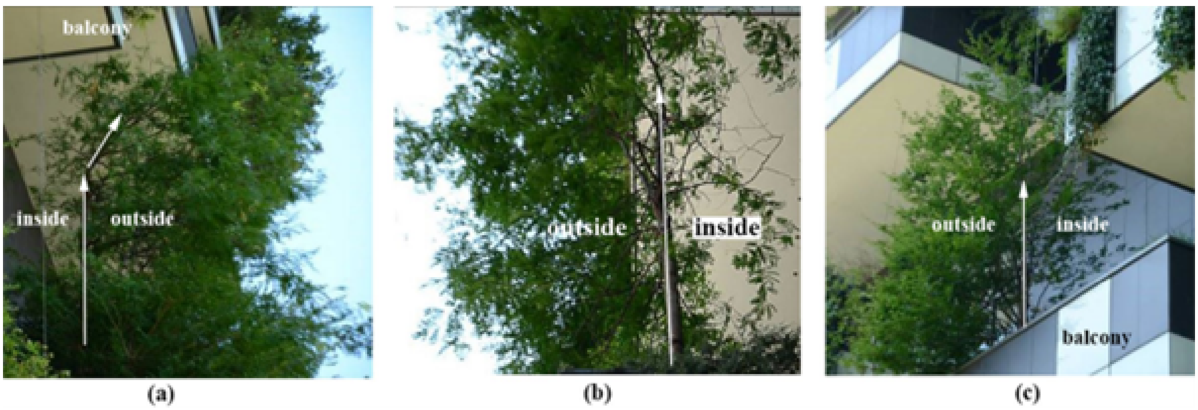


Figure 6.3: Growth of trees in Bosco Verticale, a) distorted stem and branches, b) and c) trees with different foliage density (inside near building surfaces and outside to the open air) [20]

of Bosco Verticale vary in size [90] depending on the vegetation type. They are located at the edges of the balconies furthest from the façade. Measures to prevent penetration of the roots through the planter boxes are taken in the form of a bituminous waterproofing membrane with protective sheeting [90]. The planter boxes contain a layer to provide drainage of out-flowing water. The set-up and layering of these plant containers is based on the sysstems used for green roofs (HGS) [90]. Irrigation of the system is provided via a drip line using water from a tank based in the basement of the building [90].

Trees in particular have been believed to be able to catch particulate matter from the air with their leaves more effectively than other plants [91, 92]. The orientation of the vegetation with respect to the micro climate condition between the plants and building surfaces and the intensity of the vegetation can highly influence environmental effects such as the thermal benefits caused by vertical forests [20]. However, Hsieh *et al.* [93] showed that trees close to the building envelope can reduce the cooling energy consumption with 10,3%. The dead load caused by trees on balconies depends on the height of the trees. Lievestro [94] found used loads for projects The Valley, Bosco Verticale and Wonderwoods. The values they found are shown in Table 6.8. These values are per area of balcony. They can be converted into a line load by multiplying the forces with the balcony area per floor and then dividing this value by the circumference of the building. As mentioned before, the stability of the vertical forest is a

Table 6.8: Tree and soil loads of different buildings with a VF system [94, 95]

Building	Dead load of tree container	Height of trees
Urban Woods	4 kN/m^2	
The Valley	6-10 kN/m^2	2 m
Bosco Verticale	7-13 kN/m^2	3-6 m
Wonderwoods	11 kN/m^2	4,5-6,6 m

main point of focus in the construction of a vertical forest. A large factor on the stability of the tree is the wind loads it is subjected to [43]. These wind loads can vary between the locations where a tree is placed and depends on the height and side of the building [20]. More information about the wind forces working on the trees can be found in Section 4.2. In the case of Bosco Verticale a 1:100 scale model of the building has been tested under winds with speeds of 67 m/s [88]. To deal with the wind forces the trees have to be restrained. In the case of Bosco Verticale, the trees are restrained in three different ways [90]. The restraint systems used are a temporary bind, a basic bind and a redundant bind and Giacomello [90] describes the three systems as follows. In the early life of the trees, the trees are restrained using a temporary bind. This means that the root ball of the tree is restrained and connected to the plant container by applying textile belts. Once the roots have settled and gained a strong enough connection the temporary bind is replaced by a basic bind, this is the main system used. It consists of elastic belts that fix the tree to a steel cable that in turn is anchored to the balcony on the level above the one where the tree is located. The trees on the upper floors are exposed to the most intense wind forces and are therefore restrained using a redundant bind. This means that the root ball is fixed to the plant container using a steel cage, keeping the tree in its place tightly. In Urban Woods however a different type of system was used. In the case of this project the trees were put in some sort of ball that is held up by straps. This gives the tree the ability to move along with the wind forces lowering the forces transferred to the building.

Table 6.9: Vertical Forest properties [20, 58, 59, 88, 94]

General properties	
Coverage	Mainly trees, also larger plants
Growing method	Soil-based
Cultivation	Containers with soil
Irrigation	Computerized irrigation
Supporting structure	Balconies
Loads	
Dead load	from 6 kN/m^2
Live load	2,5 kN/m^2

Figure 6.4: Bosco Verticale in Milan has Vertical Forests (VF) on its facades [1]

6.4. Green Terraces

Green Terraces are defined by Wang *et al.* [20] as a type of VGS. They consist of plants growing on horizontally placed terraces along the façade of the building. However, it could be argued that this type of VGS could be seen as a form of HGS. This is because at the location of the green terrace the façade of the building indents, which leads to a cascading type of building with plants placed on each step of the stair-like structure. A good example of such a building is the ACROSS Fukuoka Prefectural International Hall, located in Fukuoka City, Japan. This building is shown in Figures 6.5 and 6.6. In this report green terraces will not be discussed as a type of VGS, but will instead be considered as the application of a HGS on the multiple parts of the roof formed by the cascading shape of the building.

Figure 6.5: ACROSS Fukuoka Prefectural International Hall, Fukuoka City [96]

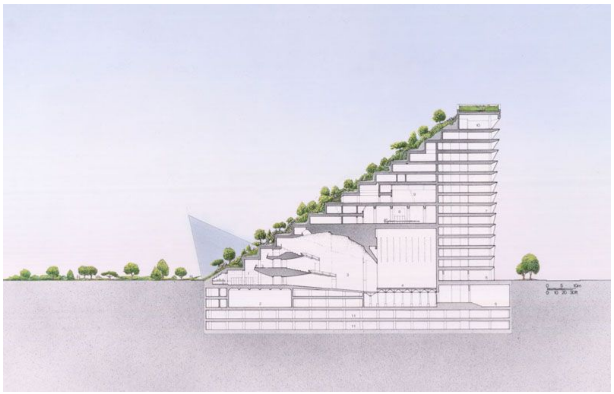


Figure 6.6: Design sketch of ACROSS Fukuoka Prefectural International Hall, Fukuoka City [96]

6.5. Overview

The vertical greenery systems that will be considered in this thesis are shown in Figure 6.7. As discussed before the Green Terraces variant is left out of the VGS that will be taken into account because it is deemed to fit better in the the HGS category.

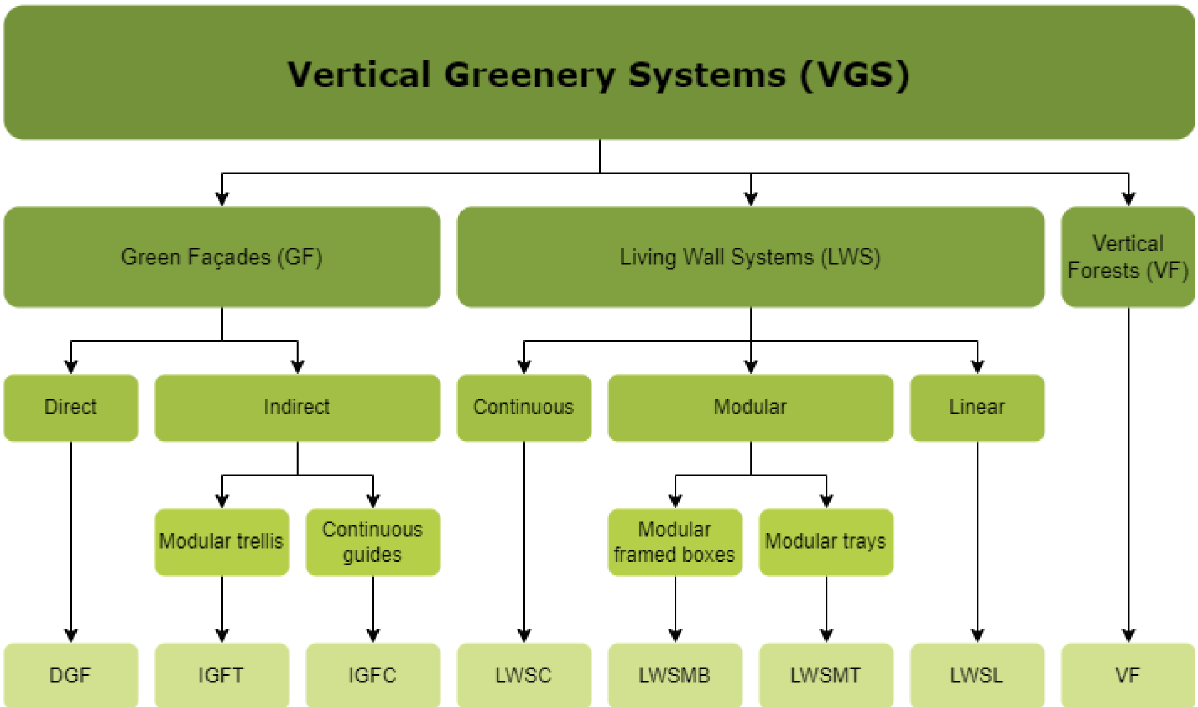


Figure 6.7: Overview of the Vertical Greenery Systems that are considered in this thesis (own work)

7 Case study: Urban Woods

Urban woods is a residential building that is currently being constructed in Delft. The building will have a total of ten floors. The building contains a total of 102 apartments which all have either two or three rooms [97]. In addition to the apartments the building contains a gym, library and a large kitchen for shared use which have a total area of about 350 m^2 [97, 98]. The building is constructed mainly from timber and also contains greenery systems. The Urban Woods building in Delft is the first one of a series of buildings. Similar buildings are planned to be built in Amsterdam, Zwolle and Groningen among others [97].

Figure 7.1: Urban Woods in Delft [99]

Figure 7.2: Close up of the facade of Urban Woods [99]

The building is designed using a beam-column structure from timber and has no concrete core, which is often used in mid-rise to high-rise timber structures [98]. Instead, the building has a timber core as well as diagonal timber beams along the façade to provide stability to the building. A beam-column structure was chosen to ensure flexibility in the arrangement of the floors [52]. In addition to the beam-column structure the building has a Cross Laminated Timber (CLT) floor system [98]. The balconies have trees on them and thus form a vertical forest. On top of the building a horizontal greenery system can be found containing sedum and solar panels for one part and the other part consists of a terrace with trees [97, 98]. The CO_2 impact of the building will be negative since the used trees can store CO_2. The building focuses on using modern insulation techniques and reducing the water demand as well. A system that reduces the water demand with 60% will be installed in comparison to a conventional building [98].

The building has a width of 19,66 meter and a length of 29,84 meter. The grid can be seen in Figure 7.3. The height is 30,71 meter, divided into ten floors. The ground floor has a height of 3,14 meters. The top floor has a height of 3,25 meters and all floors in between have a height of 3,04 meters. At the top floor the façade of the building is moved inwards, which leaves space around the top floor to be used as a roof terrace. In the original design the floors have a thickness of 180 mm. On top of this a screed is placed with a thickness of 60 mm. Most of the beams supporting the floor have a 280x280 cross section, but 280x320 and 280x360 mm cross sections also occur. The loads that are used can be seen in Table 7.1. As can be seen the green roof system used in this design is one of the more lightweight systems, weighing only 1 kN/m^2.

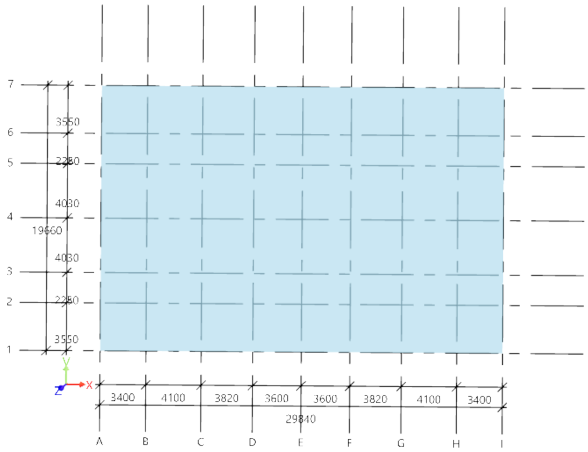


Figure 7.3: Grid of Urban Woods (own work, data from [52])

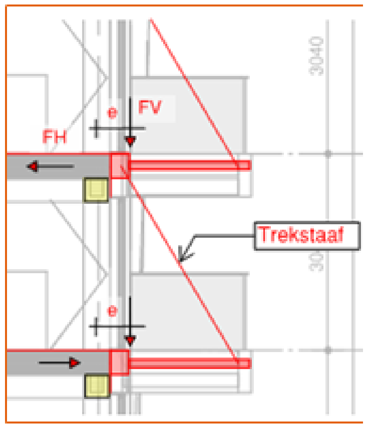


Figure 7.4: Balconies with tension rods in Urban Woods [52]

Table 7.1: Loads as taken in the original design of Urban Woods [52]

Roof		
Load	Permanent	Variable
Green roof system	1,00 kN/m^2	
Roof coverage	0,20 kN/m^2	
Insulation	0,10 kN/m^2	
Filler layer	1,16 kN/m^2	
CLT panels, t=180 mm	0,90 kN/m^2	
Life load		2,50 kN/m^2
Floors		
Cement screed, t=60 mm	1,50 kN/m^2	
Insulation	0,06 kN/m^2	
Filler layer	1,16 kN/m^2	
CLT panels, t=180 mm	0,90 kN/m^2	
Life load, class A		1,75 kN/m^2
Separating walls		0,80 kN/m^2
Balconies		
Tiles	0,96 kN/m^2	
Timber beams	0,50 kN/m^2	
Ceiling finishing	0,50 kN/m^2	

7.1. Balconies

The building Urban Woods contains multiple balconies per floor [52]. The balconies support the trees that are placed on them. The balconies are placed at every side of the building. The balconies come in five different types. The first floor has eleven balconies, while the second through eighth floor each have sixteen balconies, 2 bigger ones and fourteen smaller ones. The bigger balconies have an area of 11,2 m^2 and the smaller balconies have an area of 5,5m^2. This makes a total balcony area of 100,1m^2 for each of these floors. Each balcony is made of a steel frame to support the walkable surface. The balconies are not only attached to the building at the floor level of the balcony, but each of them is also attached to the floor above via a tension rod. This is illustrated in Figure 7.4. Due to the tension rod the load on the balcony can be divided between the beam at the floor level of the balcony and the beam that is one floor higher.

8 Models and tools

This chapter will discuss two separate tools which were made in the Viktor environment and one model set up in Grasshopper and RFEM. The first of the Viktor tools is the Greenery Systems Tool, which was set up for this thesis specifically by the author to provide the user with useful information about the greenery systems in this research. The second tool, the Building Structural Design Tool, is a tool developed by Arcadis and was used for the investigation of the steel and concrete variants of the Urban Woods building. The last model is a model of the timber variant made in Grasshopper and RFEM. This chapter will discuss all three tools and how they are used in this research.

To find the structural effects the following load combinations are used [100, 101].

$$k_F \left(1{,}35G + \sum_{i \geq 1} 1{,}5\psi_{0,i} Q_{k,i} \right) \tag{8.1}$$

$$k_F \left(1{,}2G + 1{,}5Q_{k,1} \sum_{i > 1} 1{,}5\psi_{0,i} Q_{k,i} \right) \tag{8.2}$$

The variable loads that are used are q_f, q_r, q_s and q_w for life load of the floors, life load on the roof and snow loading respectively. As explained in Section 7.2.1 wind loading can not be taken into account in the current version of the Building Structural Design Tool. The combination factors ψ used for the different variable loads are shown in Table 8.1. Roofs that are accessible only for maintenance fall into category H, this applies to a roof without greenery systems and the EGRLW, EGRBS and EGRR systems. Roofs that are accessible (EGRN, IGRR, IGRG) fall into a category according to the function of the area. In this case that would be category A, for communal floors, stairs and balconies. The defined load combinations are shown in Table 8.2 and Table 8.3.

Table 8.1: Combination factors and variable loads [100, 101]

Category	q (kN/m^2)	ψ_0	ψ_1	ψ_2
A: private floors	1,75	0,4	0,5	0,3
A: communal floors, stairs and balconies	3,0	0,4	0,5	0,3
A: private balconies	2,5	0,4	0,5	0,3
H: roofs accessible for maintenance only	1,0	0	0	0
Snow	0,56*	0	0,2	0
Wind	1,04	0	0,2	0

**Snow loads might be higher in cases of snow accumulation.*

After using both the Building Structural Design Tool and the RFEM model to find the needed element sizes to carry all loads working on the building, the number of foundation piles needed will be calculated as well. For this a Fundex pile will be used with a diameter of 540 mm. Each pile reaches down to

-32,5 meters NAP [52]. All piles have a capacity of 2000 kN. The number of piles needed is calculated dividing the total weight of the building by 2000 kN.

Table 8.2: Load combinations in case of an inaccessible roof [100, 101]

Ultimate Limit States for unfavourable permanent loads		
ULS_1	1,35G + 1,5ψ_0q$_f$ + 1,5ψ_0q$_r$ + 1,5ψ_0q$_s$ + 1,5ψ_0q$_w$	= 1,35G + 0,6q$_f$
ULS_{2a}: floor leading	1,2G + 1,5q$_f$ + 1,5ψ_0q$_r$ + 1,5ψ_0q$_s$ + 1,5ψ_0q$_w$	= 1,2G + 1,5q$_f$
ULS_{2b}: roof leading	1,2G + 1,5q$_r$ + 1,5ψ_0q$_f$ + 1,5ψ_0q$_s$ + 1,5ψ_0q$_w$	= 1,2G + 1,5q$_r$ + 0,6q$_f$
ULS_{2c}: snow leading	1,2G + 1,5q$_s$ + 1,5ψ_0q$_f$ + 1,5ψ_0q$_r$ + 1,5ψ_0q$_w$	= 1,2G + 1,5q$_s$ + 0,6q$_f$
ULS_{2d}: wind leading	1,2G + 1,5q$_w$ + 1,5ψ_0q$_f$ + 1,5ψ_0q$_r$ + 1,5ψ_0q$_s$	= 1,2G + 1,5q$_w$ + 0,6q$_f$
Ultimate Limit States for favourable permanent loads		
ULS_3	0,9G + 1,5ψ_0q$_f$ + 1,5ψ_0q$_r$ + 1,5ψ_0q$_s$ + 1,5ψ_0q$_w$	= 0,9G + 0,6q$_f$
ULS_{4a}: floor leading	0,9G + 1,5q$_f$ + 1,5ψ_0q$_r$ + 1,5ψ_0q$_s$ + 1,5ψ_0q$_w$	= 0,9G + 1,5q$_f$
ULS_{4b}: roof leading	0,9G + 1,5q$_r$ + 1,5ψ_0q$_f$ + 1,5ψ_0q$_s$ + 1,5ψ_0q$_w$	= 0,9G + 1,5q$_r$ + 0,6q$_f$
ULS_{4c}: snow leading	0,9G + 1,5q$_s$ + 1,5ψ_0q$_f$ + 1,5ψ_0q$_r$ + 1,5ψ_0q$_w$	= 0,9G + 1,5q$_s$ + 0,6q$_f$
ULS_{4d}: wind leading	0,9G + 1,5q$_w$ + 1,5ψ_0q$_f$ + 1,5ψ_0q$_r$ + 1,5ψ_0q$_s$	= 0,9G + 1,5q$_w$ + 0,6q$_f$
Serviceability Limit States		
SLS_1	G + ψ_0q$_f$ + ψ_0q$_r$ + ψ_0q$_s$ + ψ_0q$_w$	= G + 0,4q$_f$
SLS_{2a}: floor leading	G + q$_f$ + ψ_0q$_r$ + ψ_0q$_s$ + ψ_0q$_w$	= G + q$_f$
SLS_{2b}: roof leading	G + q$_r$ + ψ_0q$_f$ + ψ_0q$_s$ + ψ_0q$_w$	= G + q$_r$ + 0,4q$_f$
SLS_{2c}: snow leading	G + q$_s$ + ψ_0q$_f$ + ψ_0q$_r$ + ψ_0q$_w$	= G + q$_s$ + 0,4q$_f$
SLS_{2d}: wind leading	G + q$_w$ + ψ_0q$_f$ + ψ_0q$_r$ + ψ_0q$_s$	= G + q$_w$ + 0,4q$_f$

Table 8.3: Load combinations in case of an accessible roof [100, 101]

Ultimate Limit States for unfavourable permanent loads		
ULS_1	1,35G + 1,5ψ_0q$_f$ + 1,5ψ_0q$_r$ + 1,5ψ_0q$_s$ + 1,5ψ_0q$_w$	= 1,35G + 0,6q$_f$ + 0,6q$_r$
ULS_{2a}: floor leading	1,2G + 1,5q$_f$ + 1,5ψ_0q$_r$ + 1,5ψ_0q$_s$ + 1,5ψ_0q$_w$	= 1,2G + 1,5q$_f$ + 0,6q$_r$
ULS_{2b}: roof leading	1,2G + 1,5q$_r$ + 1,5ψ_0q$_f$ + 1,5ψ_0q$_s$ + 1,5ψ_0q$_w$	= 1,2G + 1,5q$_r$ + 0,6q$_f$
ULS_{2c}: snow leading	1,2G + 1,5q$_s$ + 1,5ψ_0q$_f$ + 1,5ψ_0q$_r$ + 1,5ψ_0q$_w$	= 1,2G + 1,5q$_s$ + 0,6q$_f$ + 0,6q$_r$
ULS_{2d}: wind leading	1,2G + 1,5q$_w$ + 1,5ψ_0q$_f$ + 1,5ψ_0q$_r$ + 1,5ψ_0q$_s$	= 1,2G + 1,5q$_w$ + 0,6q$_f$ + 0,6q$_r$
Ultimate Limit States for favourable permanent loads		
ULS_3	0,9G + 1,5ψ_0q$_f$ + 1,5ψ_0q$_r$ + 1,5ψ_0q$_s$ + 1,5ψ_0q$_w$	= 0,9G + 0,6q$_f$ + 0,6q$_r$
ULS_{4a}: floor leading	0,9G + 1,5q$_f$ + 1,5ψ_0q$_r$ + 1,5ψ_0q$_s$ + 1,5ψ_0q$_w$	= 0,9G + 1,5q$_f$ + 0,6q$_r$
ULS_{4b}: roof leading	0,9G + 1,5q$_r$ + 1,5ψ_0q$_f$ + 1,5ψ_0q$_s$ + 1,5ψ_0q$_w$	= 0,9G + 1,5q$_r$ + 0,6q$_f$
ULS_{4c}: snow leading	0,9G + 1,5q$_s$ + 1,5ψ_0q$_f$ + 1,5ψ_0q$_r$ + 1,5ψ_0q$_w$	= 0,9G + 1,5q$_s$ + 0,6q$_f$ + 0,6q$_r$
ULS_{4d}: wind leading	0,9G + 1,5q$_w$ + 1,5ψ_0q$_f$ + 1,5ψ_0q$_r$ + 1,5ψ_0q$_s$	= 0,9G + 1,5q$_w$ + 0,6q$_f$ + 0,6q$_r$
Serviceability Limit States		
SLS_1	G + ψ_0q$_f$ + ψ_0q$_r$ + ψ_0q$_s$ + ψ_0q$_w$	= G + 0,4q$_f$ + 0,4q$_r$
SLS_{2a}: floor leading	G + q$_f$ + ψ_0q$_r$ + ψ_0q$_s$ + ψ_0q$_w$	= G + q$_f$ + 0,4q$_r$
SLS_{2b}: roof leading	G + q$_r$ + ψ_0q$_f$ + ψ_0q$_s$ + ψ_0q$_w$	= G + q$_r$ + 0,4q$_f$
SLS_{2c}: snow leading	G + q$_s$ + ψ_0q$_f$ + ψ_0q$_r$ + ψ_0q$_w$	= G + q$_s$ + 0,4q$_f$ + 0,4q$_r$
SLS_{2d}: wind leading	G + q$_w$ + ψ_0q$_f$ + ψ_0q$_r$ + ψ_0q$_s$	= G + q$_w$ + 0,4q$_f$ + 0,4q$_r$

8.1. Greenery Systems Tool

The Greenery Systems Tool (GST) was developed to show useful information about a selected greenery system, either horizontal or vertical, to the user of the tool. Some of the information can afterwards be used as input for the Building Structural Design Tool (BSDT). The additional points that can be earned for the different credits of the three certification methods will also be displayed.

The tool requires the user to choose between if they would like information on a horizontal or vertical greenery system, followed by the selection of a specific type of greenery system. Depending on whether the user has chosen a horizontal or vertical greenery system, extra information might be required. The

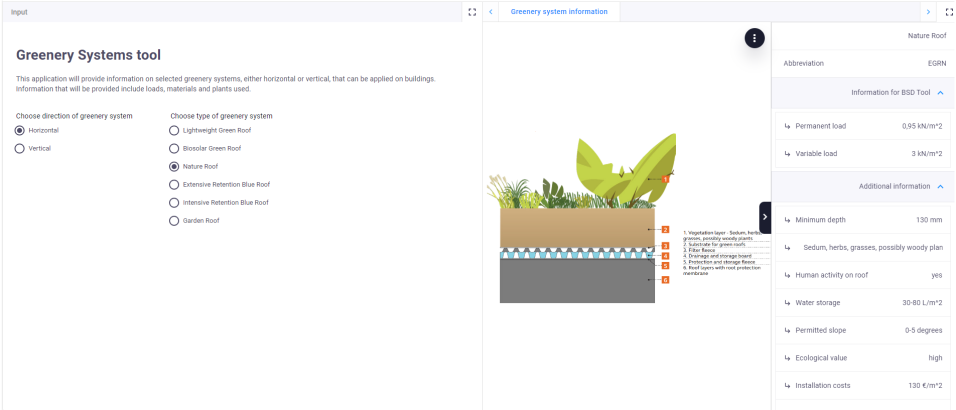


Figure 8.1: Information on HGS by the Greenery Systems Tool (own work)

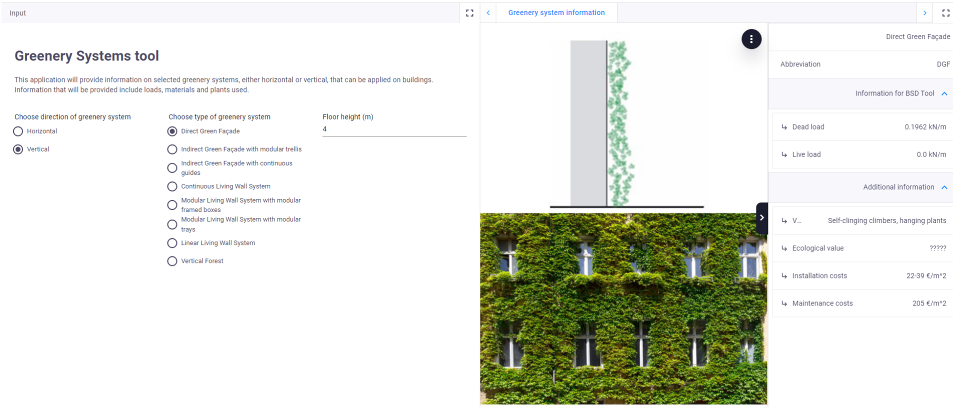


Figure 8.2: Information on VGS by the Greenery Systems Tool (own work)

information that the tool provides also differs for each of the two categories.

The aim of this tool is to make the information provided in Chapter 5 and Chapter 6 more easily accessible for the user of the BSDT. The user can easily apply the found information in the BSDT and find what the effects of the chosen greenery system on a building will be.

8.2. Steel and concrete models in the Building Structural Design Tool

The Building Structural Design Tool (BSDT) is a tool that is developed by Arcadis. The tool allows the user to test a structural design in the early phases of the design. The user can input the grid size, floor height and number of floors to construct a building. Currently users can only select steel and concrete as building materials. Eventually the user is asked to input the loads working on the floors, roof and façades. Dead load, live load and snow load are inserted separately. In addition to this the tool has a module to generate the wind loads that work on the structure. Load combinations can be generated automatically or manually. The tool makes all connections between the members hinged. Please note that the tool does not use a stability system for this building.

In the next step of the process the user can design the building using the tool. This can be done in two ways, using the automated or the manual design mode. The manual design mode will ask the user to input cross sections, the material class and in the case of concrete the type of reinforcement. Different measurements can be chosen for the roof, floors, primary internal beams, secondary internal beams, primary façade beams, secondary façade beams, internal columns, edge columns and corner columns. As can be seen the beams are split in four categories because the floors transfer load in one direction only. This leads to primary and secondary beams, where the primary beams are the ones that take up the load transferred by the floor. The secondary beams are not loaded by the floors. A sub categorization is made between beams along the façade and the ones that are not placed at the façade, which are called internal beams. The different types of beams can be seen in Figure 8.4. The load transfer direction of the floors is indicated in this figure as well. Even though the secondary beams do not cary any of the load it is not possible to remove them in the BSDT.

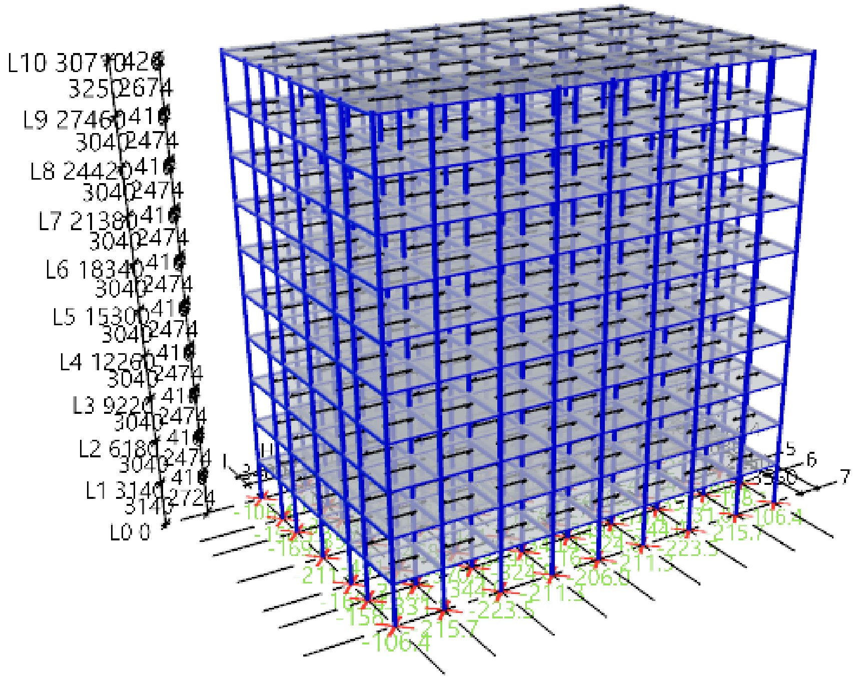


Figure 8.3: 3D view of the BSDT model of Urban Woods

After inputting the element types, the tool will give as a return the unity checks of the different members in the construction. In the automated mode the user gives as input the maximum permissible unity check. The tool will then give the cross sections needed to achieve a unity check value as close to but below the value that was given as input. This means that the cross sections of the columns will not be constant over the height of the building and the cross sections of the beams will not necessarily be equal to the cross sections of the beams that are in the same line. For this research the manual mode will be used to find a design with columns that have a constant cross section over their height and beams that have a constant cross section over the complete length of the building because this complies to usual building practices. This means for instance that the columns will be of the same cross section from the bottom all the way through the top of the building.

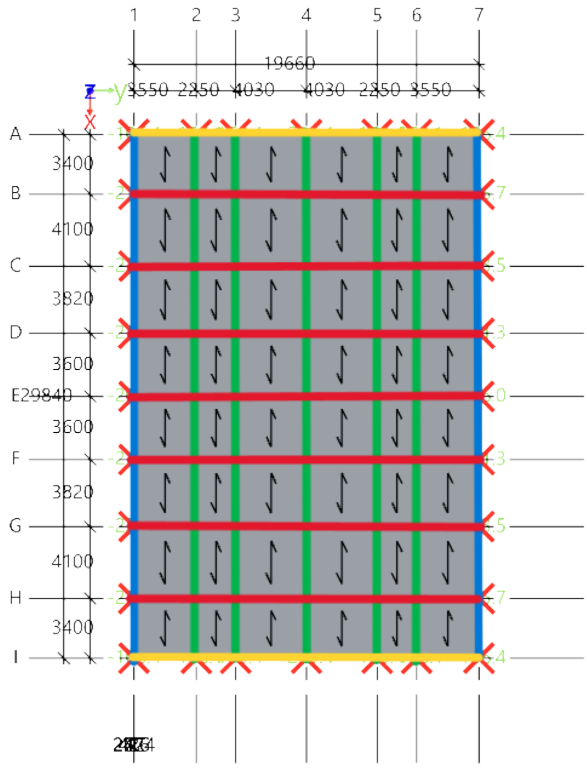


Figure 8.4: Primary internal beams (red), primary façade beams (yellow), secondary internal beams (green) and secondary façade beams (blue)

The tool was validated internally by Arcadis. The tool has the option to return a document that shows the calculations as performed by the tool so the user can review the calculations made by the tool the find the outputted results.

For the floors and roof in both the steel and the concrete model hollow-core concrete slabs were used from manufacturer Dycore. Only when the hollow-core elements were not strong enough to support the loads placed upon them they were replaced by a one-way reinforced concrete slab with concrete strength C30/37. The hollow-core slabs were chosen because they have a lower material use than the one-way reinforced concrete slabs. The decision to use floors that transfer loads in one direction only was made because the floors in the original design of Urban Woods transfer loads in one direction only as well. In the original design of Urban Woods this direction does differ per location, in some location the direction of the load transfer of the floors is x, in other locations this is the y direction. In the steel and concrete models the direction of load transfer that has been used is the x-direction. The beams and columns consist of steel elements with a HEA cross section. These cross sections have a higher lateral torsional buckling resistance than IPE members and also have a lower height. Using IPE cross sections the free height on a floor could be compromised. The steel elements are all made with steel class S355.

For buildings with a residential function and a height of more than thirteen meters the load bearing structure must have a fire resistance of at least 120 minutes. In order to provide sufficient resistance to fire the minimum cross sections were chosen as provided in the Eurocode before starting the optimization. For concrete structures this means that the minimum size of the columns must be 350x350 mm with coverage c equal to at least 57 mm [102, 103]. The beams must have width of at least 200 mm and the average value of the axis distance a must be 65 mm [102, 103]. In the case of steel structures gypsum plates will be used to provide sufficient resistance

8.2.1. Limitations of the Building Structural Design Tool

The BSDT does not allow as much freedom in design as ideal. Some aspects are not available in the tool. For instance, it is not possible to use the material timber in this tool as of now. Only steel and concrete are available as construction materials. Differentiation can be made between different element groups, as mentioned before, but not as much as wanted in this case. Applying a HGS will place a larger load on the roof of the building. In this model increasing the cross sections of the beams supporting the roof will automatically mean the beams that support the floors are increased as well because they are coupled and can not be changed separately from each other. In addition to this it is not possible to change the surface area of the floors per level. Each floor must have the same area and size. In Urban Woods the top floor has a smaller area, leaving room for a roof terrace around the top floor. This can thus not be modeled in the BSDT. Also, it is not possible to place balconies on the building. This is all because the Building Structural Design Tool was designed to be used in a very early stage of the project.

Currently it is only possible to make a beam-column structure in the BSDT. It is thus not possible to construct a core in center of the building. The construction of load-bearing walls is also not possible. Due to the use of the one-directional floors the secondary beams will be unloaded. Unfortunately these beams can not be removed in this model while still maintaining the columns at the cross points of the grids lines where the two directions of beams cross each other.

Originally it was only possible to put area loads on a building using the BSDT. However, for this research especially the option to use line loads along the facade was added to a Beta version of the tool by the Digital team of Arcadis. The line loads will be used to input the loads caused by the application of green facades. For the vertical greenery systems the load is converted from an a distributed area load into a distributed line load placed on the beams along the façade. The magnitude of the line load depends on the storey height. For the vertical forest the loads placed on the balconies will be converted into line loads by multiplying the given area load with the area of total area of the balconies per floor before dividing this value façade.

Unfortunately, in the process of implementing this extra feature some other features became unusable. It is therefore currently not possible to calculate wind loads in the Beta version of the tool. The calculation document that was previously available can also no longer be downloaded. This issue will be solved in the future, but not before the completion of this thesis.

In the end it was chosen to use this tool nonetheless because the aim of this thesis is not necessarily to find a completely optimized design, but to make a comparison between different variants and to give a general idea about the effects that the application of greenery systems have on the load bearing construction in the early stages of the design. This will still be possible with the missing functions since the limitations will be the same for every variant. The BSDT allows the user to model a building in the early design phase which fits the goal of this research.

8.3. Timber model in RFEM

The timber variant of the building is investigated using a model made in Grasshopper and RFEM software. This model was created by a colleague at Arcadis. The model differs from the actual design of the building on a few aspects.

One of the differences in this model concerns the grid size. In the design of the building the grid size is not constant but differs in each direction. In this model the distance between all grid lines is constant at 3,6 meters. The same goes for the floor height, this height is made constant at 3 meters. The model does not have any secondary beams which the BDST does have. In addition to that, unlike the previously discussed model in the BSDT, this RFEM model does have a timber core and timber diagonal beams along the façade for stability. The connections between the members are still hinged.

A second difference concerns the flexibility in design. In the RFEM model it is possible to change each of the elements separately. This means that the cross-sections of the beams that support the roof can be increased independently from the cross-sections of the beams that support the floors.

The model does not calculate the unity check of the modeled floors, therefore appropriate CLT floor types are determined using the Calculatis tool by Stora Enso [104]. The floors are dimensioned to have sufficient fire resistance as well. The CLT floors transfer the load in one direction only, which in this case is the y direction. This is The internal beams in the x direction have been removed. It can be noted that the direction of the load transfer of the floor is thus different from the direction chosen for the concrete and steel models in the BSDT.

With the modifications to the model as described in place, the cross sections as described in the original design of the beams give a maximum unity check of 0,35. These are the cross sections that would suffice for fire resistance as well. The original design [52] mentions that the members were overdimensioned in order to provide sufficient resistance to fire loads. The columns are exposed to fire on four sided and the beams are exposed to fire on three sides. The floors are only exposed to fire on the downside because the screed that is placed on top of it protects the upside of the floor. This is the reason the optimization will be performed towards a unity check with a maximum value of 0,35.

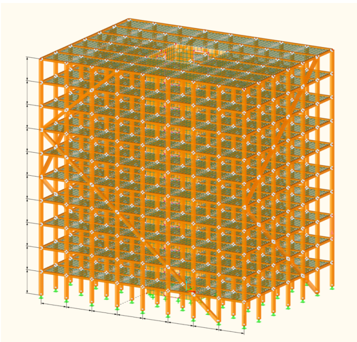


Figure 8.5: 3D view of the timber model of Urban Woods

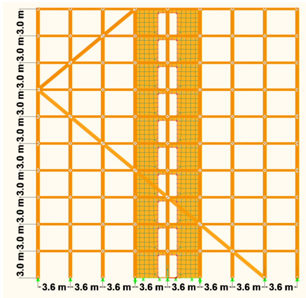


Figure 8.6: Side view 1 of the timber model of Urban Woods

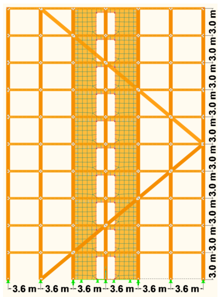


Figure 8.7: Side view 2 of the timber model of Urban Woods

Part II
Analysis and results

9

Sustainability certifications

This chapter will discuss the different certification methods introduced in Chapter 3. In that chapter the possibilities for an increase in the number of points due to the introduction of greenery systems were mentioned. This chapter will elaborate on the different credits where extra points can be obtained and determine how much points are awarded for the improved circumstances due to the application of greenery systems in the building envelope. All greenery systems were assessed on their own qualities alone.

Reading guide for the tables in this chapter
In the tables shown in this chapter points are awarded to the greenery systems according to the demands as provided by the certification method in question. The tables contain information about the quantified effects and the number of points awarded. These are displayed in the form of a number, a dash (-) or an empty cell. Table 9.1 gives an overview of the meaning of this

Table 9.1: Reading guide for the tables in Chapter 9

Cell contains	Meaning
-	No points can be awarded due to constraints of the certification method.
	Effects of the greenery systems were insufficiently quantified and no data was available to determine if the effects provided by the greenery system are sufficient in order to obtain points.
0	Effects of the greenery systems have been quantified but are not large enough to obtain any points.
Number > 0	Effects of the greenery systems have been quantified and are large enough to obtain the shown number of points.

9.1. BREEAM-NL

As discussed in Chapter 3 and shown in Table 3.1 there are nine credits for which a higher score could be obtained due to the application of greenery systems in the building envelope. Each of these credits will be discussed to explain how the available points can be obtained and which criteria have to be met. For reading convenience, the abbreviations used for the different greenery systems are listed in Table 9.2.

Table 9.2: Abbreviations of the greenery systems

Abbreviation	Full name
DGF	Direct green façade
IGFT	Indirect green façade with modular trellis
IGFC	Indirect green façade with continuous guides
LWSC	Continuous living wall system
LWSMB	Living wall system with modular framed boxes
LWSMT	Living wall system with modular trays
LWSL	Linear living wall system
VF	Vertical forest
EGRLW	Lightweight green roof
EGRBS	Biosolar green roof
EGRN	Nature roof
EGRR	Extensive retention blue roof
IGRR	Intensive retention blue roof
IGRG	Garden roof

9.1.1. HEA 05 - Acoustic performance

Three points are available to earn for this credit. One point is available for acoustic isolation of the exterior facade. In order to obtain this point, the characteristic noise reduction of the facade (GA,k) should be greater than the outside noise level - 27 dB, with a minimum of 20 dB. Green facades and roofs can help with the reduction of noise levels on the inside of a building. If the reduction is high enough a point can be earned in this category. No points are available for a sufficient acoustic insulation of the roof.

As mentioned before the reduction in noise level between the outside and inside of the exterior walls must be at least 20 dB. Table 9.3 and Table 9.4 show the noise reduction caused by the different greenery systems assessed in this thesis [105–109]. The noise reduction (in dB) depends on the frequency (in Hz) of the sound that is produced [109]. it was found that lightweight green roofs provide a maximum sound reduction of 35 dB [110]. This sound reduction increases when the thickness of the substrate increases [111], meaning it can be assumed that the HGS with a thicker substrate do also provide at least 30 dB sound reduction. However, since BREEAM does not take the acoustic insulation of the roof into account no points can be awarded for this. None of the vertical greenery systems reduces the noise level by 20 dB or more, therefore the noise reduction due to the application of the vertical greenery systems is not large enough to earn any points for this credit [105–108]. Kragh [108] even calls the acoustic damping of trees 'insignificant'.

Table 9.3: BREEAM points for credit HEA 05 - Vertical Greenery Systems, data from [105–108]

	DGF	**IGFT**	**IGFC**	**LWSC**	**LWSMB**	**LWSMT**	**LWSL**	**VF**
Noise reduction (dB)	0	6,5	6,5	8,4	4,7	5,4	3,1	0-5
Noise reduction $\geq$20 dB	no	no	no	no	no	no	no	no
Points	0	0	0	0	0	0	0	0

Table 9.4: BREEAM points for credit HEA 05 - Horizontal Greenery Systems

	EGRLW	**EGRBS**	**EGRN**	**EGRR**	**IGRR**	**IGRG**
	Points may only be awarded for acoustic insulation of façades					
Points	-	-	-	-	-	-

9.1.2. HEA 08 - Outdoor space

For credit HEA 08 points can be obtained for either private outdoor space or shared outdoor space in the building. A third point can be received if the building is close to a recreational area. To receive the point for private outside space a private balcony or roof terrace with an area of at least 6 m^2 must be available for each of the apartments. This balcony or roof terrace must be accessible to wheel chair users and disabled people. Since the Vertical Forest includes balconies points might be obtained here when applying this greenery system.

The second point can be received for shared outdoor space. This applies to the HGS that allow for human activity on the roof. The space should have an area of at least 50 m^2 and it must be clear that the space is meant for use by the tenants of the building.

All vertical greenery systems except for the vertical forest do not offer outdoor space. Therefore these systems all receive 0 points for this credit. The vertical forest type of greenery system does earn the building a point when all of the private balconies have an area of 6 m^2. Urban woods has five different types of balconies. Only three of them have an area larger than 6 m^2 [52]. Therefore the first point is not awarded in case of the Urban Woods building. The second point for shared outdoor space is awarded for some of the HGS. Nature Roofs, Intensive Retention Blue Roofs and Garden Roofs all allow for human activity on the roof. This is necessary because the roofs have to be publicly accessible to the residents of the building. Urban woods has a roof area of over 600 m^2, which is large enough [52]. Therefore these three greenery systems are awarded one point for this credit. The other horizontal systems do not allow for human activity on the roof. Since these green spaces are not accessible no points are awarded.

Table 9.5: BREEAM points for credit HEA 08 - Vertical Greenery Systems

	DGF	IGFT	IGFC	LWSC	LWSMB	LWSMT	LWSL	VF
Private outdoor space > 6 m^2	no	no	no	no	no	no	no	no
Public outdoor space > 50 m^2	no	no	no	no	no	no	no	no
Points	0	0	0	0	0	0	0	0

Table 9.6: BREEAM points for credit HEA 08 - Horizontal Greenery Systems, data from [52]

	EGRLW	EGRBS	EGRN	EGRR	IGRR	IGRG
Private outdoor space > 6 m^2	no	no	no	no	no	no
Public outdoor space > 50 m^2	no	no	yes	no	yes	yes
Points	0	0	1	0	1	1

9.1.3. HEA 10 - Biophilic design

In this credit fourteen natural elements are defined, they can be seen in Table 9.7. If four of them are incorporated in the building, one point is earned. However, when seven of the fourteen elements are incorporated in the building, the building earns two points. The elements are divided into three categories and from each category at least one element must be incorporated in order to earn the points for this credit. The categories are direct contact with nature (7 elements), indirect contact with nature through representations of nature (3 elements), and lastly experiencing location and space with natural spatial conditions (4 elements). All greenery systems except for the horizontal systems that are inaccessible incorporate elements 1, 2 and 7 in the design. To incorporate element 1 a direct visual connection with nature has to be made. The vertical greenery systems can be seen through the windows of the building and the accessible horizontal greenery systems offer this connection when one is on the roof. The horizontal greenery systems that are not accessible do not offer this visual connection as the roof cannot be seen from any location on the plot. The inaccessibility of these roof types also means that that the the non-visual connection and the awareness of natural processes as described in elements 2 and 7 respectively are hard to guarantee. Therefore these inaccessible HGS do not incorporate elements 2 and 7. In addition to elements 1, 2 and 7, a vertical forest can also offer a save, private space on a green balcony that offers a refuge. A vertical forest thus also incorporates element 11. The horizontal greenery systems where human activity on the roof is allowed can also offer an unobstructed view over a distance as meant in element 12. This does however depend on the surroundings of the building. Both the vertical and horizontal greenery systems do not necessarily contain parts that would contribute to any of the elements in category B, indirect contact with nature. In addition to this the vertical greenery

Table 9.7: Biophilic design elements [36]

Direct contact with nature
1. Direct visual connection with nature: view of natural, living ecosystems and natural elements, materials and processes
2. Non-visual connection with nature using other senses. For instance by simulating sounds, smells and tastes that refer to natural elements
3. Non-rhythmic sensory stimuli: stimuli from nature that can be analysed statistically, but can not be predicted exactly
4. Variation of warmth and air: subtle changes in air temperature, relative humidity, airflow on the skin that imitates natural surroundings
5. Presence of water: seeing, hearing or touching (moving) water
6. Dynamic and diffuse light: changing intensity of light and shadow that creates or imitates natural circumstances
7. Natural systems: awareness of natural processes, seasonal and temporary changes of the ecosystems
Indirect contact with nature
8. Biomorphic forms and patterns: symbolic references to contours, patterns, textures or numerical orders that continue to exist in nature
9. Materials: natural materials that resemble the local ecology and geology
10. Complexity and order: sensory information comparable to the spatial hierarchy in nature
Experiencing place and space
11. Refuge: a place where one can pull back and find protection
12. Vista: an unobstructed view over a distance, which suggests a sense of safety by creating the experience of oversight
13. Obscurity: the promise of more discoveries and information, by wanting to immerse into the surroundings deeper
14. Risk and danger: an identifiable threat in combination with a trustworthy security

systems, except for the vertical forest, do also not incorporate any of the elements from category C. In order to be awarded points it is required to have at least one element from each category incorporated in the design. Since this is not the case, no points are awarded to any of the greenery systems.

Table 9.8: BREEAM points for credit HEA 10 - Vertical Greenery Systems

	DGF	**IGFT**	**IGFC**	**LWSC**	**LWSMB**	**LWSMT**	**LWSL**	**VF**
A-Elements	1, 2, 7	1, 2, 7	1, 2, 7	1, 2, 7	1, 2, 7	1, 2, 7	1, 2, 7	1, 2, 7
B-Elements	-	-	-	-	-	-	-	-
C-Elements	-	-	-	-	-	-	-	11
$\geq$ 1 element from each category	no	no	no	no	no	no	no	no
Points	0	0	0	0	0	0	0	0

Table 9.9: BREEAM points for credit HEA 10 - Horizontal Greenery Systems

	EGRLW	**EGRBS**	**EGRN**	**EGRR**	**IGRR**	**IGRG**
A-Elements	-	-	1, 2, 7	-	1, 2, 7	1, 2, 7
B-Elements	-	-	-	-	-	-
C-Elements	-	-	12	-	12	12
$\geq$ 1 element from each category	no	no	no	no	no	no
Points	0	0	0	0	0	0

9.1.4. ENE 01 - Energy efficiency

Credit ENE 01 is about energy efficiency and for this credit it is possible to earn up to fifteen points. The points are awarded for lowering the fossil energy use of the building. Mandatory parts of this credit include working out an energy concept considering techniques for low CO_2 emissions. The reduction of fossil energy use should be at least 10% in order to earn one point, calculated using a BENG (Bijna Energieneutrale Gebouwen) calculation. For each additional 10% reduction of fossil energy use an extra point is awarded, meaning a 100% energy reduction would mean 10 points are granted. The last 5 points are awarded when the fossil energy use is below 0 kWh/m^3 year, meaning the building actually generates more energy than it uses. Table 9.10 and Table 9.11 display the energy reductions of the different systems split into the cooling energy reduction and heating energy reduction. In Amsterdam the yearly heating energy demand is 43638 kWh and the cooling energy demand is 24427 kWh [112]. The heating energy thus forms 64% of the energy demand and cooling energy forms 36% of the energy demand. These values are needed to calculate the total energy demand of the building. For the HGS Ascione *et al.* [112] considered different types of vegetation. Short sedum, tall sedum, grass lawn, short gramineous and tall gramineous. For the extensive greenery systems the average of the sedum and grass types coverages was taken. For the intensive horizontal greenery systems the average of the grass types coverages was taken. This choice is based on the vegetation types that are used for the different types of horizontal greenery systems. In the BREEAM assessment however, the reduction in energy use must be calculated with a BENG calculation. In this calculation it is not possible to take greenery systems into account and therefore no extra points can be achieved for this credit [113].

Table 9.10: BREEAM points for credit ENE 01 - Vertical Greenery Systems, data from [28, 93, 114–121]

	DGF	IGFT	IGFC	LWSC	LWSMB	LWSMT	LWSL	VF
Cooling energy reduction (%)	33,8	34		26	58,9-97			10,3
Heating energy reduction (%)	8-50	1,9	1,9		4,2-20			
Total energy reduction (%)	24,5	22,5	0,7	16,7	39,3			6,6
BENG score decrease (%)	0	0	0	0	0			0
Points	-	-	-	-	-	-	-	-

Table 9.11: BREEAM points for credit ENE 01 - Horizontal Greenery Systems, data from [112]

	EGRLW	EGRBS	EGRN	EGRR	IGRR	IGRG
Cooling energy reduction (%)	4,5	4,5	4,5	4,5	6,5	6,5
Heating energy reduction (%)	6,8	6,8	6,8	6,8	6,4	6,4
Total energy reduction (%)	5,9	5,9	5,9	5,9	6,5	6,5
BENG score decrease (%)	0	0	0	0	0	0
Points	-	-	-	-	-	-

9.1.5. WAT 04 - Water efficiency and reuse

Credit WAT 04 consider water efficiency and reuse. One point can be earned for the collection of rainwater. This is particularly interesting for the HGS which are able to collect and store rainwater within the system. In order for this point to be awarded the storage of water must be able to store the water of a shower of 40 mm/m^2 for at least one hour. This means every m^2 of area should be able to hold 40 liters of water. In addition to this the system should be able to use the collected water for the shared greenery or, if there is no shared greenery, let the collected water discharge into the sewage system with a maximum rate of 3,6 mm per hour.

The direct and indirect green facade systems are not able to retain water in a location that is not the ground soil since they do not make use of boxes or trays that could serve as catchments for the water. The retention capacity of the living wall systems differs. Wouw *et al.* [122] found that a vertical m^2 of a panel system (such as a LWSC and LWSMB system) has a retention capacity of 18,8% of the retention capacity of a horizontal m^2. For the planter box systems such as LWSMT and LWSL this retention capacity is 33,0% of the retention capacity of an equally sized horizontal area. This equals 19 or 25 L/m^3 respectively. Water is not available for outdoor use afterwards since VGS typically do not contain a storage system for water. Water is only retained within the soil and can not directly be withdrawn from said soil. The VGS do therefore not obtain the point available in this credit. All of the HGS are able to catch water since it can saturate the soil. Only the two retention systems however are able to store the water and make it possible to reuse it. Therefore the EGRR and IGRR systems earn a point.

Table 9.12: BREEAM points for credit WAT 04 - Vertical Greenery Systems, data from [122]

	DGF	IGFT	IGFC	LWSC	LWSMB	LWSMT	LWSL	VF
Water retention (L/m^3)	0	0	0	19	19	25	25	
Water available for outdoor use	no	no	no	no	no	no	no	no
Points	0	0	0	0	0	0	0	0

Table 9.13: BREEAM points for credit WAT 04 - Horizontal Greenery Systems, data from [57, 60]

	EGRLW	EGRBS	EGRN	EGRR	IGRR	IGRG
Water retention (L/m^2)	18	18	30-80	95-150	150-370	180-320
Water available for outdoor use	no	no	no	yes	yes	no
Points	0	0	0	1	1	0

9.1.6. LE 04 - Nature inclusive location

LE 04 is a credit that awards points for a nature inclusive building. If provisions are made for at least two habitats one point is awarded. This point is mandatory to reach an excellent qualification. To reach the qualification outstanding provisions must be made for at least five habitats, which would award an additional point to obtain a total of two points for this credit. The provisions made should be on creating habitats for animal species such as birds, bats, reptiles or mammals. VGS and HGS are both mentioned as ways to create these habitats and thus have the potential to help a building reach more points for this credit. Of the plants used in the GS, at least 60% should consist of native species. The measures taken to reach a nature inclusive design should be chosen based on recommendations by an ecologist, who has to provide a report about their recommendations. In order to obtain (one of) the points available for credit LE04 the building must also comply to the criteria of answer C of credit LE02. This credit prescribes that existing elements of ecological value should be protected during the building process.

Table 9.14: BREEAM points for credit LE 04 - Vertical Greenery Systems

	DGF	IGFT	IGFC	LWSC	LWSMB	LWSMT	LWSL	VF
Habitats created >2	yes	yes	yes	yes	yes	yes	yes	yes
Points	1	1	1	1	1	1	1	1

Table 9.15: BREEAM points for credit LE 04 - Horizontal Greenery Systems

	EGRLW	EGRBS	EGRN	EGRR	IGRR	IGRG
Habitats created >2	yes	yes	yes	yes	yes	yes
Points	1	1	1	1	1	1

9.1.7. LE 05 - Long term use ecological value

The credit LE 05, long term use of ecological value, concerns the maintenance and management of the outdoor space and ecological elements aimed at the long term use of these elements. In order to receive points for this credit, at least one point must be earned for credit LE 04. One point can be earned when residents are stimulated to plan their private outdoor space to contain plants and trees and to maintain this private outdoor space. This applies for the VF systems. A second point is available when the private or shared nature are maintained by a designated person or company. To earn the third and last point, monitoring of the ecological elements must take place. How to monitor these ecological elements must be established in a nature report which gives recommendations for monitoring for a period of six years.

In this case it can be assumed that the shared green spaces are managed by a designated person or company. This applies to all systems except the vertical forests, where the green space is placed on private balconies. Each of these systems thus earns one point. Vertical forests earn one point for stimulating residents to make their private outdoor space green with plants and trees and to maintain this greenery.

Table 9.16: BREEAM points for credit LE 05 - Vertical Greenery Systems

	DGF	IGFT	IGFC	LWSC	LWSMB	LWSMT	LWSL	VF
Stimulating green design and maintenance of private spaces	no	no	no	no	no	no	no	yes
Designated maintenance of shared green spaces	yes	yes	yes	yes	yes	yes	yes	no
Points	1	1	1	1	1	1	1	1

Table 9.17: BREEAM points for credit LE 05 - Horizontal Greenery Systems

	EGRLW	EGRBS	EGRN	EGRR	IGRR	IGRG
Stimulating green design and maintenance of private spaces	no	no	no	no	no	no
Designated maintenance of shared green spaces	yes	yes	yes	yes	yes	yes
Points	1	1	1	1	1	1

9.1.8. POL 03 - Run off rain water

POL 03 is about run off rain water. Greenery systems can help meeting the demands for three of the five available points in this credit. The first point is awarded when the building is able to handle a shower of 70 mm per hour for one hour, which equals 70 liters of water per m^2. There should be enough capacity to store this water at the location and the full capacity of the storage should be available again within 72 hours. An additional two points can be earned when measures have been taken to control the runoff rate of the plot. The water should discharge in to the sewage or into natural water bodies at a maximum speed of 3,6 mm/m^2/hour. The two points for the controlled runoff speed are only awarded when the demands for the storage of water (the first point of this credit) are met as well. An exemplary point can be awarded when the timely availability of the retention capacity can be managed. This point can also only be awarded when the retention capacity is sufficient, meaning more than 70 liters of water can be stored per m^2.

Most of the horizontal greenery systems are able to retain more than 70 liters of rainwater and thus earn one point. The lightweight roof and biosolar roof are not able to retain enough rainwater. The nature roof can retain between 30 and 80 liters of water per m^2. For this thesis it is assumed that this retention capacity will be above 70 liters most of the time, and therefore the point is awarded. Only the retention blue roofs (EGRR and IGRR) have the ability to actively manage the water that is retained. These types of systems also lower the discharge velocity of the rainwater. The retention blue roof systems therefore both earn the additional 2 points for the reduced discharge velocity, and the exemplary point awarded fro the management of the availability of the retention capacity.

VGS are not able to retain such a large amount of water as required in this case. Stormwater runoff can be reduced up to 4% for LWSC and 55% for LWSMB [81, 123].

Table 9.18: BREEAM points for credit POL 03 - Vertical Greenery Systems, data from [122, 123]

	DGF	IGFT	IGFC	LWSC	LWSMB	LWSMT	LWSL	VF
Water retention (L/m^2)	0	0	0	19	19	25	25	
Ability to manage flow down velocity	no	no	no	no	no	no	no	no
Ability to manage availability of retention capacity	no	no	no	no	no	no	no	no
Points	0	0	0	0	0	0	0	0

Table 9.19: BREEAM points for credit POL 03 - Horizontal Greenery Systems, data from [57, 60]

	EGRLW	EGRBS	EGRN	EGRR	IGRR	IGRG
Water retention (L/m^2)	18	18	30-80	95-150	150-370	180-320
Ability to manage flow down velocity	no	no	no	yes	yes	no
Ability to manage availability of retention capacity	no	no	no	yes	yes	no
Points	0	0	1	4	4	1

9.1.9. POL 05 - Reduce noise disturbance

Credit POL 05 grants points for limiting the noise pollution. One point is available for this credit. The point is awarded when the location complies with the standards for maximum noise levels as provided in the Bouwbesluit. This means that the maximum outside noise level at the window or door closest to the origin of the noise is at most 40 dB(A). Greenery systems have the ability to reduce noise levels in the area around the building and could therefore contribute to earning the point for this credit.

In a Dutch urban area such as Rotterdam the average noise level is about 60 dB [124]. This means that the greenery systems would have to dampen out at least 20 dB in order to comply to the set maximum noise level. HGS offer a noise reduction of 3 dBA [109] for traffic noise, which is the leading noise type in urban areas [10]. Traffic has a frequency of around 1000 Hz [125], which means that the noise reduction for horizontal greenery systems is equal to 3 dB. Therefore, none of the greenery systems offers enough noise reduction to earn points for this credit.

Table 9.20: BREEAM points for credit POL 05 - Vertical Greenery Systems, data from [105–108]

	DGF	IGFT	IGFC	LWSC	LWSMB	LWSMT	LWSL	VF
Noise reduction (dB)	0	6,5	6,5	8,4	4,7	5,4	3,1	0-5
Noise reduction $\geq$20 dB	no	no	no	no	no	no	no	no
Points	0	0	0	0	0	0	0	0

Table 9.21: BREEAM points for credit POL 05 - Horizontal Greenery Systems, data from [109]

	EGRLW	EGRBS	EGRN	EGRR	IGRR	IGRG
Noise reduction (dB)	3	3	3	3	3	3
Noise reduction $\geq$20 dB	no	no	no	no	no	no
Points	0	0	0	0	0	0

9.1.10. Total amount of points earned

A total of 163 normal points and an additional 14 points for exemplary performance can be obtained for a BREEAM-NL certification. The greenery systems in this research contribute to earning between 2 and 8 points as shown in Table 9.22 and Table 9.23. For the Urban Woods project a BREEAM certification was also performed during the design phase. This certification was however performed in an older version of BREEAM, which is BREEAM 2014 v2.0 [113], while the certification in this thesis was performed according to BREEAM 2023. Some credits that were assessed in this chapter were not yet implemented in BREEAM 2014 v2.0 and therefore Urban Woods did naturally not receive any points for these credits. This concerns credits HEA05, HEA08 and HEA10 [113]. HEA05 (Acoustics) in BREEAM 2023 awards points for acoustic insulation of the outer facades of the building too. In BREEAM 2014v2.0 however, HEA13 considers the acoustics but only awards points for acoustic insulation between different interior spaces. Greenery systems do not influence this. In addition to this WAT04, LE04, LE05 and POL03 have been taken into account in other credits [113].

The total amount of points that can be awarded to a building when implementing a greenery system can be seen in Table 9.22 and Table 9.23. It can be seen that every greenery system obtained at least two points, with the IGRR being awarded the highest number of points with a score of 8 additional points.

Table 9.22: BREEAM total points - Vertical Greenery Systems

	DGF	IGFT	IGFC	LWSC	LWSMB	LWSMT	LWSL	VF
HEA 05	0	0	0	0	0	0	0	0
HEA 08	0	0	0	0	0	0	0	0
HEA 10	0	0	0	0	0	0	0	0
ENE 01	-	-	-	-	-	-	-	-
WAT 04	0	0	0	0	0	0	0	0
LE 04	1	1	1	1	1	1	1	1
LE 05	1	1	1	1	1	1	1	1
POL 03	0	0	0	0	0	0	0	0
POL 05	0	0	0	0	0	0	0	0
Total points	2	2	2	2	2	2	2	2

Table 9.23: BREEAM total points - Horizontal Greenery Systems

	EGRLW	EGRBS	EGRN	EGRR	IGRR	IGRG
HEA 05	-	-	-	-	-	-
HEA 08	0	0	1	0	1	1
HEA 10	0	0	0	0	0	0
ENE 01	-	-	-	-	-	-
WAT 04	0	0	0	1	1	0
LE 04	1	1	1	1	1	1
LE 05	1	1	1	1	1	1
POL 03	0	0	1	4	4	1
POL 05	0	0	0	0	0	0
Total points	2	2	4	7	8	4

The analyisi in BREEAM 2014v2.0 was performed by Thunnissen [113] from Lois Advies BV. The building scored a total of 77 points for the residential parts of the building. Points that were scored because by Urban Woods because of the greenery systems present in the original design were subtracted from the total score and the remaining points were translated into a BREEAM 2023 certification, resulting in a total of 50 points. The conversion of the credits can be seen in Appendix B. The number of points is lower in BREEAM 2023 because for certain credits the amount of available points has been reduced, sometimes even to zero. The reason behind these changing numbers of points is that some innovative measures in 2014 are today normal practise, and new innovations have occurred. The certification method was changed accordingly. For instance, reducing the energy use of a building by 100% gains a project 15 points in BREEAM 2014v2.0, while in BREEAM 2023 this only awards 10 points and the last 5 points can be obtained by ensuring the building has a negative fossil energy use. Secondly, in BREEAM 2014v2.0 up to 4 points can be obtained by being able to declare the origin of a certain amount of the used building materials. In BREEAM 2023 this is not longer worth any points, but is instead made a mandatory requirement that must be met.

Since some points that can be obtained by implementing a greenery system have already been awarded to Urban Woods, the points obtained for each greenery system as shown in Table 9.22 and Table 9.23 must be adjusted accordingly, since buildings cannot receive the same points twice. The awarded points for applying a greenery system to Urban Woods can be seen in Table 9.24 and Table 9.25. These tables also show the new score and the percentage increase in the BREEAM score of the building.

Table 9.24: BREEAM total points for Urban Woods - Vertical Greenery Systems

	DGF	IGFT	IGFC	LWSC	LWSMB	LWSMT	LWSL	VF
HEA 05	0	0	0	0	0	0	0	0
HEA 08	0	0	0	0	0	0	0	0
HEA 10	0	0	0	0	0	0	0	0
ENE 01	-	-	-	-	-	-	-	-
WAT 04	0	0	0	0	0	0	0	0
LE 04	1	1	1	1	1	1	1	1
LE 05	1	1	1	1	1	1	1	1
POL 03	0	0	0	0	0	0	0	0
POL 05	0	0	0	0	0	0	0	0
Additional points	2	2	2	2	2	2	2	2
Original score	50	50	50	50	50	50	50	50
New score	52	52	52	52	52	52	52	52
Increase (%)	4,0	4,0	4,0	4,0	4,0	4,0	4,0	4,0

Table 9.25: BREEAM total points for Urban Woods - Horizontal Greenery Systems

	EGRLW	EGRBS	EGRN	EGRR	IGRR	IGRG
HEA 05	-	-	-	-	-	-
HEA 08	0	0	1	0	1	1
HEA 10	0	0	0	0	0	0
ENE 01	-	-	-	-	-	-
WAT 04	0	0	0	1	1	0
LE 04	1	1	1	1	1	1
LE 05	1	1	1	1	1	1
POL 03	0	0	1	2	2	1
POL 05	0	0	0	0	0	0
Additional points	2	2	4	5	6	4
Original score	50	50	50	50	50	50
New score	52	52	54	55	56	54
Increase (%)	4,0	4,0	8,0	10,0	12,0	8,0

9.2. LEED

Table 3.5 shows the categories and credits for the program Residential: Multifamily Homes: Core and Shell, which applies to buildings with two or more units. The credits highlighted in green have to potential to receive an increased amount of points due to the implementation of a greenery system. The information about the different credits is all taken from the United States Green Building Council [38]. For reading convenience, the abbreviations used for the different greenery systems are listed in Table 9.26.

Table 9.26: Abbreviations of the greenery systems

Abbreviation	Full name
DGF	Direct green façade
IGFT	Indirect green façade with modular trellis
IGFC	Indirect green façade with continuous guides
LWSC	Continuous living wall system
LWSMB	Living wall system with modular framed boxes
LWSMT	Living wall system with modular trays
LWSL	Linear living wall system
VF	Vertical forest
EGRLW	Lightweight green roof
EGRBS	Biosolar green roof
EGRN	Nature roof
EGRR	Extensive retention blue roof
IGRR	Intensive retention blue roof
IGRG	Garden roof

9.2.1. Protect or restore habitat

There are two options to obtain the point available for this credit. The first option is to restore nature or habitats on site. For instance, by using native or adapted vegetation to restore 25% of the disturbed portions of the site [38]. Both soils and vegetation will have to be replaced or restored. According to the United States Green Building Council [38] vegetation on roofs can also be included to count to this goal, however the plants have to be adapted or native to the area. In addition to that they have to provide habitat. Both intensive and extensive horizontal greenery systems may be used. The second option to achieve this point is to donate money to a conservation land trust or accredited conservation organization, but greenery systems will not help towards this goal so therefore option 2 is in this case not a possible way to achieve the point for this credit.

As noted, green roofs are mentioned specifically as a means to achieve the point available for this credit. As it is assumed that the building in question covers the entirety of the plot and the HGS covers the whole surface area of the roof, at least 25% of the disturbed area of nature on the site is restored. Therefore all HGS are awarded the one point available for this credit. Contrary to that, VGS are not specifically named as an option to reach the goal of this credit. They do not restore 25% of the disturbed area of the plot. Vertical areas are not counted in this case. The VGS do therefore not earn a point in this category.

Table 9.27: LEED points for credit 'Protect or restore habitat' - Vertical Greenery Systems

	DGF	IGFT	IGFC	LWSC	LWSMB	LWSMT	LWSL	VF
Restored $\geq$25% of disturbed area	no	no	no	no	no	no	no	no
Points	0	0	0	0	0	0	0	0

Table 9.28: LEED points for credit 'Protect or restore habitat' - Horizontal Greenery Systems

	EGRLW	EGRBS	EGRN	EGRR	IGRR	IGRG
Restored $\geq$25% of disturbed area	yes	yes	yes	yes	yes	yes
Points	1	1	1	1	1	1

9.2.2. Open space

One point can be achieved for access to open space. There are two options to receive this point, either by creating an accessible outdoor space on the site which covers at least 30% of the total area of the site. Of this outdoor space at least 25% must be vegetated area, including at least two different types of vegetation. Vertical forests and the types of horizontal greenery systems that allow for human activity could contribute to this. The second option to obtain this point would be access to a separate open space within 800 meters from the building.

The HGS that are accessible to humans, which are EGRN, IGRR and IGRG, all earn the point available for this credit. From the vertical greenery systems only the VF has potential to earn this point, however this would depend on the area of the balconies in this system. These should form at least 30% of the size of the plot.

In the case of Urban Woods the balconies do form at least 30% of the area of the plot. The plot has a size of about 600 m^2. The area of all balconies combined is approximately the same. A point can be awarded if at least 25% of each balcony is vegetated, which is assumed to be the case.

Table 9.29: LEED points for credit 'Open space' - Vertical Greenery Systems

	DGF	IGFT	IGFC	LWSC	LWSMB	LWSMT	LWSL	VF
Accessible open space $\geq$30% of total plot size	no	no	no	no	no	no	no	yes
Vegetated part of open space $\geq$25%	-	-	-	-	-	-	-	yes
Points	0	0	0	0	0	0	0	1

Table 9.30: LEED points for credit 'Open Space' - Horizontal Greenery Systems

	EGRLW	EGRBS	EGRN	EGRR	IGRR	IGRG
Accessible open space $\geq$30% of total plot size	no	no	yes	no	yes	yes
Vegetated part of open space $\geq$25%	-	-	yes	-	yes	yes
Points	0	0	1	0	1	1

9.2.3. Rainwater management

For rainwater management up to four points can be received. United States Green Building Council [38] mentions vegetated roofs as one of the options to obtain the goals set to receive these points. As the percentage of rainwater that can be retained increases, the amount of points earned increases as well. When there is no open space around the building the building is called a Zero Lot Line Project' and the percentage of water that has to be retained in order to earn a point becomes lower. However, still at least 70% of the water must be retained in order to obtain the first point. The points may also be awarded based on the percentage of the total area that is permeable and therefore able to let the water infiltrate. Vegetated roofs are again mentioned as one of the ways to achieve this. A minimum of 50% of the area must be permeable in order to earn the first of four available points. For a permeable area covering 80% or more of the plot area all four points are awarded.

Based on the percentage of permeable surface, all horizontal greenery systems earn four points for this credit. Each of them has a permeable area of at least 80% of the total area of the plot since the greenery systems cover the entirety of the roof. The VGS are not able to retain the required 70% of the water and do also not make at least 50% of the plot permeable [122, 123].

Table 9.31: LEED points for credit 'Rainwater management' - Vertical Greenery Systems, data from [122]

	DGF	IGFT	IGFC	LWSC	LWSMB	LWSMT	LWSL	VF
Water retention (L/m^3)	0	0	0	19	19	25	25	
Permeable area (%)	<50	<50	<50	<50	<50	<50	<50	<50
Points	0	0	0	0	0	0	0	0

Table 9.32: LEED points for credit 'Rainwater management' - Horizontal Greenery Systems

	EGRLW	EGRBS	EGRN	EGRR	IGRR	IGRG
Permeable area (%)	>80	>80	>80	>80	>80	>80
Points	4	4	4	4	4	4

9.2.4. Heat island reduction

Two points are available for reduction of the heat island effect. The points can be earned in two ways that have to do with keeping the hardscape material, such as the roof and pavement on the plot, out of the sun. The first option considers the shading of the hardscape area on the plot. If between 50 and 75% of the hardscape area is shaded one point is awarded. If this percentage is over 75% two points are awarded. The two points can also be obtained by meeting the following criterion. Only horizontal areas are considered [126], so this includes roofs and pieces of land on the plot surrounding the building. Facades are not included. Therefore, no points can be earned by the vertical greenery systems.

$$\frac{A_{nonroof\ measures}}{0.5} + \frac{A_{high-reflectance\ roof}}{0.75} + \frac{A_{vegetated\ roof}}{0.75} \leq A_{site\ paving,tot} + A_{roof,tot} \tag{9.1}$$

Implementing a vegetated roof is one of the ways to shade the entirety of the roof. As it was assumed that this building covers the complete plot, Therefore each of the HGS lets the building obtain two points for this credit. Using the formula the same result would be obtained. With $A_{nonroof\ measures}$, $A_{high-reflectance\ roof}$ and $A_{site\ paving,tot}$ all being equal to zero and $A_{vegetated\ roof}$ being equal to $A_{roof,tot}$ because the horizontal greenery system covers the complete roof, the criterion would be met since $A_{roof,tot}\ /\ 0.75 > A_{roof,tot}$.

Table 9.33: LEED points for credit 'Heat island reduction' - Vertical Greenery Systems [126]

	DGF	IGFT	IGFC	LWSC	LWSMB	LWSMT	LWSL	VF
	Points are only awarded for shading of horizontal surfaces							
Points	-	-	-	-	-	-	-	-

Table 9.34: LEED points for credit 'Heat island reduction' - Horizontal Greenery Systems

	EGRLW	EGRBS	EGRN	EGRR	IGRR	IGRG
Shaded part of hardscape surface $\geq$ 50%	yes	yes	yes	yes	yes	yes
Shaded part of hardscape surface $\geq$ 75%	yes	yes	yes	yes	yes	yes
Points	2	2	2	2	2	2

9.2.5. Optimize energy performance

This credit awards points for the reduction of energy use. A total of eighteen points can be obtained. The number of parts awarded can be determined in three different ways.

The first option uses the Performance Cost Index (PCI). The PCI is determined in two different facets, firstly on basis of the costs and secondly on basis of the greenhouse gas emissions. For each facet nine points can be earned. Points are awarded based on the percentage the PCI is below the Performance Cost Index Target (PCIt).

The second option awards points according to the requirements of the New Buildings Institute's Multifamily Guide.

The third option determines the amount of points awarded based on the HERS (Home Energy Rating System) score of the building. In this thesis the third option is applied. The HERS score is determined based on the energy consumption of a standard new home. A HERS score of 60 means that the building is 40% more energy efficient than the predetermined standard new home, while a score of 120 would mean the building is 20% less energy efficient than the predetermined standard new home [127]. The HERS score must be determined by a professional energy auditor who has to perform a detailed analysis of the structure. For this research it was assumed that an energy reduction of X percent would result in a HERS score of 100-X percent.The amount of points available is shown in Table 9.35.

Table 9.35: Points for credit Optimize energy performance [38]

HERS index	Points
70	5
68	6
66	7
64	8
62	9
60	10
58	11
56	12
54	13
52	14
50	15
40	16
30	17
20	18

Table 9.36: LEED points for credit 'Optimize energy performance' - Vertical Greenery Systems, data from [28, 114–121]

	DGF	IGFT	IGFC	LWSC	LWSMB	LWSMT	LWSL	VF
Cooling energy reduction (%)	33,8	34		26	58.9-97			10,3
Heating energy reduction (%)	8-50	1,9	1,9		4,2-20			
Total energy reduction (%)	24,5	22,5	0,7	16,7	39,3			6,6
HERS score	75,5	77,5	99,3	83,3	60,7			93,4
Points	0	0	0	0	9			0

Table 9.37: LEED points for credit 'Optimize energy performance' - Horizontal Greenery Systems, data from [112]

	EGRLW	EGRBS	EGRN	EGRR	IGRR	IGRG
Cooling energy reduction (%)	4,5	4,5	4,5	4,5	6,5	6,5
Heating energy reduction (%)	6,8	6,8	6,8	6,8	6,4	6,4
Total energy reduction (%)	5,9	5,9	5,9	5,9	6,5	6,5
HERS score	94,1	94,1	94,1	94,1	93,5	93,5
Points	0	0	0	0	0	0

9.2.6. Renewable energy

Up to five points can be obtained by using renewable energy. By using the renewable energy sources the greenhouse gas emissions are reduced. Points are awards based on the percentage decrease in green house gas emissions. This can be done by using renewable energy sources both on-site and off-site. The off-site sources will have to be leased for a minimum of fifteen years. In this thesis only the on-site sources will be considered. Implementation of bio-solar roofs could earn the project points in this category. The other greenery systems do not contain renewable energy sources.

Table 9.38: Points for Renewable energy [38]

On-Site renewables	Points
2%	1
6%	2
15%	3
35%	4
60%	5

To determine the amount of points earned by a biosolar roof it is necessary to know the energy use of the complete building because points are awarded based on the percentage of the total energy use. Up to five points can be earned on the basis of Table 9.38. An appartment in the Netherlands has an average net energy supply of 1900 kWh per year [128]. Urban Woods has a total of 102 apartments bringing the total energy use to 193800 kWh per year. Solar panels can produce on average 120 kWh of energy per year per m^2 [129]. Some space must be left between the solar panels of a biosolar green roof, so assuming half of the roof, approximately 300 m^2, can be filled with solar panels the total energy production is 36000 kWh per year. This solar energy can provide 18,6% of the total energy consumption. The energy consumption can thus be reduced by 18,6% as well thereby reducing the greenhouse gas emissions produced in the energy production with this percentage as well. Therefore, three points can be awarded for this credit to a bio-solar green roof.

Table 9.39: LEED points for credit 'Renewable energy' - Vertical Greenery Systems

	DGF	IGFT	IGFC	LWSC	LWSMB	LWSMT	LWSL	VF
Energy supply from on-site renewables (%)	0	0	0	0	0	0	0	0
Points	0	0	0	0	0	0	0	0

Table 9.40: LEED points for credit 'Renewable energy' - Horizontal Greenery Systems, data from [128]

	EGRLW	EGRBS	EGRN	EGRR	IGRR	IGRG
Energy supply from on-site renewables (%)	0	18,6	0	0	0	0
Points	0	3	0	0	0	0

9.2.7. Enhanced indoor air quality strategies

This credit awards points for the filtering of air inside the building. Greenery systems have proven to be able to purify the air and filter out harmful particles [130–132]. This credit however only awards points for the use of a mechanical ventilation system. This means that no points can be awarded for the use of greenery systems towards this credit.

Table 9.41: LEED points for credit 'Enhanced indoor air quality strategies' - Vertical Greenery Systems

	DGF	IGFT	IGFC	LWSC	LWSMB	LWSMT	LWSL	VF
	Points may only be awarded for the use of mechanical ventilation systems							
Points	-	-	-	-	-	-	-	-

Table 9.42: LEED points for credit 'Enhanced indoor air quality strategies' - Horizontal Greenery Systems

	EGRLW	EGRBS	EGRN	EGRR	IGRR	IGRG
	Points may only be awarded for the use of mechanical ventilation systems					
Points	-	-	-	-	-	-

9.2.8. Daylight and quality views

In the category indoor environmental quality the score of the credit daylight and quality views could be improved by greenery systems, however not always for the building that has the greenery systems applied to it. One point can be awarded when 50% of the rooms has a quality view through at least one window. A quality view is defined as a view on flora, fauna or sky. The greenery systems could contribute to this credit when they are visible from the window of the building. Not all VGS will be within sight through a window of the building itself, but neighbouring buildings can earn points for their view on the building that has greenery systems applied. Vertical Forests might however be able to provide a point in this category since the balconies that contain the greenery systems can be seen from the inside of the building [90]. Vertical forests thus obtain the point available for this credit.

Table 9.43: LEED points for credit 'Daylight and quality views' - Vertical Greenery Systems

	DGF	IGFT	IGFC	LWSC	LWSMB	LWSMT	LWSL	VF
Quality view	no	no	no	no	no	no	no	yes
Points	0	0	0	0	0	0	0	1

Table 9.44: LEED points for credit 'Daylight and quality views' - Horizontal Greenery Systems

	EGRLW	EGRBS	EGRN	EGRR	IGRR	IGRG
Quality view	no	no	no	no	no	no
Points	0	0	0	0	0	0

9.2.9. Total amount of points earned

A total of 131 points can be obtained for a LEED certification. The greenery systems in this research contribute to earning between 0 and 10 points as shown in Table 9.45 and Table 9.46.

Table 9.45: LEED total points - Vertical Greenery Systems

	DGF	IGFT	IGFC	LWSC	LWSMB	LWSMT	LWSL	VF
Protect or restore habitat	0	0	0	0	0	0	0	0
Open space	0	0	0	0	0	0	0	1
Rainwater management	0	0	0	0	0	0	0	0
Heat island reduction	-	-	-	-	-	-	-	-
Optimize energy performance	0	0	0	0	9			0
Renewable energy	0	0	0	0	0	0	0	0
Enhanced indoor air quality strategies	-	-	-	-	-	-	-	-
Daylight and quality views	0	0	0	0	0	0	0	1
Total points	0	0	0	0	9	0	0	2

Table 9.46: LEED total points - Horizontal Greenery Systems

	EGRLW	EGRBS	EGRN	EGRR	IGRR	IGRG
Protect or restore habitat	1	1	1	1	1	1
Open space	0	0	1	0	1	1
Rainwater management	4	4	4	4	4	4
Heat island reduction	2	2	2	2	2	2
Optimize energy performance	0	0	0	0	0	0
Renewable energy	0	3	0	0	0	0
Enhanced indoor air quality strategies	-	-	-	-	-	-
Daylight and quality views	0	0	0	0	0	0
Total points	7	10	8	7	8	8

For Urban Woods no LEED certification was made. Also it was not possible to obtain a LEED certification for a comparable building. Therefore the certifications of the twelve most recently assessed multifamily midrise project were taken from the website of LEED [38]. These twelve projects scored an average of 64 points. This number of points will be taken as the starting number to determine the percent increase of the LEED certification score. It must be noted that it was not possible to determine which points were already achieved by the buildings found on the LEED website. Therefore it is assumed that the extra points that can be awarded due to the application of greenery systems were not already obtained.

Table 9.47: LEED total points for Urban Woods - Vertical Greenery Systems

	DGF	IGFT	IGFC	LWSC	LWSMB	LWSMT	LWSL	VF
Protect or restore habitat	0	0	0	0	0	0	0	0
Open space	0	0	0	0	0	0	0	1
Rainwater management	0	0	0	0	0	0	0	0
Heat island reduction	-	-	-	-	-	-	-	-
Optimize energy performance	0	0	0	0	9			0
Renewable energy	0	0	0	0	0	0	0	0
Enhanced indoor air quality strategies	-	-	-	-	-	-	-	-
Daylight and quality views	0	0	0	0	0	0	0	1
Additional points	0	0	0	0	9	0	0	2
Original score	64	64	64	64	64	64	64	64
New score	64	64	64	64	73	64	64	66
Increase (%)	0	0	0	0	14,06	0	0	3,13

Table 9.48: LEED total points for Urban Woods - Horizontal Greenery Systems

	EGRLW	EGRBS	EGRN	EGRR	IGRR	IGRG
Protect or restore habitat	1	1	1	1	1	1
Open space	0	0	1	0	1	1
Rainwater management	4	4	4	4	4	4
Heat island reduction	2	2	2	2	2	2
Optimize energy performance	0	0	0	0	0	0
Renewable energy	0	3	0	0	0	0
Enhanced indoor air quality strategies	-	-	-	-	-	-
Daylight and quality views	0	0	0	0	0	0
Additional points	7	10	8	7	8	8
Original score	64	64	64	64	64	64
New score	71	74	72	71	72	72
Increase (%)	10,94	15,63	12,50	10,94	12,50	12,50

9.3. WELL

There are six credits in which a higher number of points could be earned due to the implementation of a greenery system. Each of these credits will be discussed. For reading convenience, the abbreviations used for the different greenery systems are listed in Table 9.49.

Table 9.49: Abbreviations of the greenery systems

Abbreviation	Full name
DGF	Direct green façade
IGFT	Indirect green façade with modular trellis
IGFC	Indirect green façade with continuous guides
LWSC	Continuous living wall system
LWSMB	Living wall system with modular framed boxes
LWSMT	Living wall system with modular trays
LWSL	Linear living wall system
VF	Vertical forest
EGRLW	Lightweight green roof
EGRBS	Biosolar green roof
EGRN	Nature roof
EGRR	Extensive retention blue roof
IGRR	Intensive retention blue roof
IGRG	Garden roof

9.3.1. A05 - Enhanced air quality

The feature A05 can earn a building up to four points for a good air quality inside the building. The feature is divided into three parts.
Part 1 sets threshold for particulate matter. Plants can improve the air quality by filtering out particulate matter. Points are awarded in this category are awarded in two tiers. If the amount of $PM_{2.5}$ in the air is below 12 $\mu g/m^3$ and the amount of PM_{10} is below 30 $\mu g/m^3$ 1 point is awarded. Two points are awarded when the amount of $PM_{2.5}$ in the air is below 10 $\mu g/m^3$ and the amount of PM_{10} is below 20 $\mu g/m^3$.
Part 2 and part 3 consider the amount of organic and inorganic gasses in the air respectively, both having a worth of one point. The gasses in question include acetaldehyde, benzene, carbon monoxide and nitrogen dioxide among others.

In a Dutch urban environment the average amount of $PM_{2,5}$ in the outside air is 10,87 $\mu g/m^3$. In addition to this there is an average of 19,5 $\mu g/m^3$ PM_{10} in the air [133, 134]. Data for PM$2,5$ is available up to the year 2022 and for PM_{10} up to the year 2020. However, most of the particulate matter in the air is caused by combustion forces mainly caused by traffic. During the COVID-19 pandemic traffic intensity was reduced which could have affected the levels of particulate matter in the air. The data from 2019 is therefore used to make sure the data is representative for normal circumstances in an urban environment. The data from 2019 shows that an average Dutch city environment already complies to the demands for the first point. Not for every greenery system data is available, but for some greenery systems the amount of particulate matter that can be captured from the air is known.

Table 9.50: WELL points for credit A05 - Vertical Greenery Systems, data from [130–132]

	DGF	IGFT	IGFC	LWSC	LWSMB	LWSMT	LWSL	VF
$PM_{2,5}$ capture ($\cdot 10^7$ parts/m)	2090			8,24	8,24			
PM_{10} capture ($\cdot 10^7$ parts/m)	2090			4,45	4,45			
Points	0			0	0			

Table 9.51: WELL points for credit A05 - Horizontal Greenery Systems, data from [22]

	EGRLW	EGRBS	EGRN	EGRR	IGRR	IGRG
$PM_{2,5}$ capture						
PM_{10} capture (g/m^2/year)	1,12	1,12	1,52	1,52	2,16	2,16
NO_2 capture (g/m^2/year)	2,33	2,33	2,94	2,94	3,57	3,57
Points	0	0	0	0	0	0

9.3.2. A12 - Air filtration

Credit A12 awards points for the air filtration in order to remove harmful particles. Greenery systems have proven to purify the air and could thus help towards reaching the goals set for this credit. In order to earn the points, the following thresholds must be met.

Table 9.52: Thresholds for WELL credit A12 [39]

Annual average outdoor $PM_{2,5}$ threshold	Average air filtration efficiency
$\leq$ 23 μg/m^3	$\geq$ 35%
24-39 μg/m^3	$\geq$ 75%
$\geq$ 40 μg/m^3	$\geq$ 95%

The method prescribes that a mechanical ventilation with media filters must be used in order to obtain the points for this credit. Therefore, no points can be earned by the greenery systems for this credit.

Table 9.53: WELL points for credit A12 - Vertical Greenery Systems

	DGF	IGFT	IGFC	LWSC	LWSMB	LWSMT	LWSL	VF
	Points may only be awarded for the use of mechanical ventilation systems							
Points	-	-	-	-	-	-	-	-

Table 9.54: WELL points for credit A12 - Horizontal Greenery Systems

	EGRLW	EGRBS	EGRN	EGRR	IGRR	IGRG
	Points may only be awarded for the use of mechanical ventilation systems					
Points	-	-	-	-	-	-

9.3.3. N12 - Food production

If a gardening space if available within 400 meters of the building, two points can be obtained for feature N12. This could be a possibility for the horizontal greenery systems that allow for human activity on the roof. The points can also be earned if there is a garden on the roof with trees or plants that are food-bearing. In addition to this the space must be accessible to all occupants of the building and have an area of at least 1,4 m^2 per dwelling unit with a minimum of 18,6 m^2. Since the balconies of a vertical forest are private in the case of a residential building, gardening space on these balconies will not lead to earning any points for this credit.

Table 9.55: WELL points for credit N12 - Vertical Greenery Systems

	DGF	IGFT	IGFC	LWSC	LWSMB	LWSMT	LWSL	VF
Public gardening space available	no	no	no	no	no	no	no	no
Points	0	0	0	0	0	0	0	0

Table 9.56: WELL points for credit N12 - Horizontal Greenery Systems

	EGRLW	EGRBS	EGRN	EGRR	IGRR	IGRG
Public gardening space available	no	no	yes	no	yes	yes
Points	0	0	2	0	2	2

9.3.4. T09 - β Outdoor thermal comfort

Credit T09 considers outdoor thermal comfort. A maximum of three points are available for this credit, one for each part of this credit. The points can be earned separately as well. The point available for part 1 can be earned for managing outdoor heat. There are two options to obtain this point. The first option is by providing outdoor shade on pedestrian pathways and building entrances (at least 50%), parking spaces (at least 25%) or plazas, seating areas, exercise facilities and other areas of congregation (at least 25%). Trees and vegetated canopies could provide shade on the outdoor areas on the roof, meaning they could earn the project a point for this credit. The second option to earn the first point is to apply temperature modelling.
Part 2 considers avoiding excessive wind. If wind speeds remain below a set speed points can be awarded.
The last point is available for part 3, supporting outdoor nature access. This point is awarded when at least one point has already been obtained for T09 (either part 1 or part 2) and the point for feature M09 is was achieved.

Trees can provide shade on the roofs of buildings. Since it was assumed that the building fills the whole plot, there are no pedestrian pathways and parking spaces that need shading. Focus can be on the third set that needs shading: plazas, seating areas, exercise facilities and other areas of congregation. The green roofs that are accessible to humans can be designated as an area of congregation. If the HGS can also include trees, those trees can offer shading of at least 25% of the roof area. One point is therefore awarded to the intensive retention blue roof and the garden roof. The nature roofs are also accessible, however they do not include trees for shade. If the intensive retention blue roof and the garden roof do also score the available point for credit M09, they can be awarded a second point for part 3 of this credit. The VGS are not awarded points for this credit since the focus is on horizontal surfaces [126], which are not shaded by application of a vertical greenery system.

Table 9.57: WELL points for credit T09 - Vertical Greenery Systems

	DGF	IGFT	IGFC	LWSC	LWSMB	LWSMT	LWSL	VF
Shading $\geq$ 25% of congregation spaces	no	no	no	no	no	no	no	no
Points	0	0	0	0	0	0	0	0

Table 9.58: WELL points for credit T09 - Horizontal Greenery Systems

	EGRLW	EGRBS	EGRN	EGRR	IGRR	IGRG
Shading $\geq$ 25% of congregation spaces	no	no	no	no	yes	yes
Points	0	0	0	0	1 (+1)	1 (+1)

9.3.5. S02 - Maximum noise levels

For dwelling units a maximum noise level for background noise has been set at 35 dB. Three points are awarded when noise levels inside are below this threshold. As mentioned in Section 9.1.9 the average noise level in a Dutch urban area such as Rotterdam is about 60 dB [124]. This means that the greenery systems would have to dampen out at least 25 dB in order to comply to the set maximum noise level.

Table 9.59: WELL points for credit S02 - Vertical Greenery Systems, data from [105–107]

	DGF	IGFT	IGFC	LWSC	LWSMB	LWSMT	LWSL	VF
Noise reduction (dB)	0	6,5	6,5	8,4	4,7	5,4	3,1	0-5
Noise reduction $\geq$25 dB	no	no	no	no	no	no	no	no
Points	0	0	0	0	0	0	0	0

Table 9.60: WELL points for credit S02 - Horizontal Greenery Systems, data from [109]

	EGRLW	EGRBS	EGRN	EGRR	IGRR	IGRG
Noise reduction (dB)	3	3	3	3	3	3
Noise reduction $\geq$25 dB	no	no	no	no	no	no
Points	0	0	0	0	0	0

9.3.6. M09 - Enhanced access to nature

Two points are available for this feature which is divided into two parts. Each part being worth one point. The first part considers access to nature that is indoors, such as potted plants. A point can also be awarded for views on nature.
The second part considers access to natural elements outdoors. The outdoor space is required to have an area of at least 5% of the total indoor area. 70% of the outdoor space must consist of natural elements such as plants. In addition to this occupants must be encouraged to access the outdoor nature available. The outdoor area must be accessible to all regular occupants of the building.

As greenery systems on the outside of the building are not properly visible from the inside, except for the vertical forest, the first part will award one point only to the vertical forest type of VGS. Neighbouring buildings could however also earn points for this part, when they have a view on the VGS on the building in question. The HGS do not earn this point as the roof is not visible from the inside. The accessible HGS will earn a point for the second part of this credit. Since the nature considered in this credit must be accessible to all regular occupants, vertical forests do not obtain a point for this part of this credit because the balconies will be private.

Table 9.61: WELL points for credit M09 - Vertical Greenery Systems

	DGF	IGFT	IGFC	LWSC	LWSMB	LWSMT	LWSL	VF
View on nature	no	no	no	no	no	no	no	yes
Access to nature	no	no	no	no	no	no	no	no
Points	0	0	0	0	0	0	0	1

Table 9.62: WELL points for credit M09 - Horizontal Greenery Systems

	EGRLW	EGRBS	EGRN	EGRR	IGRR	IGRG
View on nature	no	no	no	no	no	no
Access to nature	no	no	yes	no	yes	yes
Points	0	0	1	0	1	1

9.3.7. Total amount of points earned

A total of 131 points can be obtained for a WELL certification. The greenery systems in this research contribute to earning between 0 and 5 points as shown in Table 9.63 and Table 9.64.

Table 9.63: WELL total points - Vertical Greenery Systems

	DGF	IGFT	IGFC	LWSC	LWSMB	LWSMT	LWSL	VF
A05	0			0	0			
A12	-	-	-	-	-	-	-	-
N12	0	0	0	0	0	0	0	0
T09	0	0	0	0	0	0	0	0
S02	0	0	0	0	0	0	0	0
M09	0	0	0	0	0	0	0	1
Total points	0	0	0	0	0	0	0	1

Table 9.64: WELL total points for Urban Woods - Horizontal Greenery Systems

	EGRLW	EGRBS	EGRN	EGRR	IGRR	IGRG
A05	0	0	0	0	0	0
A12	-	-	-	-	-	-
N12	0	0	2	0	2	2
T09	0	0	0	0	2	2
S02	0	0	0	0	0	0
M09	0	0	1	0	1	1
Total points	0	0	3	0	5	5

For Urban Woods no WELL certification was performed. However, a WELL certification was made for the CubeHouse building. This certification was made by Arcadis [126]. CubeHouse is a comparable building in Amsterdam. It is therefore assumed that Urban Woods would obtain an amount of points that is comparable to the amount of points obtained by CubeHouse. The CubeHouse scored a total of 88, however points that were awarded solely because of the use of a greenery system were subtracted from this number resulting in a score of 86 points for a building without greenery systems. Points that were obtained already by different means than a greenery system were not subtracted and remain, in these cases no extra points were awarded when a greenery system is applied that would award the same points. Table 9.65 and Table 9.66 show the awarded points in case a greenery system is applied to Urban Woods. In addition to this the tables show the percentage increase of the WELL score.

Table 9.65: WELL total points for Urban Woods - Vertical Greenery Systems

	DGF	IGFT	IGFC	LWSC	LWSMB	LWSMT	LWSL	VF
A05	0			0	0			
A12	-	-	-	-	-	-	-	-
N12	0	0	0	0	0	0	0	0
T09	0	0	0	0	0	0	0	0
S02	0	0	0	0	0	0	0	0
M09	0	0	0	0	0	0	0	1
Additional points	0	0	0	0	0	0	0	1
Original score	86	86	86	86	86	86	86	86
New score	86	86	86	86	86	86	86	87
Increase (%)	0	0	0	0	0	0	0	1,2

Table 9.66: WELL total points for Urban Woods - Horizontal Greenery Systems

	EGRLW	EGRBS	EGRN	EGRR	IGRR	IGRG
A05	0	0	0	0	0	0
A12	-	-	-	-	-	-
N12	0	0	2	0	2	2
T09	0	0	0	0	2	2
S02	0	0	0	0	0	0
M09	0	0	1	0	1	1
Additional points	0	0	3	0	5	5
Original score	86	86	86	86	86	86
New score	86	86	89	86	91	91
Increase (%)	0	0	3,5	0	5,8	5,8

10 Structural effects

This chapter will discuss the results that were found using the models that were introduced in Chapter 8. As mentioned before the building was investigated in three different variants, each consisting of a different material: steel, concrete and timber. The variants will be discussed separately. For each variant the ECI value is determined for the standard structure without greenery systems, a building with a roof terrace with concrete tiles and for each of the greenery systems. The variant with the concrete roof terrace (which is not a greenery system) was included to provide extra context into the differences between a normal roof terrace and an accessible green roof instead of only comparing the accessible green roof systems with an inaccessible normal roof. The ECI value displayed in the tables is for the load bearing structure only. Increases in ECI value do thus not take into account the parts of the greenery system itself, but only the effect it has on the load bearing elements of the building. The steel and concrete variants were assessed using the Building Structural Design Tool (BSDT) and the timber model was assessed using a RFEM model. More information about these models can be found in Chapter 8. This chapter also describes the differences between the elements that are mentioned such as the primary and secondary beams. For reading convenience, the abbreviations used for the different greenery systems are listed in Table 10.1.

Table 10.1: Abbreviations of the greenery systems

Abbreviation	Full name
DGF	Direct green façade
IGFT	Indirect green façade with modular trellis
IGFC	Indirect green façade with continuous guides
LWSC	Continuous living wall system
LWSMB	Living wall system with modular framed boxes
LWSMT	Living wall system with modular trays
LWSL	Linear living wall system
VF	Vertical forest
EGRLW	Lightweight green roof
EGRBS	Biosolar green roof
EGRN	Nature roof
EGRR	Extensive retention blue roof
IGRR	Intensive retention blue roof
IGRG	Garden roof

10.1. Steel structure

Table 10.2 shows the element types that result in sufficing unity checks and the increase in ECI value for all different greenery systems applied. A more elaborate overview that includes the inputted loads and total material volumes can be found in Appendix C.

The structure consists of HEA columns and beams. The beams support the floors and the roof, which consist of hollow-core elements or solid reinforced concrete slabs. The finishing of the floor consists of an insulation layer and two finishing layers. Each of the floors is loaded by As mentioned before the BSDT does not implement a stability system such as a concrete core or braces. As introduced in Chapter 7, the spans of the beams are between 2,25 and 4,10 meters. The columns parts have a minimum length of 3,04 meters and a maximum length of 3,25 meters. The foundation consists of Fundex pile with a diameter of 540 mm reaching down to -32,5 meters NAP. The number of piles needed is calculated by dividing the total weight of the building by the capacity of one pile, which is 2000 kN.

As can be seen from the table, the differences in ECI value are zero in many cases. Only five cases lead to an increase in ECI. Most of them are HGS, namely the nature roof, the intensive retention green roof and the garden roof. From the vertical greenery systems only the vertical forest results in an increased ECI value. The combination of an intensive retention blue roof with a vertical forest gives the highest increase in ECI.

Table 10.2: Results for a steel building

Applied system	Roof	Floors	Beams*				Columns	#Piles	ECI value	ECI increase
			IP	IS	FP	FC				
-	Dycore K150-8	Dycore K150-8	HE200A	HE100A	HE160A	HE100A	HE240A	28	€190813,94	-
Standard roof terrace	Dycore K150-8	Dycore K150-8	HE220A	HE100A	HE160A	HE100A	HE240A	29	€196692,61	3,08%
Horizontal Greenery Systems										
EGRLW	Dycore K150-8	Dycore K150-8	HE200A	HE100A	HE160A	HE100A	HE240A	29	€191353,62	0,28%
EGRBS	Dycore K150-8	Dycore K150-8	HE200A	HE100A	HE160A	HE100A	HE240A	29	€191353,62	0,28%
EGRN	Dycore K150-8	Dycore K150-8	HE220A	HE100A	HE160A	HE100A	HE240A	29	€196692,61	3,08%
EGRR	Dycore K150-8	Dycore K150-8	HE200A	HE100A	HE160A	HE100A	HE240A	29	€191353,62	0,28%
IGRR	Slab t=160mm	Dycore K150-8	HE260A	HE100A	HE180A	HE100A	HE240A	32	€208941,83	9,50%
IGRG	Slab t=160mm	Dycore K150-8	HE260A	HE100A	HE180A	HE100A	HE240A	32	€208941,83	9,50%
Vertical Greenery Systems										
DGF	Dycore K150-8	Dycore K150-8	HE200A	HE100A	HE160A	HE100A	HE240A	28	€190813,94	0%
IGFT	Dycore K150-8	Dycore K150-8	HE200A	HE100A	HE160A	HE100A	HE240A	29	€191353,62	0,28%
IGFC	Dycore K150-8	Dycore K150-8	HE200A	HE100A	HE160A	HE100A	HE240A	29	€191353,62	0,28%
LWSC	Dycore K150-8	Dycore K150-8	HE200A	HE100A	HE160A	HE100A	HE240A	29	€191353,62	0,28%
LWSMB	Dycore K150-8	Dycore K150-8	HE200A	HE100A	HE160A	HE100A	HE240A	29	€191353,62	0,28%
LWSMT	Dycore K150-8	Dycore K150-8	HE200A	HE100A	HE160A	HE100A	HE240A	29	€191353,62	0,28%
LWSL	Dycore K150-8	Dycore K150-8	HE200A	HE100A	HE160A	HE100A	HE240A	29	€191353,62	0,28%
VF	Dycore K150-8	Dycore K150-8	HE200A	HE100A	HE180A	HE140A	HE240A	33	€196696,93	3,08%
Combination										
IGRR + VF	Slab t=160mm	Dycore K150-8	HE260A	HE100A	HE200A	HE140A	HE240A	37	€215130,58	12,74%

** IP = Internal Primary, IS = Internal Secondary, FP = Façade Primary, FS = Façade Secondary*

10.2. Concrete structure

An overview of the inputs and outputs per variant can be seen in Appendix D. Compact results are shown in Table 10.3.

The structure consists of concrete beams and columns. The beams support the floors and the roof, which consist of hollow-core elements or solid reinforced concrete slabs. The finishing of the floor consists of an insulation layer and two finishing layers. As mentioned before the BSDT does not implement a stability system such as a concrete core or braces. As introduced in Chapter 7, the spans of the beams are between 2,25 and 4,10 meters. The columns parts have a minimum length of 3,04 meters and a maximum length of 3,25 meters. The foundation consists of Fundex pile with a diameter of 540 mm reaching down to -32,5 meters NAP. The number of piles needed is calculated by dividing the total weight of the building by the capacity of one pile, which is 2000 kN.

As can be seen from the table, the differences in ECI value are 0% in a few cases. In six cases the increase in ECI value is 0,39% In these cases the ECI is only increased due to the addition of an extra foundation pile. Four cases lead to a higher increase in ECI. Most of them are HGS, namely the intensive retention green roof and the garden roof. From the vertical greenery systems only the vertical forest results in an increased ECI value. The combination of an intensive retention blue roof with a vertical forest gives the highest increase in ECI.

It must be noted that for the concrete variant the BSDT gave faulty results. Applying no greenery system would result in higher cross sections for the beams supporting the roof (250x400 mm) than for instance the application of a nature roof (200x400 mm), even though the load was increased. This was due to a mistake in the tool. More information about this can be found in Section 11.2.4. In these results the 200x400 mm beams where used for the situation without extra loads on the roof as well. In addition to this, warnings kept appearing stating the columns could not be classified as short columns, no matter how large the cross sections of the columns were made. Therefore, the columns were verified for the slenderness criterion manually according to the Eurocode [135, 136]. The column complies to the slenderness criterion when $\lambda < \lambda_{lim}$.

$$\lambda_{lim} = 20 \cdot A \cdot B \cdot C / \sqrt{n} \tag{10.1}$$

where: $A =$ 0,7
$B =$ 1,1
$C =$ 0,7
$n =$ relative normal force: $N_{Ed}/(A_c f_{cd})$

$$\lambda = \frac{l_o}{i} \tag{10.2}$$

where: $l_0 =$ effective length
$i =$ radius of gyration of the uncracked concrete section: $\sqrt{I/A}$

Using the normative normal forces in the lower parts of the columns, it is found that in both the case without a greenery system (smallest loads) and the case with the combination of a intensive retention blue roof and a vertical forest (biggest loads) a cross section of 600x600 mm would suffice this check. It can be assumed that for all other cases this cross section will suffice the slenderness criterion for a short column as well. These calculations can be found in Section D.15.

Table 10.3: Results for a concrete building

Applied system	Roof	Floors	Beams*				Columns	#Piles	ECI value	ECI increase
			IP	IS	FP	FC				
-	Dycore K150-8	Dycore K150-8	200x400	200x400	300x600	200x400	600x600	43	€143353,02	-
Standard roof terrace	Dycore K150-8	Dycore K150-8	200x400	200x400	300x600	200x400	600x600	44	€143892,70	0,38%
Horizontal Greenery Systems										
EGRLW	Dycore K150-8	Dycore K150-8	200x400	200x400	300x600	200x400	600x600	43	€143353,02	0%
EGRBS	Dycore K150-8	Dycore K150-8	200x400	200x400	300x600	200x400	600x600	43	€143353,02	0%
EGRN	Dycore K150-8	Dycore K150-8	200x400	200x400	300x600	200x400	600x600	44	€143892,70	0,38%
EGRR	Dycore K150-8	Dycore K150-8	200x400	200x400	300x600	200x400	600x600	44	€143892,70	0,38%
IGRR	Slab t=160mm	Dycore K150-8	300x500	200x400	350x700	200x400	600x600	48	€151336,96	5,57%
IGRG	Slab t=160mm	Dycore K150-8	300x500	200x400	350x700	200x400	600x600	48	€151336,96	5,57%
Vertical Greenery Systems										
DGF	Dycore K150-8	Dycore K150-8	200x400	200x400	300x600	200x400	600x600	43	€143353,02	0%
IGFT	Dycore K150-8	Dycore K150-8	200x400	200x400	300x600	200x400	600x600	43	€143353,02	0%
IGFC	Dycore K150-8	Dycore K150-8	200x400	200x400	300x600	200x400	600x600	43	€143353,02	0%
LWSC	Dycore K150-8	Dycore K150-8	200x400	200x400	300x600	200x400	600x600	43	€143353,02	0%
LWSMB	Dycore K150-8	Dycore K150-8	200x400	200x400	300x600	200x400	600x600	43	€143353,02	0%
LWSMT	Dycore K150-8	Dycore K150-8	200x400	200x400	300x600	200x400	600x600	43	€143353,02	0%
LWSL	Dycore K150-8	Dycore K150-8	200x400	200x400	300x600	200x400	600x600	43	€143353,02	0%
VF	Dycore K150-8	Dycore K150-8	200x400	200x400	400x600	250x400	600x600	48	€148098,16	3,31%
Combination										
IGRR + VF	Slab t=160mm	Dycore K150-8	300x500	200x400	450x700	250x500	600x600	54	€156848,31	9,41%

** IP = Internal Primary, IS = Internal Secondary, FP = Façade Primary, FS = Façade Secondary*

10.3. Timber structure

Table 10.4 shows the increase in ECI value for all different greenery systems applied. A more elaborate overview of the inputted loads and the cross sections received as output can be found in Appendix E.

The structure consists of glued laminated timber (GLT) beams and columns. The beams support the floors and the roof, which consist of cross laminated timber (CLT) elements. The finishing of the floor consists of a cement screed, an insulation layer and a filler layer. This model did include a stability system in the form of diagonal elements and a CLT core. THese elements have not been counted towards the ECI value because in the other two variants a stability system was lacking. As introduced in Chapter 8, the spans in this model all have a width of 3,60 meters. The columns parts all have a length of 3 meters. The foundation consists of Fundex pile with a diameter of 540 mm reaching down to -32,5 meters NAP. The number of piles needed is calculated by dividing the total weight of the building by the capacity of one pile, which is 2000 kN.

As can be seen from the table, the differences in ECI value are zero in a five cases. Ten cases lead to an increase in ECI. Most of them are HGS, namely the bio-solar roof, nature roof, the extensive retention blue roof, the intensive retention green roof and the garden roof. From the vertical greenery systems the continuous living wall system, both modular living wall systems (with modular boxes and with modular trellis) and the vertical forest results in an increased ECI value. The combination of an intensive retention blue roof with a vertical forest gives the highest increase in ECI.

Table 10.4: Results for a timber building

Applied system	Roof	Floors	Beams*				Columns	#Piles	ECI value	ECI increase
			RI	RF	FI	FF				
-	CLT t=180mm	CLT t=180mm	280x280	280x280	280x280	280x280	400x400	23	€74263,74	-
Standard roof terrace	CLT t=200mm	CLT t=180mm	280x280	280x280	280x280	280x280	420x420	24	€76594,81	3,14%
Horizontal Greenery Systems										
EGRLW	CLT t=180mm	CLT t=180mm	280x280	280x280	280x280	280x280	400x400	23	€74263,74	0%
EGRBS	CLT t=180mm	CLT t=180mm	280x280	280x280	280x280	280x280	420x420	23	€75612,88	1,82%
EGRN	CLT t=180mm	CLT t=180mm	300x300	300x300	280x280	280x280	420x420	24	€76284,04	2,72%
EGRR	CLT t=200mm	CLT t=180mm	280x280	280x280	280x280	280x280	420x420	24	€76594,81	3,14%
IGRR	CLT t=200mm	CLT t=180mm	550x550	550x550	280x280	280x280	450x450	26	€82361,27	10,90%
IGRG	CLT t=200mm	CLT t=180mm	550x550	550x550	280x280	280x280	450x450	26	€82361,27	10,90%
Vertical Greenery Systems										
DGF	CLT t=180mm	CLT t=180mm	280x280	280x280	280x280	280x280	400x400	23	€74263,74	0%
IGFT	CLT t=180mm	CLT t=180mm	280x280	280x280	280x280	280x280	400x400	23	€74263,74	0%
IGFC	CLT t=180mm	CLT t=180mm	280x280	280x280	280x280	280x280	400x400	23	€74263,74	0%
LWSC	CLT t=180mm	CLT t=180mm	280x280	280x280	280x280	280x280	400x400	24	€74803,43	0,73%
LWSMB	CLT t=180mm	CLT t=180mm	280x280	280x280	280x280	280x280	400x400	24	€74803,43	0,73%
LWSMT	CLT t=180mm	CLT t=180mm	280x280	280x280	280x280	280x280	400x400	24	€74803,43	0,73%
LWSL	CLT t=180mm	CLT t=180mm	280x280	280x280	280x280	280x280	400x400	23	€74263,74	0%
VF	CLT t=180mm	CLT t=180mm	280x280	280x280	280x280	340x340	400x400	28	€78675,89	5,94%
Combination										
IGRR + VF	CLT t=200mm	CLT t=180mm	550x550	550x550	280x280	340x340	400x400	30	€86233,74	16,12%

** RI = Roof Internal, RF = Roof Façade, FI = Floor Internal, FF = Floor Façade*

Part III
Discussion and conclusions

11
Discussion

This research has aimed to provide insight into the advantages and disadvantages caused by the application of a greenery system, either horizontal or vertical, in the building envelope. This chapter will discuss the results of this research, the value of this research and the limitations that have influenced the outcome.

11.1. Discussion of the results

The effect of the greenery systems was been assessed on two levels, the effect on the sustainability certification of a building and the effect on the material use and the related ECI value. The results have been presented in Chapter 9 and Chapter 10. For convenience all results have been bundled and are shown in Table 11.1. In this section the results will be discussed.
As can be seen in the table specifically in the sustainability certifications the scores differ a lot. For instance, each of the greenery systems will improve the BREEAM score of Urban Woods with at least 4,0%. For LEED and WELL however almost all vertical greenery systems score zero points and therefore do not improve the total certification score of the building. In the case of the EGRBS the improvement of the LEED score is almost four times as high as the improvement of the BREEAM score. This can at least partly be ascribed to the given that it was not possible to determine which of the extra points earned by a greenery system were already awarded to the building. Therefore, the points awarded for some credits might have been counted twice. In LEED all HGS will increase the total score, however in WELL halve of the horizontal greenery systems did not score any additional points. The LEED certification shows big differences in the percentage increase. Half of the systems receives a 0% increase, while the other half almost all have an increase in LEED score of at least 10%. It can be seen that the greenery systems that have the highest improvements in certification score often also have a higher increase in ECI value. On the side of the building materials it can be seen that as expected the systems that impose higher loads also have a higher increase in ECI. In all cases where the ECI increase is between 0% and 1% this is because one extra foundation pile is needed in comparison to the standard building. The other parts of the structure remain unchanged. The accessible green roof systems (EGRN, IGRR and IGRG) can also be compared to the standard roof terrace. It can be seen that when an accessible roof is preferred, a nature roof would not result in an increased ECI in comparison to a standard concrete roof terrace. When using timber the nature roof would result in a lower ECI value.

To determine whether or not the positive effects of the greenery systems (increased sustainability certification score) outweigh the negative effects (increased ECI score) the percentages can be compared. When the increase in the sustainability certification score is larger than the increase in ECI, the greenery system receives a ’positive score’. If this is the other way around, the greenery system has a ’negative score’. When both are equal, which in this thesis is the case when both scores have an increase of 0%, the system has a ’neutral score’. An overview of these scores is depicted in Figure 11.1.

Comparing the results of the certification methods
Figure 11.2 shows the same results as Figure 11.1, but ordered by certification method. Looking at the specific certification methods, it can be seen that in case of the BREEAM certification the increase in the

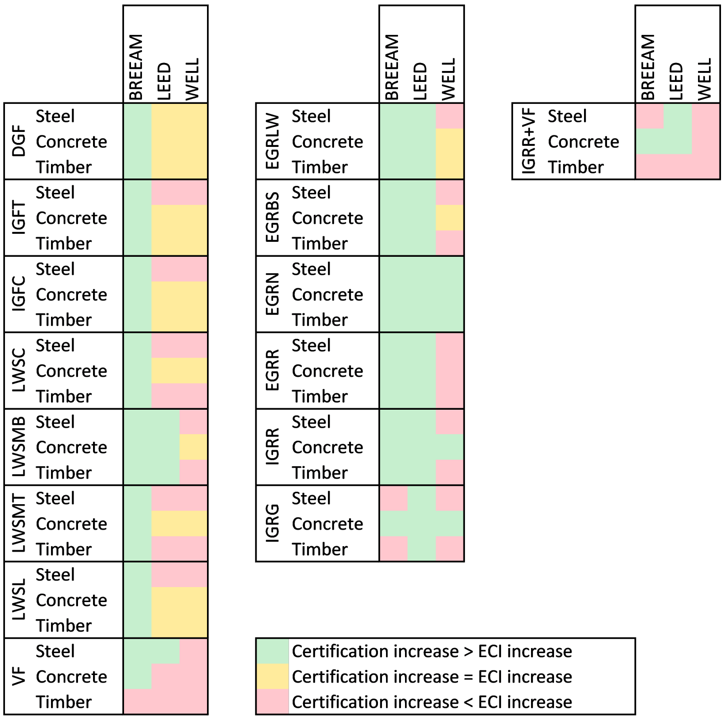
Table 11.1: Overview of all results

Greenery system	Sustainability score increase BREEAM	LEED	WELL	ECI increase Steel	Concrete	Timber
- Standard roof terrace				3,08%	0,38%	3,14%
Horizontal Greenery Systems						
EGRLW	4,0%	10,94%	0%	0,28%	0%	0%
EGRBS	4,0%	15,63%	0%	0,28%	0%	1,82%
EGRN	8,0%	12,50%	3,5%	3,08%	0,38%	2,72%
EGRR	10,0%	10,94%	0%	0,28%	0,38%	3,14%
IGRR	12,0%	12,50%	5,8%	9,50%	5,57%	10,90%
IGRG	8,0%	12,50%	5,8%	9,50%	5,57%	10,90%
Vertical Greenery Systems						
DGF	4,0%	0%	0%	0%	0%	0%
IGFT	4,0%	0%	0%	0,28%	0%	0%
IGFC	4,0%	0%	0%	0,28%	0%	0%
LWSC	4,0%	0%	0%	0,28%	0%	0,73%
LWSMB	4,0%	14,06%	0%	0,28%	0%	0,73%
LWSMT	4,0%	0%	0%	0,28%	0%	0,73%
LWSL	4,0%	0%	0%	0,28%	0%	0%
VF	4,0%	3,13%	1,2%	3,08%	3,31%	5,94%
Combination						
IGRR + VF	12,0%	14,06%	5,8%	12,74%	9,41%	16,12%

EGRLW: Lightweight green roof - EGRBS: Biosolar green roof - EGRN: Nature roof - EGRR: Extensive retention blue roof - IGRR: Intensive retention blue roof - IGRG: Garden roof DGF: Direct green façade - IGFT: Indirect green façade with modular trellis - IGFC: Indirect green façade with continuous guides - LWSC: Continuous living wall system - LWSMB: Living wall system with modular framed boxes - LWSMT: Living wall system with modular trays - LWSL: Linear living wall system - VF: Vertical forest

certification score is higher than the percent increase in the ECI score of a building after implementing a greenery system in most of the cases. Only the garden roof will have a negative score in the steel and timber variant of the building and the vertical forest in case of a timber structure. In the LEED certification all HGS systems always receive a positive score. The VGS only receive a positive score in case of the LWSMB system and a VF in the steel variant. For the VF in a concrete or timber building the percentage increase in LEED points was lower than the percentage increase in ECI, therefore application of a VF results in a negative score in these two cases. The other VGS did not receive any LEED points, so their score depends on whether or not the ECI value of the building was increased (negative score) or not (neutral score). In the WELL certification only four greenery systems received points. One of these systems, the nature roof, received a positive score in combination with all three construction materials. For two of the other three systems that received WELL points, the intensive retention blue roof and garden roof, this was only the case in the concrete variant. In the steel and timber variant the ECI increase turned out to be higher than the increase of the WELL score resulting in a negative score. The VF did not receive enough points to outweigh the increased ECI score so this always results in a negative score. The other systems did not receive any WELL points, so their score depends on whether or not the ECI value of the building was increased (negative score) or not (neutral score).

Comparing the results of the different greenery systems
Looking at all systems it can be noted that one system always received a positive score. This is the nature roof. In addition to this the direct green façade never receives a negative score, but always gets a positive or neutral score. This means these two systems can always be applied to a building without possibly decreasing the building's sustainability. The other systems do also receive a negative or sometimes neutral score in different cases. None of the systems never receives a positive score.

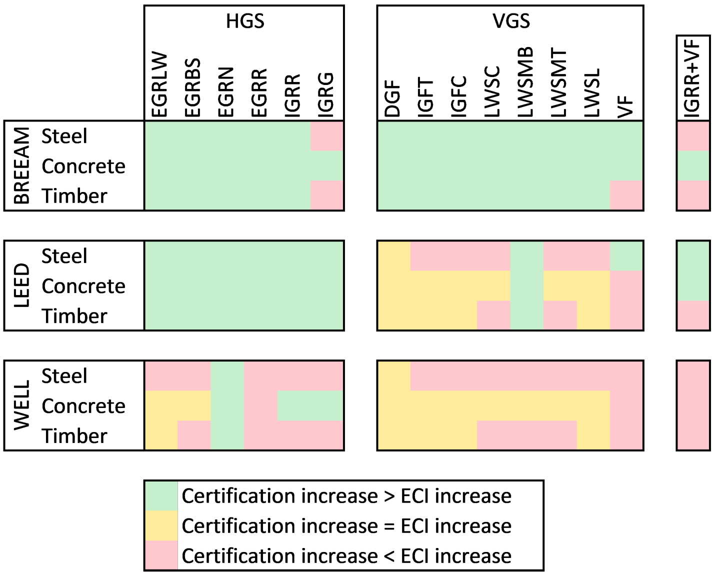


DGF	Direct Green Façade
IGFT	Indirect Green Façade with modular Trellis
IGFC	Indirect Green Façade with Continuous guides
LWSC	Continuous Living Wall System
LWSMB	Living Wall System with Modular framed Boxes
LWSMT	Living Wall System with Modular Trays
LWSL	Linear Living Wall System
VF	Vertical Forest
EGRLW	Lightweight green roof
EGRBS	Biosolar green roof
ERGN	Nature roof
EGRR	Extensive retention blue roof
IGRR	Intensive retention blue roof
IGRG	Garden roof

Figure 11.1: Comparison between positive and negative effects of greenery systems (own work)

The IGRR and IGRG systems have a significantly higher ECI value than the other horizontal greenery systems for each of the three construction materials. In the case of the concrete and steel structures this is mainly because these systems are significantly heavier than the other systems. In addition to the weight of the systems themselves the roof that supports the greenery system must be modified too. A hollow core slab is not strong enough to support this weight according to the BSDT. This means the hollow core slabs are replaced by solid concrete slabs which are much heavier. These two factors together lead to a significant required increase in the cross sections of the beam elements that support the roof and thus a larger increase in ECI value as well.

It may also be noted that the implementation of a horizontal greenery system will in general most often lead to a positive score, namely in 72% of the cases. Only in 22% of the cases implementation of a HGS would lead to a negative score, leaving 6% of the cases with a neutral score. For vertical greenery systems the a neutral score is achieved more often. This occurs in 32% of the cases, leaving 37% of the tested VGS cases with a positive score and 31% of the cases with a negative score. The horizontal greenery systems were mentioned specifically for some credits as a means to earn the points available and they often contribute to credits that award points for access to green spaces. This is the reason they more often earn points and more often result in a positive sustainability score. The combination of



DGF Direct Green Façade
IGFT Indirect Green Façade with modular Trellis
IGFC Indirect Green Façade with Continuous guides
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LWSL Linear Living Wall System
VF Vertical Forest
EGRLW Lightweight green roof
EGRBS Biosolar green roof
ERGN Nature roof
EGRR Extensive retention blue roof
IGRR Intensive retention blue roof
IGRG Garden roof

Figure 11.2: Comparison between positive and negative effects of greenery systems, order by certification method (own work)

an intensive retention blue roof with a vertical forest results in a negative score in over half of the cases. This is always the case for the WELL certification and the timber variant. A steel building in combination with BREEAM will also result in a negative score for the combination of an IGRR with a VF. Overall, a positive score is achieved in 52% of the cases, a negative score in 27% of the cases and a neutral score in 21% of the cases.

Finally, it can also be noted that there is one greenery system that always receives a positive score. This is the nature roof (EGRN). This result can be attributed to the fact that the nature roof is a relatively lightweight HGS in comparison to the other accessible green roof systems. Therefore, the ECI increase is low for the steel and timber variants and in the concrete variant there is no ECI increase. Because the roof is accessible the EGRN receives points for the accessibility of nature and outdoor space that the other lightweight green roof systems do not receive. The combination of these two factors results in a positive score in each of the variants.

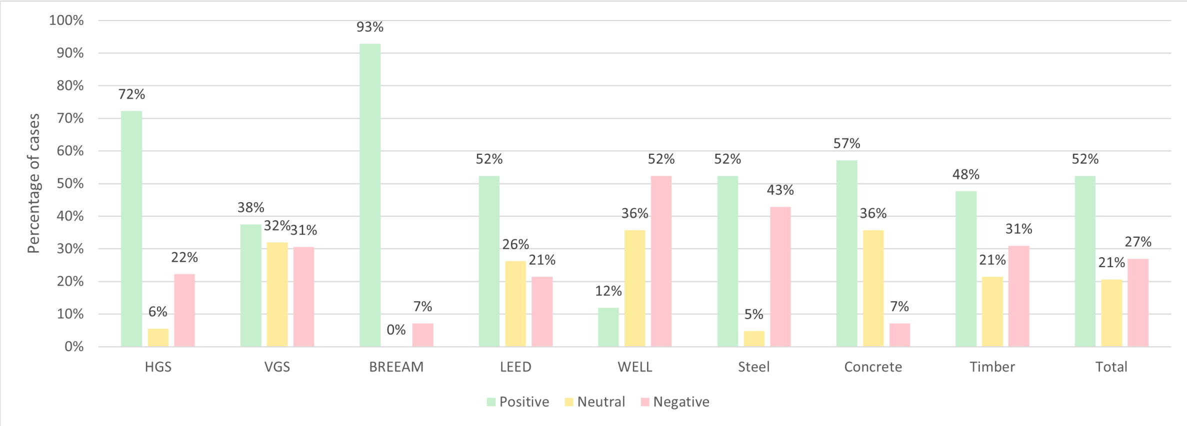

Figure 11.3: Distribution of the results (own work)

Free height requirements
The required free height of the passageways is 2,3 meters [137]. It should be checked if the cross sections that were found in these design do not compromise this requirement.

In the steel variants this is not a problem, the largest cross section used is a HE260A cross section in case of a garden roof or an intensive retention blue roof. In this situation the beam (h = 250 mm), the floor (t = 150 mm) and the finishing of the floor (t = 90 mm) reduce the original height between the levels from 3,04 meters to 2,55 meters which is still high enough. The top floor has a height of 3,25 meters and a thicker roof (t=160 mm) when an IGRG or IGRR are applied. In this case the remaining free height is 2,76 meters which is high enough. Sketches of these situations are shown in Figure 11.4.

In the concrete variant the internal primary beams have a height of 500 mm. A beam with height 500 mm and the floor including finishing as described for the steel variant would result in passageways with a free height of 2,30 meters for the middle floors and 2,51 meters for the top floor. This complies to the demands from the Bouwbesluit [137], but larger beams would result in a situation where the demands are no longer met. Sketches of these situations are shown in Figure 11.4 as well.

The largest beams in the timber variant have a height of 550 mm on the top floor. The top floor has a height of 3,25 meters. With the beam (h = 550 mm), floor (t = 200 mm) and floor finishing (t = 170 mm) 2,34 meters are left, which is enough. The other floors have a beam with a height of 280 mm and floors width a thickness of 180 mm. This leads to a remaining free height of 2,41 meters. This does not cause any problems. Sketches can again be seen in Figure 11.4. In this case the timber variant of the building was assessed in a different model which allowed the beams in the top floor to be given a different cross section than the beams in the remaining floors. If this would not have been the case, the lower floors would also have been given beams with a height of 550 mm. This would have resulted in a free height of 2,14 meters, which would have been too little.

11.2. Limitations of this research

During the execution of this research the results were influenced by a few factors. Factors that have influenced the result will be discussed in this section.

11.2.1. Quantification of effects of greenery systems

The way that the different greenery systems influence their surroundings depends on many aspects of the greenery system. The type of plant used influences aspects such as the level of air purification and the way a vertical greenery system is set up influences the thermal insulation the system provides. For instance, when the steel cables of an indirect green facade system are placed closer together, the density of the foliage will be higher which leads to a better thermal insulation [81]. In this thesis the most common characteristics were assumed, but many different variations exist. However, the assumed values might thus not always actually apply.

In addition to this some effects currently have not properly been quantified. For instance data about the amount of air purification induced by greenery systems is not available as much as required for this thesis. This goes for all greenery systems. There are however also situations were data was available for some of the greenery systems assessed in this thesis but not for all. An example of this is the heating and cooling energy reduction that the greenery systems can provide. In this case data was available for the Living Wall System with Modular Boxes which resulted in nine points for LEED credit 'Optimize energy performance'. For the Living Wall System with Modular Trellis no data was available which means no points could be awarded. It can however be argued that since the systems are similar on many levels one could assume the data available for the LWSMB also applies to the LWSMT. In this research the choice was made to only award points when actual data was available, since the certifications all require the assessor to provide evidence of the effects of the measures taken in order to receive points. The data from the LWSMB however does trigger the expectation that the LWSMT also has a good heating and cooling energy reduction and therefore good potential to receive points for this credit. Further research into the actual effects of the LWSMT on energy reduction are therefore advisable.

11.2.2. The sustainability certifications in relation to greenery systems

The positive effects of the greenery systems were evaluated using three different certification methods: BREEAM, LEED and WELL. These certification methods aim to provide a sustainability score for a building project. Greenery systems can provide positive effects to the building itself and its surroundings, however these effects can not always be translated into points directly. This can occur in two different ways.

1. A certain effect is not at all taken into account by the classification method
2. Due to specific requirements effects can not be awarded points when caused by a greenery system

Both situations will be discussed in this section.

Effect is not taken into account by the classification method

None of the tree assessed certification methods is able to take into account all seven benefits that were distinguished at the beginning of this researched.

BREEAM does not award points for the reduction of the urban heat island effect and the purification of the air. The credit reduce air pollution sounds like it is about air purification, but this considers only reducing the pollution of the air in the process of polluting and not undoing the pollution afterwards, which is what a greenery system would do. This means that in total BREEAM has credits relating to five of the seven benefits provided by greenery systems.

Another good example of the first situation is the damping of noise coming from the outside of the building, which is not part of the LEED certification. LEED only awards points for using quiet installations and not for the damping of noise produced by these installations. LEED thus has credits that relate to six of the benefits of greenery systems.

Lastly, WELL does not award any point for storm water management and increasing biodiversity. Insulation as an absolute value is also not worth any points in WELL, only the subjective experience of thermal comfort by the inhabitants can be translated into points. Four of the seven benefits can thus directly result in points in WELL, which means that WELL has the lowest number of benefits that can be linked to a credit in comparison to BREAAM and LEED.

Points cannot be rewarded due to specific requirements

The second situation occurs for instance in BREEAM credit ENE01 which is about the energy use of the building. Points are awarded when the energy use is reduced. The energy reduction must be determined using a BENG calculation. As of now it is not possible to take greenery systems into account in the BENG calculation. Therefore, even though there is proof that the greenery systems can help reduce the energy consumption of a building, this can not be translated into points. The same is the case for the LEED credit "Heat Island Reduction" in LEED. In this credit points are only awarded for the shading of horizontal surfaces. This automatically means that the vertical greenery systems will not be of any help towards points available for this credit. However it is not true that vertical surfaces of a building such as the façades are not exposed to sunlight and heat. The façades can, just like the roof, reflect this heat and contribute to the UHI. Covering the facade with vegetation by applying a VGS could therefore help with the reduction of the UHI, however can currently not result in any points. It does not become abundantly clear from the criteria provided by LEED or from the conversations held with the LEED assessor from Arcadis [126] what the reasoning is for this. A possible reason could be that the horizontal surface of the roof is exposed to sunlight for a larger part of the day than the individual façades. In this research the criteria as provided by LEED were followed, which means zero points were awarded and the shading of the façades was not translated into points. The purification of the air in LEED credit 'Enhanced indoor air quality strategies' and WELL credit A12: Air filtration do both not award points to greenery systems since they require the air to be purified by mechanical ventilation systems. The effects provided by greenery systems could thus not be translated into points for these credits.

A similar exclusion as in the Heat Island reduction credit of LEED occurs in BREEAM credit HEA 05 which considers the acoustic performance of the building. In this credit points can only be awarded for acoustic performance of the façades and not for the acoustic performance of the roof. The reasons behind this are again not stated by BREEAM, but a possible explanation would be that the largest noise sources will not cause their noise to try and enter the building via the roof. In general the horizontal greenery systems could more often be awarded points than the vertical greenery systems. Specifically in LEED and WELL the HGS were often mentioned as a ways to acquire the points available for certain credits.

As discussed in this section the number of benefits that can be awarded points is even further reduced by specific constraints set by the certification methods. For BREEAM the ENE01 credit cannot result in points by using greenery systems, therefore BREEAM can award points for four of the seven distinguished benefits by greenery systems. LEED cannot fully award points for the credits linked to UHI reduction and air purification. Therefore LEED covers four remaining benefits as well. Lastly, WELL also covers four remaining credits. WELL has two credits that can be linked to air purification. One of them (A12: Air filtration) cannot be awarded points due to the constraints as described in this section. However, since credit A05 (Enhanced air quality) can result in points the benefit air filtration is still covered. A visual overview of the covered benefits per certification method is shown in Figure 11.5.

Subjectivity of the certification methods

When the different certification methods are compared it can be seen that they score different parts rather differently. For instance, BREEAM credit HEA05 and WELL credit S02 both consider the acoustic damping of the building for noise traveling from outside to the inside. BREEAM credit HEA05 awards a maximum of 1 point of the total 163 points, which equals 0,6% of the available points. WELL credit S02 however can award the building 3 points of the 229 available points which equals 1,31%. In WELL the acoustic damping thus forms a larger part of the available points. The same is true for the reduction of energy use. In BREEAM credit ENE01 offers a maximum of 15 of the total 163 points, which equals 9,2%. In LEED the credit "Optimize energy performance" is worth 18 of the total 131 points, which equals 13,7%. These differences show that the value of the different aspects is subjective and not equally scored in each method.

The certification methods also show that sustainability is still a subjective topic. WELL for instance has credits where points are awarded based on an investigation into how people experience different thermal conditions. Also the feeling that people have when seeing nature is highly subjective and differs per person. Awarding the points based on surveys among the residents and users of the building makes the WELL certification even more subjective than the other two certification methods. The certification methods are also subject to change over time. Previous sustainability goals have become normalized practice and new goals have arisen. All of this proves that sustainability remains a subjective and ever changing subject. Subjectivity is not desired in an academic research such as this one and the goal should be to make the research and results as objective as possible.

To make the topic of sustainability less subjective it might be useful to gain insight into how the different certification methods determine the number of available points per credit. Currently there is no insight to this as a user of these certification methods. Gaining insight into this will help to place the number of points available in perspective and comparing and combining the different views of the certification methods might result in a more objective consensus.

Awarding points to greenery systems
It must be noted that in this research the greenery systems have only been awarded points if their effects would be big enough to meet the thresholds for points by themselves. In reality however the situation is not that straightforward. An example of this is credit HEA05 of the BREEAM certification. In this credit points are awarded for sufficient noise reduction. In this case the credit is been treated as if a vertical greenery system on its own should reduce the noise enough to earn the point. In reality however a wall will be placed behind the greenery system that reduces noise levels as well. Taking the noise reduction caused by both the greenery system and the wall together might result in a reduction large enough to be awarded points. When the greenery systems are taken into consideration from the first phases of the design process it is possible that the greenery systems can help the building obtain more points. For instance because the benefits of greenery systems can result in points in collaboration with other elements of the building. In thesis it was also seen that some points a greenery system could provide were already obtained by Urban Woods via other elements of the building. If the greenery systems were taken into consideration in the design from an early stage this could result in more points earned by the greenery systems because some other measures that were taken in the case of Urban Woods to earn the points can be left out.

While for some credits a greenery system in the building might not be able to award the building in question any points, it might lead to in increased certification score for neighbouring buildings. This is for instance in LEED credit ”Daylight and quality views” and WELL credit M09 - Enhanced access to nature. In both these credits points can be awarded for views on nature, since it has been proven that seeing natural elements can have a positive effect on a humans happiness and health. Points are awarded when a person can see these natural elements from inside the building. This is generally not the case so therefore points were not awarded. Other people however, for instance in a neighbouring building looking out onto the building with greenery systems or people on the street can benefit from seeing the greenery systems. This does however not result in any points for the building itself.

11.2.3. Suitability of the certification methods in relation to this research
As shown in the paragraphs above, the certification methods that were used in this thesis all have limitations. None of them is able to award points for each of the seven benefits that were distinguished. In addition to that there are multiple situations where effects could not be taken into account due to restrictions of the certification methods themselves. As discussed, each of the certification methods has credits that are linked to four of the seven benefits as distinguished in this research. Which four benefits the credits are linked to differs per certification method. An overview can be found in Figure 11.5. Since none of the certification methods can award points for each benefit, it can be concluded that none of these certification methods fits the purpose of this research perfectly. However, with some modifications to ensure that all proven benefits of greenery systems can be taken into account this fitness of the certification methods can be improved. Even though none of the certification methods is a perfect fit to score the benefits of the greenery systems, BREEAM is the best fit. This is because BREEAM is able to take into account most of the benefits of greenery systems that were distinguished at the beginning of this research. There are more credits to take into account different aspects of the defined benefits. Because BREEAM is the most suitable for this research, the results from the found using BREEAM are deemed more valuable than the results found with LEED and WELL. Some adaptions however are still needed to make it fit better to greenery systems.

Benefits	BREEAM	LEED	WELL
Noise reduction	1 / 1		1
UHI reduction		1	1
Insulation and energy use	1	2	
Air purification		1	1 / 1
Increased wellbeing	2	2	2
Increased biodiversity	2	1	
Stormwater attenuation	2	1	

	Benefit can be scored
	Benefit cannot be scored due to set constraints
	Benefit cannot be linked to any credit
2	Nr. of credits

Figure 11.5: Number of credits that can be linked to greenery systems (own work)

Proposed improvements of the certification methods
As mentioned earlier, there are a few credits for which points can only be awarded only for VGS or only for HGS. A first improvement to the certifications would be to determine if it is possible to award points for the other type of systems as well. The criteria should be changed to fit the other system type accordingly. For instance making it possible to award points for the shading of vertical surfaces in the LEED credit ”Heat island reduction” to acknowledge the cooling benefits caused by vertical greenery systems. Points in this credit are awarding for the shading of surfaces. Since the façades might be less exposed to sunlight due to shading by other objects like neighbouring buildings or simply because of the orientation of the façade in question the it must be determined whether or not it is necessary to change the criteria to obtain the points or scale the number of available points based on exposure to sun of the surface in question. Additionally the certification methods could me improved by including the benefits that are currently not worth any points because the benefits are either not included in any of the credits or due to the restrictions and criteria provided by the certification method itself. It has been proven that the implication of greenery systems has a beneficial effect on the environment so this should be worth points in the different certification methods.

As mentioned before, BREEAM shows the most potential for the assessment of greenery systems due to the higher number of credits that cover different aspects. A few major improvements can be proposed. Including greenery systems into the BENG energy certification is a good example of this because this would make it possible to award points for the proven beneficial effect of greenery systems on the heating and cooling energy demand for BENG credit ENE01. Secondly, including the Urban Heat Island reduction in a credit will improve this certification. LEED credit ’Heat Island reduction’ is suitable for this as it awards points for covering of hardscape (heat reflecting) surfaces, however the adjustments as discussed in the previous paragraph to allow for the valuation of vertical surfaces as well must be taken into account too. For air purification a credit based on WELL credit A05 would be good to implement into BREEAM as well, thereby covering the last of the seven benefits. A combination of the different certifications is thus a good option. However, as discussed in Section 11.2.2 the different certifications all apply a different weight to their credits. Alterations of these weights might thus be needed when copying a credit from one certification method to another.

Another big improvement would be to make one method that includes both the benefits of the application of greenery systems as well as the negative effects to give a more holistic image of the consequences of implementing a greenery system. The optimal tool to assess the sustainability of the application of greenery systems should meet the following requirements.

- Be able to take into account both the benefits and the negatives (increased CO_2 footprint due to use of extra building materials) of the application of a greenery system
- Be able to score all proven benefits of greenery systems and not use methods in which the greenery systems cannot be assessed
- Be as objective as possible in determining the weight of the credits

Implementing these changes to the certification methods so they cover all benefits will give the greenery systems the potential to earn more points in the certification, thus resulting in a higher percentage increase. The ECI increase will not change, meaning that when comparing the results from the modified certification method with the ECI value has to potential to result in a positive score more often than it does now.

11.2.4. Structural models and tools used

Two different modelling tools were used to make a preliminary design for this research. Firstly the BSDT in which the steel and concrete variants of the building were assessed and secondly the RFEM model that was used to assess the timber variant of the building. Assumptions made in setting up these models and limitations of the tools used will be discussed.

The BDST does not offer as much freedom in design as wanted for the modeling of green roofs and façades on a building. When modelling the green roofs a load is added to the roof only, while the load on the floors remains unchanged. However in the BSDT the beams of the roof can not be altered independently from the beams that support the floors. This means that when the loads on the roof are increased and stronger beams are needed, the beams that support the floors are changed as well and become overdimensioned. This results in an additional increase in the ECI that would not occur in a real building project.

As previously explained in Chapter 8 the BSDT had to be modified in order to be able to place line loads on the structure. These line loads were necessary to model the loads caused by the HGS. In the process of implementing this function some other functions were unfortunately disabled. An important function that was disabled is the modelling of horizontal wind forces. This was no longer possible. This was specifically significant because some of the greenery systems contain trees that increase the surface that is exposed to wind forces while others do not. The effect of this could thus not be modeled which is unfortunate.

A second function that became unavailable is the download option for a document containing the calculations made by the model. A document can still be downloaded, however the calculations are missing and replaced with a statement that the calculations are not available just yet. Because of this, the calculations could not be consulted in case of unexpected results or simply to check which failure mechanism turned out to be the normative one. This increased the feeling of doubt that occurred when working on the concrete variant of the building. At some point, unexpected unity checks were shown as results. Figure 11.6 shows the unity checks (above the beams in yellow and orange numbers) and the maximum moments of the members (below the beams in red numbers). In this situation, all beams have the same cross section and reinforcement. There is no line load placed on the beams along the façade. The roof is loaded with a distributed load of 2,5 kN/m^2. Logically the beam that is at the edge (highlighted red in Figure 11.6) should carry less load than the beam placed one grid line more towards the centre of the building (highlighted green in Figure 11.6. This is reflected in the moments that are shown below the beam. The façade beam (red) has a maximum bending moment of approximately 75 kNm while the inner beam (green) has a bending moment of approximately 140 kNm. The moments shown are for the normative load combination which is ULS2b in this case. These values have been validated with hand calculations and are as would be expected. A similar check was performed for the shear forces working on the beams. Since the cross sections and reinforcement of the beam are equal, the beam with the higher bending moment is expected to result in a higher unity check than that of the beam with the smaller bending moment. As shown in Figure 11.6 the beam at the façade however has a higher unity check with a value of 0,91 than the beam one step more inward which has a unity check of 0,73. This is not as expected and this means that there is probably a error in the calculation of the unity check of the façade beams. However, since the calculations can not be consulted it is not possible to check these results.

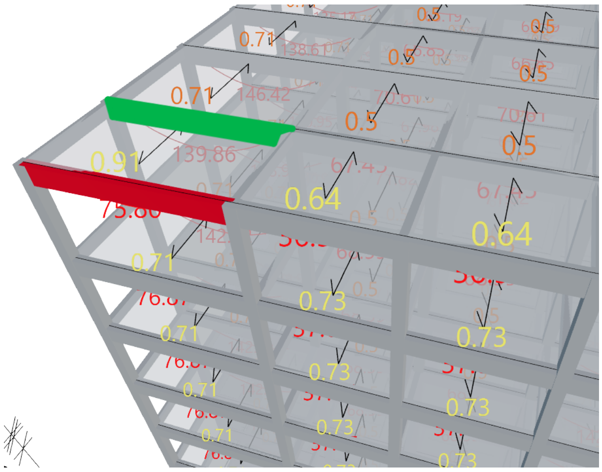

Figure 11.6: Unexpected unity checks for the concrete variant

A similar situation occurred when it was found that the application of a HGS on the roof of the concrete building would result in beams below the roof with smaller cross sections (200x400 mm) than when the roof was not loaded with a greenery system, in which case a 250x400 mm cross section was the smallest size to suffice. These results were wrong as was confirmed after contact with one of the developers of the BSDT. The model was run by the developer in an unreleased version of the tool where this problem that caused the error was fixed and the smaller cross section of 200x400 mm was confirmed to suffice for the situation with no VGS applied as well, as was expected. In the results of this research therefore the smaller beams of 200x400 mm are stated. For the columns a warning popped up that the concrete columns could not be classified as short columns. The tool itself was not programmed to make the calculations for a long or slender column (which includes buckling), so it warns the user to change the cross section of the columns in order to achieve short columns. Increasing the cross section of the columns however did not cause the warning to go away, so hand calculations were made in order to define the needed cross section of the columns.

Lastly, the hollow core floors that were used in this design also gave some results that are doubtful. This design started with the slimmest hollow-core slab that is available in the BSDT, a slab of 150 mm thick. As seen in the results, the BSDT did not find a sufficiently strong hollow-core slab to support the intensive retention blue roof or garden roof systems. This result however is debatable. It would be expected that increasing the thickness of the hollow-core element would result in a lower unity check when the induced load remains unchanged. This is however not the case in the results as presented by the BSDT. The unity checks obtained for the different hollow-core slabs loaded with an IGRR are shown in Table 11.2. It can be seen that from a thickness of 200 mm upward the unity check does not decrease. This again, is an unexpected result which cannot be checked because the calculation report is not available. It can be concluded that the BSDT has shown multiple erroneous results for different concrete elements.

Having found these errors and unexpected results, it must be discussed whether or not an engineer should make use of tools of which the calculations cannot be seen. Not being able to see the calculations makes it hard to check the results and determine whether or not the results are correct and usable. Hand calculations could be used to validate the design as discussed above, but especially when unexpected were found this increased the doubts about the correctness of the tool in general. Normally it would

Table 11.2: Unity checks for hollow-core slabs with different thicknesses loaded with an IGRR system

Hollow-core slab thickness	Unity check
150 mm	1,39
200 mm	1,13
260 mm	1,13
320 mm	1,13
400 mm	1,13

not be advised for an engineer to use tools of which the results cannot be said to be correct for certain since it is very important that all calculations are performed correctly. In this case however due to time constraints the tool was used because the downsides and restrictions of this tool only came to light bit by bit during the performance of this research.

Looking back the BSDT was not the best fit for this research. During the research bit by bit more defects in the tool came to light. When this research would be performed again opting for a model using different software than the BSDT would be a better choice. This would ensure more control over the model by the one performing the investigation and not result in an unwanted dependence on someone else to make alterations and repair defects in the existing BSDT. This ultimately influenced the planning of this research and limited the flexibility in testing. Using another tool of which the results and calculations can be checked more properly would also ensure a better insight into the correctness of the results which automatically increases the strength of the results and conclusions in the thesis.

11.2.5. Method of comparison

In this thesis the results of the different certification methods and increases in ECI value have all been compared in percentage terms. This makes comparing the two different types of results more easy, however it does also take away some valuable insight into the results.

The absolute value of the ECI increase of the different materials could differ more than the shown percentages might insinuate. Looking for instance in the case of the application of a vertical forest combined with a intensive retention blue roof. Table 11.3 shows that unlike what the percentages might suggest, the timber variant of the building does not have the highest absolute increase in ECI value. As can be seen timber has the highest percentage increase, but the steel variant has an absolute increase in ECI value that is more than twice as high. This is also visualized in Figure 11.7. In this case, this results in the situation where the steel structure receives a positive in some cases score while the timber variant always receives a negative score even though the absolute ECI increase of the timber variant is lower than that of the steel variant. The percentage increases used for the comparison in this thesis might thus give a distorted image of the actual situation. It gives the idea that the steel variant has a lower impact on the environment than the timber variant, which is actually not the case. The use of this percentage increase in the comparison influences the comparison itself and the results that follow from it. It is thus important to always look at the results in the broader picture.

Table 11.3: Comparing percentage and absolute ECI increases of applying an intensive retention blue roof and a vertical forest

Building material	ECI increase (%)	ECI increase (€)
Steel	12,74	24316,64
Concrete	9,41	13495,29
Timber	16,12	11969,99

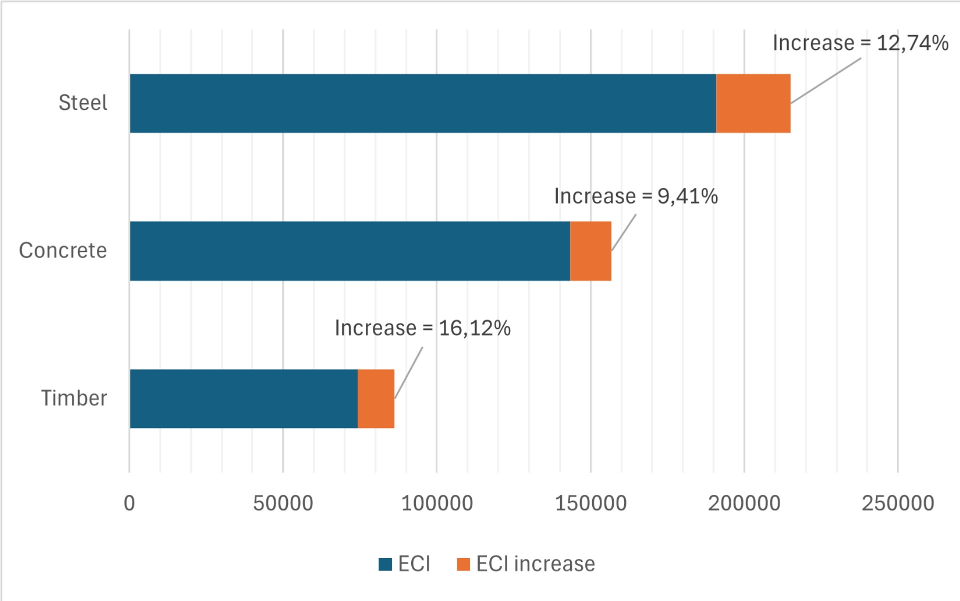

Figure 11.7: Visualizing percentage and absolute ECI increases of applying an intensive retention blue roof and a vertical forest (own work)

11.2.6. Scope

In this research not all aspects of the application of greenery systems were taken into account. The results can not automatically be assumed to remain unchanged when applying a greenery system to another building. The structural aspects are dependent on the design of the building. In this thesis only one specific building was investigated in the form of a case study. In a different structure the percentage increase in ECI can be different.

This is also true for the increase in the scores of the different sustainability certification methods. The points that can be obtained are dependent on many factors from the environment around the building [36, 38, 39]. These factors are building and location specific. For instance the required characteristic noise reduction in BREEAM credit HEA05 is dependent on the outside noise levels. If noise levels are already low points can more easily be obtained. For WELL credit A05 the points can also be obtained with less needed filtering in areas where the amount of PM in the air is already low. This thesis specifically focused on building in urban areas, but in a rural area the amount of points earned, either through a greenery system or because of other elements of the building and its surroundings, and therefore the percentage increase in sustainability certification score could be different.

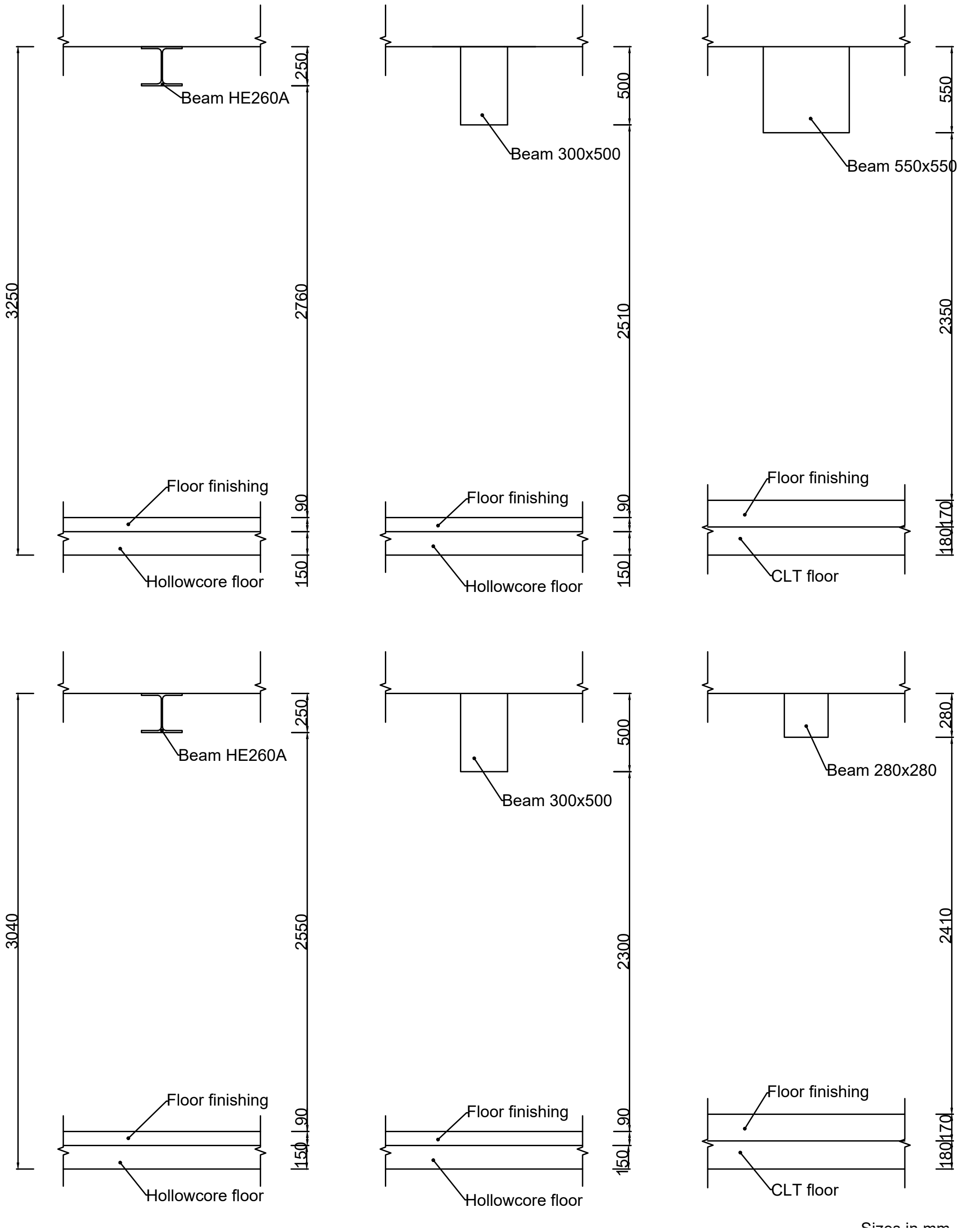

Figure 11.4: Check of the free height requirements for the different variants (left to right: steel, concrete, timber), for the top floor (top) and the lower floors (bottom) (own work)

12 Conclusion

This chapter will give answers to the posed research questions, starting with the sub questions before answering the main research questions of this thesis. After all research are answered the main conclusions taken from this research will be stated.

12.1. Answering the sub-research questions

RQ1: How can the sustainability of a building with greenery systems be determined?

In this thesis it was found that determining the sustainability of a building with greenery can be done by comparing results from a Green Building Rating Systems (GBRS), also called certification methods in this thesis) with those of the Environmental Cost Indicator (ECI). A comparison is needed because currently there is no GBRS that can also take into account the the negative side effects in the form of a higher environmental impact due to increased material use. GBRS can only score the benefits of greenery systems while the ECI is able to determine the negative impact on the environment due to increased material use and a higher carbon footprint.

From using the different certification methods it can be concluded that the horizontal greenery systems are generally included better into the certification methods and are more often mentioned as a means to obtain available points. The weight of certain aspects of sustainability differs for each GRBS which means the methods are not completely objective. In some cases the certification methods have specific requirements or constraints that make it impossible to award points for some effects when caused by a greenery system which makes that none of the used certification methods is a perfect fit for assessing the impact of greenery systems. The weight of the credits that can be linked to a benefit differs per certification method. This indicates that there is a certain subjectivity included in the methods and they are not as objective as preferred. These differing weights and the fact that the three certification methods do not all have credits linked to the same benefits results in differences in the results. None of the used systems (BREEAM, LEED, WELL) is able to award points for each of the seven benefits provided by greenery systems. Of the used methods BREEAM is currently the best fit for the purpose of this research because it can take into account most aspects of the benefits caused by the greenery systems. The results found with BREEAM can therefore be deemed more valuable.

RQ2: What are the differences in building characteristics for different use-purposes of buildings?

In this research a typical office building and a typical residential building were compared. The office building has a beam-column structure which offers more flexibility because non-load bearing walls can easily be removed or added. The residential building had load bearing walls. This is convenient since the walls in a residential building must already be thicker since noise transfer regulations between apartments are in place.

While the differences between these two specific buildings are clear, it can not be concluded that therefore a residential building will always be a structure with load bearing walls and an office building always has a beam-column structure. The structural effects are in this research only investigated for a beam-column structure, but the additional loads might have a different effect on a building with load bearing walls.

RQ3: Which types of horizontal greenery systems exist?

Two main types of horizontal greenery systems exist: extensive green roofs (EGR) and intensive green roofs (IGR). The distinction is made based on the thickness of the substrate layer which is smaller than 300 mm for EGR and equal to or larger than 300 mm for IGR. EGR generally have a practical function only while IGR often also serve as an extension of the living space. EGR contain smaller types of vegetation such as herbs and grasses while IGR can contain larger types of plants and even trees. Within these two categories variations can be made based on plant types used, accessibility of the roof and water retention. In this research four EGR systems and two IGR systems were assessed but more variations exist.

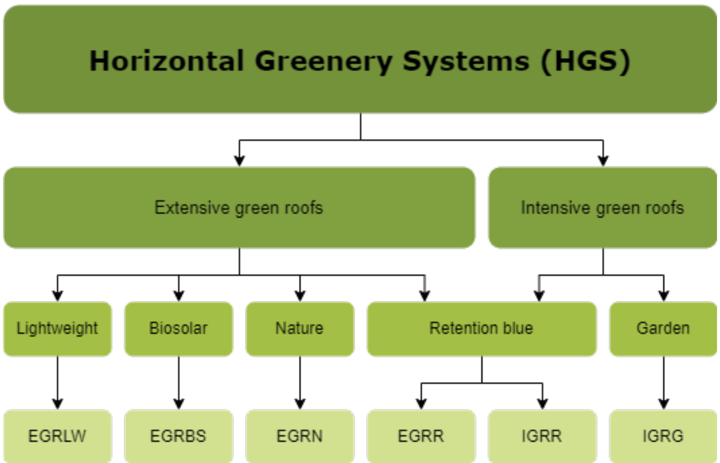

Figure 12.1: Overview of the assessed horizontal greenery systems in this thesis (own work)

RQ4: Which types of vertical greenery systems exist?

Vertical greenery systems can be divided into three main categories: green façades (GF), living wall systems (LWS) and vertical forests (VF). The distinction is made based on the growing method of the plants and the supporting structure of the VGS. Within each category a variation of different systems exists. Green façades have plants that are rooted in the soil, often climber plants. Living wall systems have a structure with planter boxes, modular panels or pockets that contain a growing medium allowing non-climber plants to grow at greater heights. Vertical Forests consist of balconies with trees and larger plants placed upon them.

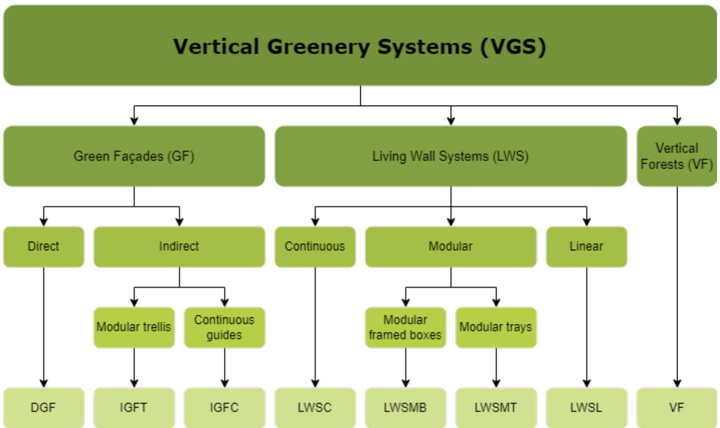

Figure 12.2: Overview of the assessed vertical greenery systems in this thesis (own work)

RQ5: What is the positive impact on the sustainability certification score of the building caused by application of a greenery system?

It can be concluded that when using the BREEAM certification to assess the sustainability of a building the total sustainability certification score of the building always increases with at least 4%. The highest increase is found in the case of an Intensive retention blue roof with an increased of 12%.

In LEED the application of a HGS always results in an increased score but from the VGS only the Living Wall System with Modular framed Boxes and the Vertical Forest result in an increased score. The remaining VGS do not improve the sustainability certification score of the building. The VF sees an increase in score of 3,13%, while the other listed greenery systems see an increase between 10 and 16%.

Using WELL only the Nature Roof, Intensive Retention Blue Roof, Garden Roof and Vertical Forest result in an increased sustainability certification score. The remaining systems do not increase the sustainability certification score.

It can be concluded that the increase in sustainability certification score depends on the certification method used. Of the three certification methods used BREEAM has the most credits that can be linked to the benefits of the greenery systems.

Table 12.1: Overview of increased sustainability certification scores

	Sustainability score increase		
Greenery system	**BREEAM**	**LEED**	**WELL**
Horizontal Greenery Systems			
EGRLW	4,0%	10,94%	0%
EGRBS	4,0%	15,63%	0%
EGRN	8,0%	12,50%	3,5%
EGRR	10,0%	10,94%	0%
IGRR	12,0%	12,50%	5,8%
IGRG	8,0%	12,50%	5,8%
Vertical Greenery Systems			
DGF	4,0%	0%	0%
IGFT	4,0%	0%	0%
IGFC	4,0%	0%	0%
LWSC	4,0%	0%	0%
LWSMB	4,0%	14,06%	0%
LWSMT	4,0%	0%	0%
LWSL	4,0%	0%	0%
VF	4,0%	3,13%	1,2%

Table 12.2: Additional loads due to the implementation of a greenery system in comparison to a normal, inaccessible roof

Greenery system	Roof loads			Façade loads	
	Permanent	Life	Snow	Permanent	Life
Horizontal Greenery Systems					
EGRLW	0,55	0	0	0	0
EGRBS	1,2	0	0,64	0	0
EGRN	0,95	2,0	0	0	0
EGRR	2,5	0	0	0	0
IGRR	6,8	2,0	0	0	0
IGRG	6,0	2,0	0	0	0
Vertical Greenery Systems					
DGF	0	0	0	0,05	0
IGFT	0	0	0	0,25	0
IGFC	0	0	0	0,25	0
LWSC	0	0	0	0,49	0
LWSMB	0	0	0	0,49	0
LWSMT	0	0	0	0,49	0
LWSL	0	0	0	0,39	0
VF	0	0	0	6	2,5

DGF: Direct green façade - IGFT: Indirect green façade with modular trellis - IGFC: Indirect green façade with continuous guides - LWSC: Continuous living wall system - LWSMB: Living wall system with modular framed boxes - LWSMT: Living wall system with modular trays - LWSL: Linear living wall system - VF: Vertical forest

RQ6: What is the impact of the different greenery systems in terms of added loads?

Greenery systems always impose extra load on the building when applied. It can be concluded that the HGS impose a higher additional load than on the building than VGS in most cases. All VGS have a dead load smaller than 0,5 kN/m^2 except the vertical forest with. HGS impose dead loads starting at 0,55 kN/m^2 up to 6,8 kN/m^2. The vertical forest and half of the HGS lead to higher variable loads due to their accessibility to humans. Bio-solar green roof systems lead to higher snow loads due to the risk of snow accumulating. All additional loads are shown in Table 12.2.

RQ7: What is the influence of the added loads due to greenery systems on the amount of material needed for the load bearing construction and the sustainability score?

It can be concluded that when applying a VGS the amount of material used for the load bearing structure is only increased in the case of a vertical forest. Applying an intensive green roof (IGR) also always leads to an increase in material use. It can also be concluded that applying a HGS that allows for human activity (nature roof, intensive retention blue roof and garden roof) almost always results in increased material use. Only when a nature roof is applied to a concrete structure this is not the case. Timber structures also see an increase in material use when applying a bio-solar green roof or an extensive retention blue roof.

12.2. Answering the main research question

With the answers to the sub-questions the main research question of this thesis can be answered.

When does the application of a greenery system have a positive effect on the sustainability performance of a mid rise building in an urban area?

From the results it was found that only the implementation of a nature roof always has a positive effect on the sustainability score of a building. In addition to this it can be concluded that application of a direct green façade never results in a negative effect on the sustainability score, but rather always results in a positive or neutral score. For all other greenery the application can result in either a positive, negative or neutral score depending on the certification method and construction material used. When comparing the positive effects (increased sustainability certification score) with the negative effects (increased material use and ECI), it can be concluded that based on this research a horizontal greenery system ends up with a positive score more often than a vertical greenery system because they are more explicitly included in the certification methods. Horizontal greenery systems received a positive score in 72% of the tested cases, while the vertical greenery systems result in a positive score in only 38% of the cases. Comparing the different sustainability certification methods it can be concluded that using the

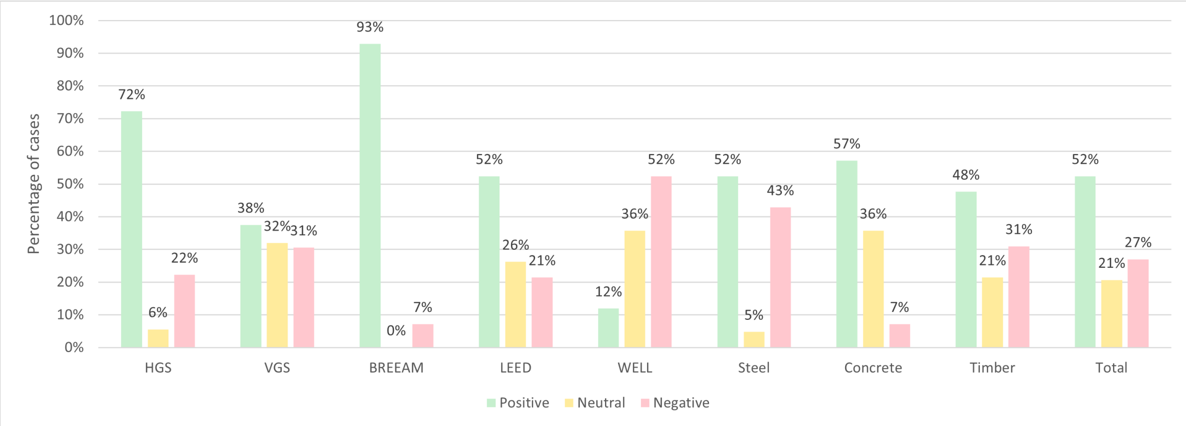

Figure 12.3: Distribution of the results (own work)

BREEAM certification will most often result in a positive score, namely in 93% of the cases. For LEED and WELL this percentage is lower with 52% and 12% of the cases respectively. The weight of the credits that can be linked to a benefit differ per certification method. This indicated that there is a certain subjectivity included in the methods and they are not as objective as preferred. These differing weights and the fact that the three certification methods do not all have credits linked to the same benefits results in differences in the results.

Overall, a positive score is obtained in 52% of all tested cases. The EGRN always results in a positive score and the DGF always results in a positive or neutral score. HGS generally receive a positive score more often than VGS. When implementing a VGS, the chances for a positive score are highest when using the BREEAM-NL certification method. In case of a HGS a LEED certification would give the highest chances for a positive score (100%), followed closely by BREEAM-NL.

12.3. Main conclusions

Based on the research as presented in this report the following conclusions can be drawn:

- **None of the sustainability certification methods is able to award points for all benefits provided by greenery systems**
- **BREEAM is currently the most suitable of the three used certification methods for the purpose of this research**
  None of the certification methods used in this research (BREEAM, LEED and WELL) is able to cover all seven benefits as defined. All of them have credits that can be linked to four of the seven benefits. BREEAM has the most credits that can be linked to greenery systems (7) and is therefore the most suitable to assess the influence of greenery systems because it can cover the most different aspects. Some additions and improvements however are recommended to include credits that can award points for the missing benefits. The proposed improvements are expected to result in positive sustainability scores for even more cases.

- **The certification methods are currently more applicable to assessing horizontal greenery systems than vertical greenery systems**
  Horizontal greenery systems are often mentioned as a means to earn the points available for certain credits while this is not the case for vertical greenery systems. Therefore they more often

earn points and more often result in a positive sustainability score than vertical greenery systems.

- **Application of a nature roof always results in a positive effect on the sustainability performance of a building**
  The nature roof system does earn points for being accessible to people but is relatively lightweight in comparison with the other accessible green roof systems. This combination makes that the greenery system always receives a positive score.

- **Application of a direct green façade never results in a negative effect on the sustainability performance of a building**
  The direct green façade is very lightweight and never leads to an increased ECI value. Therefore the effect on the sustainability is never negative but rather positive (in BREEAM, where the direct green façade earned extra certification points) or neutral (LEED and WELL, where the direct green façade earned no extra certification points).

- **Using BREEAM results in a positive effect on the sustainability performance in almost all cases**
  A negative score is only received for the application of a garden roof when using a steel or timber construction or the application of a vertical forest on a timber building. A positive effect on the sustainability score is obtained in 93% of the cases when using BREEAM.

- **Using LEED always results in a positive score when implementing a horizontal greenery system**
  LEED awards many points for to horizontal greenery systems rainwater management, habitat restoration and urban heat island reduction. This results in increases in LEED score of at least 10%. These increases in LEED score are always higher than the increase in ECI value, leading to a positive score for every application of a HGS in LEED.

- **When no structural adaptions are required the application of a greenery system always results in either a positive or a neutral score**
  A neutral score is only obtained when both the increase in sustainability certification and ECI value are 0%. When the increase in sustainability certification is >0% but the increase in ECI value is still 0%, a positive score is obtained.

- **When structural adaptions are required this will almost always result in a negative effect on the sustainability performance when using the WELL certification**
- **Using WELL results in a positive effect on the sustainability performance in few cases, the sustainability score will most often be a negative or neutral**
  When structural adaptions are needed there are only three cases where using WELL still results in a positive effect on the sustainability performance. This is when applying a nature roof using any of the three materials. Applying an intensive retention blue roof or a garden roof will still result in a positive effect on the sustainability performance when using the material concrete.

- **Using concrete will almost never result in a negative effect on the sustainability performance**
  A negative effect on the sustainability performance of a concrete structure is only obtained when a vertical forest is assessed with either LEED or WELL, or when a extensive retention blue roof is assessed with WELL. This is in 7% of the cases.

12.4. Recommendations

After performing this research a few recommendations for future research remain.

In addition to this it should be investigated how the criteria that currently prevent awarding points for proven benefits of greenery systems can be changed to include greenery systems as a posible way of obtaining the available points as well. All certification methods used in this research cover four of the seven benefits, but they do not cover the same four benefits. It is recommended to investigate how LEED or WELL credits for UHI reduction and air purification can be implemented into BREEAM (be it with some modifications) to make sure one method covers all seven benefits allowing us to score all beneficial aspects of the application of greenery systems.

In this research a limited number of sustainability certifications was considered. As discussed, there are differences in the value attached to certain effects of the greenery systems. Other certifications could thus lead to different results. It could be useful to asses more certification methods to see if there is one that might be able to take both the positive and negative implications into account. GPR Gebouw is a tool that might be useful for this because this tool also includes an MPG calculation.

Each of the used certification methods offers different variants of their certification for different use-purposes of a building. In this case the variants that apply to a residential building were used, but the variants for for instance office buildings can have different credits or award a different amount of points for certain credits. This can lead to different results, so it is interesting to investigate this as well in further research.

The CO_2 uptake of the plants and trees used on a building could be compared with the CO_2 footprint of the building materials of the building itself. Via photosynthesis plants are able to convert CO_2 into O_2. Also, timber building elements can 'store' CO_2 inside the elements. Currently, it is not possible to take either this stored CO_2 or the conversion of CO_2 to O_2 into account in the ECI. It could be useful to investigate if it is possible to implement this into the ECI in the future and whether this would be useful.

In this thesis a case study has been performed on a building with a beam-column structure. As discussed in Chapter 4 buildings can also have a structure consisting of load-bearing walls. Effects on this structure might be different, so it is interesting to perform a similar test on a building with load-bearing walls es well to determine if the increase in ECI value will differ much from the structure assessed in this research.

Lastly, wind forces on trees remains a subject with little consensus. Different parties make different assumptions and determine the wind forces induced on trees in a different way. Additional wind forces have not been taken into account in this research due to constraints given by the models used. Extra research into the loads posed by wind forces on trees could be useful if the goal is to increase the amount of trees on buildings in the future. Especially when applied in areas where buildings are built closely together and and higher wind speeds occur in street canyons.

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Part IV
Appendices

A
GPR Gebouw

GPR is a software that aims to make it possible to measure and discuss the sustainability of a building project [138]. The information about this methodology as described in this appendix is taken from the GPR website [138]. The goal of the GPR method is to create building projects with a the highest quality while keeping the environmental burden at a minimum. GPR itself states that their methodology is a great fit for nature inclusive, climate adaptive or circular building projects. In the GPR methodology, sustainability is measured on the basis of five themes, which are Energy, Environment,Human Health, Quality of use and Value for the future. Each theme can be divided in multiple subthemes and each theme the project receives a score between one 1 and 10.

Table A.1: GPR themes [138]

Theme	**Subthemes**
Energy	Energy performance Energy performance - additional
Environment	Material Water Location and nature
Human health	Acoustic comfort Air quality Thermal comfort Visual comfort
Quality of use	Accessibility Functionality Technical qualities Social value
Value for the future	Existing quality Building adaptivity Climate adaptivity Value of experience

GPR Gebouw calculations can be made without the need for a separate degree or certificate. A subscription is however required to make use of the tool.

The GPR includes the Milieu Prestatie Gebouwen (MPG) (in English: Environmental Performance of Buildings) is included in the Environment theme. Because of this, this method might be an interesting one to use for this research.

B

BREEAM points conversion

Table B.1 shows the conversion of the credits from BREEAM 2014v2.0 to BREEAM2023. The credits included in the table are the credits for which the building Urban Woods in Delft was awarded points. For some credits the available points in BREEAM 2023 have been reduced or removed in comparison to BREEAM 2014v2.0. This is stated in the table.

Table B.1: Conversion of credits from BREEAM 2014v2.0 to BREEAM 2023

BREEAM 2014v2.0		BREEAM 2023		
Credit	**Points**	**Credit**	**Points**	**Notes**
MAN1	3	-		No longer worth any points
MAN2	2	MAN03	2	
MAN3	4	MAN03	0	
MAN4	1	MAN04	1	
MAN6	0	MAN01	0	
MAN8	1	-		No longer worth any points
MAN9	1	-		No longer worth any points
MAN12	2	MAN02	3	
HEA1	1	HEA01	2	
HEA8	2	HEA03	1	
HEA10	2	HEA04	2	
HEA13	0	HEA05	0	
HEA14	0	HEA08	0	
HEA15	0	HEA06	0	
ENE1	15	ENE01	10	
ENE2B	2	ENE02	2	
ENE4	1	ENE03	2	
ENE5	3	-		No longer worth any points
ENE8	2	ENE06	2	
ENE26	2	-		No longer worth any points
TRA1C	2	TRA01	4	
TRA2	1	TRA02	2	
TRA3B	1	TRA03	2	
WAT1B	2	WAT01		
WAT5	0	WAT04	0	
WAT6	1	WAT04	1	
MAT1	3	MAT01	0	Demands for points have been increased
MAT5	4	MAT01	0	No longer worth any points, changed to mandatory requirement
WST1	3	WST01	3	
WST3B	1	WST03	1	
LE1	4	LE01	2	
LE3	1	LE02	2	
LE4B	3	LE04	2	
LE9	2	-		No longer worth any points
POL1	0	POL01	1	
POL4	3	POL01	1	Point value reduced
POL6	3	POL03	2	
Total	77		51	

C
Steel variant

This appendix gives a more elaborate overview of the loads that were used as input for for the BSDT and gives an overview of the outputted unity checks, member cross sections and ECI value as well. The structure consists of HEA columns and beams. The beams support the floors and the roof, which consist of hollow-core elements or solid reinforced concrete slabs. As mentioned before the BSDT does not implement a stability system such as a concrete core or braces. As introduced in Chapter 7, the spans of the beams are between 2,25 and 4,10 meters. The columns parts have a minimum length of 3,04 meters and a maximum length of 3,25 meters. The foundation consists of Fundex pile with a diameter of 540 mm reaching down to -32,5 meters NAP. The number of piles needed is calculated by dividing the total weight of the building by the capacity of one pile, which is 2000 kN.

Figure C.1 shows a top view of the building Urban Woods as modelled in the BSDT. The grid sizes can be seen and the different types of beams are shown. The beams are split in four categories because the floors transfer load in one direction only. This leads to primary and secondary beams, where the primary beams are the ones that take up the load transferred by the floor. The secondary beams are not loaded by the floors. A sub categorization is made between beams along the façade and the ones that are not placed at the façade, which are called internal beams. The different types of beams can be seen in Figure C.1. The load transfer direction of the floors is indicated in this figure as well. Even though the secondary beams do not cary any of the load it is not possible to remove them in the BSDT.

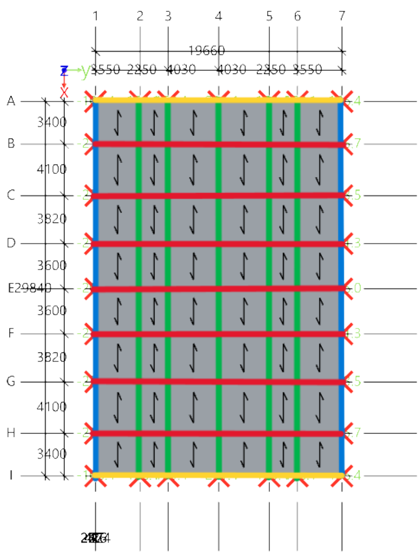

Figure C.1: Primary internal beams (red), primary façade beams (yellow), secondary internal beams (green) and secondary façade beams (blue)

C.1. Standard building

Table C.1: Inputted loads and outputted information for a steel building without greenery system

INPUT		
Load type	**Value**	**Notes**
Roof, dead load	1,5 kN/m^2	1,5 kN/m^2 roof finishing
Roof, live load	1,0 kN/m^2	Category H: inaccessible roof
Roof, snow load	0,56 kN/m^2	
Roof, façade beam, dead load	0 kN/m	
Roof, façade beam, live load	0 kN/m	
Floors, dead load	1,8 kN/m^2	1,8 kN/m^2 floor finishing
Floors, live load	2,95 kN/m^2	1,75 kN/m^2 Category A: private floors, 1,2 kN/m^2 walls
Floors, façade beam, dead load	0 kN/m	
Floors, façade beam, live load	0 kN/m	
OUTPUT		
Location	**Element size**	**Notes**
Roof	Dycore K150-8	max. u.c. = 0,57
Floors	Dycore K150-8	max. u.c. = 0,57
Beams, internal primary	HE200A	max. u.c. roof = 0,58, max. u.c. floors = 0,86
Beams, internal secondary	HE100A	max. u.c. roof = 0,03, max. u.c. floors = 0,03
Beams, façade primary	HE160A	max. u.c. roof = 0,49, max. u.c. floors = 0,71
Beams, façade secondary	HE100A	max. u.c. roof = 0,03, max. u.c. floors = 0,03
Columns	HE240A	max. u.c. = 0,79
Foundation piles	Fundex pile ∅540	28 piles with capacity 2000 kN
Element types	**Total mass or volume**	**ECI class**
Roof and floors	879,98 m^3	Precast concrete hollowcore slab, ECI = 81,18 €/m^3
Beams and columns	221,65 kg	Steel rolled profiles, ECI = 0,47 €/kg
Foundation piles	208,41 m^3	In-situ concrete C30/37 CEM I reinf. 200 kg/m^3, ECI = 72,51 €/m^3
ECI value	**€190813,94**	

C.2. Standard roof terrace

Table C.2: Inputted loads and outputted information for a steel building with a standard roof terrace

	INPUT	
Load type	**Value**	**Notes**
Roof, dead load	2,75 kN/m^2	1,5 kN/m^2 roof finishing, 1,25 kN/m^2 concrete tiles
Roof, live load	3,0 kN/m^2	Category A: communal floors, stairs and balconies
Roof, snow load	0,56 kN/m^2	
Roof, façade beam, dead load	0 kN/m	
Roof, façade beam, live load	0 kN/m	
Floors, dead load	1,8 kN/m^2	1,8 kN/m^2 floor finishing
Floors, live load	2,95 kN/m^2	1,75 kN/m^2 Category A: private floors, 1,2 kN/m^2 walls
Floors, façade beam, dead load	0 kN/m	
Floors, façade beam, live load	0 kN/m	
	OUTPUT	
Location	**Element size**	**Notes**
Roof	Dycore K150-8	max. u.c. = 0,61
Floors	Dycore K150-8	max. u.c. = 0,57
Beams, internal primary	HE220A	max. u.c. roof = 0,7, max. u.c. floors = 0,62
Beams, internal secondary	HE100A	max. u.c. roof = 0,03, max. u.c. floors = 0,03
Beams, façade primary	HE160A	max. u.c. roof = 0,82, max. u.c. floors = 0,71
Beams, façade secondary	HE100A	max. u.c. roof = 0,03, max. u.c. floors = 0,03
Columns	HE240A	max. u.c. = 0,79
Foundation piles	Fundex pile ∅540	29 piles with capacity 2000 kN
Element types	**Total mass or volume**	**ECI class**
Roof and floors	879,98 m^3	Precast concrete hollowcore slab, ECI = 81,18 €/m^3
Beams and columns	233,00 kg	Steel rolled profiles, ECI = 0,47 €/kg
Foundation piles	215,85 m^3	In-situ concrete C30/37 CEM I reinf. 200 kg/m^3, ECI = 72,51 €/m^3
ECI value	**€196692,61**	**Increase: 3,08%**

C.3. Lightweight green roof

Table C.3: Inputted loads and outputted information for a steel building with EGRLW

INPUT		
Load type	**Value**	**Notes**
Roof, dead load	2,05 kN/m^2	1,5 kN/m^2 roof finishing, 0,55 kN/m^2 green roof
Roof, live load	1,0 kN/m^2	Category H: inaccessible roof
Roof, snow load	0,56 kN/m^2	
Roof, façade beam, dead load	0 kN/m	
Roof, façade beam, live load	0 kN/m	
Floors, dead load	1,8 kN/m^2	1,8 kN/m^2 floor finishing
Floors, live load	2,95 kN/m^2	1,75 kN/m^2 Category A: private floors, 1,2 kN/m^2 walls
Floors, façade beam, dead load	0 kN/m	
Floors, façade beam, live load	0 kN/m	
OUTPUT		
Location	**Element size**	**Notes**
Roof	Dycore K150-8	max. u.c. = 0,57
Floors	Dycore K150-8	max. u.c. = 0,57
Beams, internal primary	HE200A	max. u.c. roof = 0,64, max. u.c. floors = 0,86
Beams, internal secondary	HE100A	max. u.c. roof = 0,03, max. u.c. floors = 0,03
Beams, façade primary	HE160A	max. u.c. roof = 0,54, max. u.c. floors = 0,71
Beams, façade secondary	HE100A	max. u.c. roof = 0,03, max. u.c. floors = 0,03
Columns	HE240A	max. u.c. = 0,79
Foundation piles	Fundex pile ∅540	29 piles with capacity 2000 kN
Element types	**Total mass or volume**	**ECI class**
Roof and floors	879,98 m^3	Precast concrete hollowcore slab, ECI = 81,18 €/m^3
Beams and columns	221,65 kg	Steel rolled profiles, ECI = 0,47 €/kg
Foundation piles	215,85 m^3	In-situ concrete C30/37 CEM I reinf. 200 kg/m^3, ECI = 72,51 €/m^3
ECI value	**€191353,62**	**Increase: 0,28%**

C.4. Biosolar green roof

Table C.4: Inputted loads and outputted information for a steel building with EGRBS

INPUT		
Load type	**Value**	**Notes**
Roof, dead load	2,7 kN/m^2	1,5 kN/m^2 roof finishing, 1,2 kN/m^2 green roof
Roof, live load	1,0 kN/m^2	Category H: inaccessible roof
Roof, snow load	1,2 kN/m^2	Increased value due to possible snow accumulation
Roof, façade beam, dead load	0 kN/m	
Roof, façade beam, live load	0 kN/m	
Floors, dead load	1,8 kN/m^2	1,8 kN/m^2 floor finishing
Floors, live load	2,95 kN/m^2	1,75 kN/m^2 Category A: private floors, 1,2 kN/m^2 walls
Floors, façade beam, dead load	0 kN/m	
Floors, façade beam, live load	0 kN/m	
OUTPUT		
Location	**Element size**	**Notes**
Roof	Dycore K150-8	max. u.c. = 0,57
Floors	Dycore K150-8	max. u.c. = 0,57
Beams, internal primary	HE200A	max. u.c. roof = 0,74, max. u.c. floors = 0,86
Beams, internal secondary	HE100A	max. u.c. roof = 0,03, max. u.c. floors = 0,03
Beams, façade primary	HE160A	max. u.c. roof = 0,63, max. u.c. floors = 0,71
Beams, façade secondary	HE100A	max. u.c. roof = 0,03, max. u.c. floors = 0,03
Columns	HE240A	max. u.c. = 0,80
Foundation piles	Fundex pile ∅540	29 piles with capacity 2000 kN
Element types	**Total mass or volume**	**ECI class**
Roof and floors	879,98 m^3	Precast concrete hollowcore slab, ECI = 81,18 €/m^3
Beams and columns	221,65 kg	Steel rolled profiles, ECI = 0,47 €/kg
Foundation piles	215,85 m^3	In-situ concrete C30/37 CEM I reinf. 200 kg/m^3, ECI = 72,51 €/m^3
ECI value	**€191353,62**	**Increase: 0,28%**

C.5. Nature roof

Table C.5: Inputted loads and outputted information for a steel building with EGRN

INPUT		
Load type	**Value**	**Notes**
Roof, dead load	2,45 kN/m^2	1,5 kN/m^2 roof finishing, 0,95 kN/m^2 green roof
Roof, live load	3,0 kN/m^2	Category A: communal floors, stairs and balconies
Roof, snow load	0,56 kN/m^2	
Roof, façade beam, dead load	0 kN/m	
Roof, façade beam, live load	0 kN/m	
Floors, dead load	1,8 kN/m^2	1,8 kN/m^2 floor finishing
Floors, live load	2,95 kN/m^2	1,75 kN/m^2 Category A: private floors, 1,2 kN/m^2 walls
Floors, façade beam, dead load	0 kN/m	
Floors, façade beam, live load	0 kN/m	
OUTPUT		
Location	**Element size**	**Notes**
Roof	Dycore K150-8	max. u.c. = 0,57
Floors	Dycore K150-8	max. u.c. = 0,57
Beams, internal primary	HE220A	max. u.c. roof = 0,67, max. u.c. floors = 0,62
Beams, internal secondary	HE100A	max. u.c. roof = 0,03, max. u.c. floors = 0,03
Beams, façade primary	HE160A	max. u.c. roof = 0,79, max. u.c. floors = 0,71
Beams, façade secondary	HE100A	max. u.c. roof = 0,03, max. u.c. floors = 0,03
Columns	HE240A	max. u.c. = 0,81
Foundation piles	Fundex pile ∅540	29 piles with capacity 2000 kN
Element types	**Total mass or volume**	**ECI class**
Roof and floors	879,98 m^3	Precast concrete hollowcore slab, ECI = 81,18 €/m^3
Beams and columns	233,00 kg	Steel rolled profiles, ECI = 0,47 €/kg
Foundation piles	215,85 m^3	In-situ concrete C30/37 CEM I reinf. 200 kg/m^3, ECI = 72,51 €/m^3
ECI value	**€196692,61**	**Increase: 3,08%**

C.6. Extensive retention blue roof

Table C.6: Inputted loads and outputted information for a steel building with EGRR

	INPUT	
Load type	**Value**	**Notes**
Roof, dead load	4,0 kN/m^2	1,5 kN/m^2 roof finishing, 1,0 kN/m^2 green roof, 1,5 kN/m^2 water storage
Roof, live load	1,0 kN/m^2	Category H: inaccessible roof
Roof, snow load	0,56 kN/m^2	
Roof, façade beam, dead load	0 kN/m	
Roof, façade beam, live load	0 kN/m	
Floors, dead load	1,8 kN/m^2	1,8 kN/m^2 floor finishing
Floors, live load	2,95 kN/m^2	1,75 kN/m^2 Category A: private floors, 1,2 kN/m^2 walls
Floors, façade beam, dead load	0 kN/m	
Floors, façade beam, live load	0 kN/m	
	OUTPUT	
Location	**Element size**	**Notes**
Roof	Dycore K150-8	max. u.c. = 0,57
Floors	Dycore K150-8	max. u.c. = 0,57
Beams, internal primary	HE200A	max. u.c. roof = 0,86, max. u.c. floors = 0,86
Beams, internal secondary	HE100A	max. u.c. roof = 0,03, max. u.c. floors = 0,03
Beams, façade primary	HE160A	max. u.c. roof = 0,73, max. u.c. floors = 0,71
Beams, façade secondary	HE100A	max. u.c. roof = 0,03, max. u.c. floors = 0,03
Columns	HE240A	max. u.c. = 0,81
Foundation piles	Fundex pile ∅540	29 piles with capacity 2000 kN
Element types	**Total mass or volume**	**ECI class**
Roof and floors	879,98 m^3	Precast concrete hollowcore slab, ECI = 81,18 €/m^3
Beams and columns	221,65 kg	Steel rolled profiles, ECI = 0,47 €/kg
Foundation piles	215,85 m^3	In-situ concrete C30/37 CEM I reinf. 200 kg/m^3, ECI = 72,51 €/m^3
ECI value	**€191353,62**	**Increase: 0,28%**

C.7. Intensive retention blue roof

Table C.7: Inputted loads and outputted information for a steel building with IGRR

INPUT		
Load type	**Value**	**Notes**
Roof, dead load	8,3 kN/m^2	1,5 kN/m^2 roof finishing, 3,1 kN/m^2 green roof, 3,7 kN/m^2 water storage
Roof, live load	3,0 kN/m^2	Category A: communal floors, stairs and balconies
Roof, snow load	0,56 kN/m^2	
Roof, façade beam, dead load	0 kN/m	
Roof, façade beam, live load	0 kN/m	
Floors, dead load	1,8 kN/m^2	1,8 kN/m^2 floor finishing
Floors, live load	2,95 kN/m^2	1,75 kN/m^2 Category A: private floors, 1,2 kN/m^2 walls
Floors, façade beam, dead load	0 kN/m	
Floors, façade beam, live load	0 kN/m	
OUTPUT		
Location	**Element size**	**Notes**
Roof	One-way slab t=160 mm	max. u.c. = 0,9
Floors	Dycore K150-8	max. u.c. = 0,57
Beams, internal primary	HE260A	max. u.c. roof = 0,76, max. u.c. floors = 0,36
Beams, internal secondary	HE100A	max. u.c. roof = 0,03, max. u.c. floors = 0,03
Beams, façade primary	HE180A	max. u.c. roof = 0,85, max. u.c. floors = 0,51
Beams, façade secondary	HE100A	max. u.c. roof = 0,03, max. u.c. floors = 0,03
Columns	HE240A	max. u.c. = 0,90
Foundation piles	Fundex pile ∅540	32 piles with capacity 2000 kN
Element types	**Total mass or volume**	**ECI class**
Roof	93,86 m^3	In-situ concrete, ECI = 57,61 €/m^3
Floors	791,98 m^3	Precast concrete hollowcore slab, ECI = 81,18 €/m^3
Beams and columns	259,29 kg	Steel rolled profiles, ECI = 0,47 €/kg
Foundation piles	238,18 m^3	In-situ concrete C30/37 CEM I reinf. 200 kg/m^3, ECI = 72,51 €/m^3
ECI value	**€208941,83**	**Increase: 9,50%**

C.8. Garden roof

Table C.8: Inputted loads and outputted information for a steel building with IGRG

INPUT		
Load type	**Value**	**Notes**
Roof, dead load	7,5 kN/m^2	1,5 kN/m^2 roof finishing, 6 kN/m^2 green roof
Roof, live load	3,0 kN/m^2	Category A: communal floors, stairs and balconies
Roof, snow load	0,56 kN/m^2	
Roof, façade beam, dead load	0 kN/m	
Roof, façade beam, live load	0 kN/m	
Floors, dead load	1,8 kN/m^2	1,8 kN/m^2 floor finishing
Floors, live load	2,95 kN/m^2	1,75 kN/m^2 Category A: private floors, 1,2 kN/m^2 walls
Floors, façade beam, dead load	0 kN/m	
Floors, façade beam, live load	0 kN/m	
OUTPUT		
Location	**Element size**	**Notes**
Roof	One-way slab t=160 mm	max. u.c. = 0,9
Floors	Dycore K150-8	max. u.c. = 0,57
Beams, internal primary	HE260A	max. u.c. roof = 0,72, max. u.c. floors = 0,36
Beams, internal secondary	HE100A	max. u.c. roof = 0,03, max. u.c. floors = 0,03
Beams, façade primary	HE180A	max. u.c. roof = 0,81, max. u.c. floors = 0,51
Beams, façade secondary	HE100A	max. u.c. roof = 0,03, max. u.c. floors = 0,03
Columns	HE240A	max. u.c. = 0,89
Foundation piles	Fundex pile ∅540	32 piles with capacity 2000 kN
Element types	**Total mass or volume**	**ECI class**
Roof	93,86 m^3	In-situ concrete, ECI = 57,61 €/m^3
Floors	791,98 m^3	Precast concrete hollowcore slab, ECI = 81,18 €/m^3
Beams and columns	259,29 kg	Steel rolled profiles, ECI = 0,47 €/kg
Foundation piles	238,18 m^3	In-situ concrete C30/37 CEM I reinf. 200 kg/m^3, ECI = 72,51 €/m^3
ECI value	**€208941,83**	**Increase: 9,50%**

C.9. Direct green façade

Table C.9: Inputted loads and outputted information for a steel building with DGF

INPUT		
Load type	**Value**	**Notes**
Roof, dead load	1,5 kN/m^2	1,5 kN/m^2 roof finishing
Roof, live load	1,0 kN/m^2	Category H: inaccessible roof
Roof, snow load	0,56 kN/m^2	
Roof, façade beam, dead load	0,08 kN/m	
Roof, façade beam, live load	0 kN/m	
Floors, dead load	1,8 kN/m^2	1,8 kN/m^2 floor finishing
Floors, live load	2,95 kN/m^2	1,75 kN/m^2 Category A: private floors, 1,2 kN/m^2 walls
Floors, façade beam, dead load	0,15 kN/m	
Floors, façade beam, live load	0 kN/m	
OUTPUT		
Location	**Element size**	**Notes**
Roof	Dycore K150-8	max. u.c. = 0,57
Floors	Dycore K150-8	max. u.c. = 0,57
Beams, internal primary	HE200A	max. u.c. roof = 0,58, max. u.c. floors = 0,86
Beams, internal secondary	HE100A	max. u.c. roof = 0,03, max. u.c. floors = 0,03
Beams, façade primary	HE160A	max. u.c. roof = 0,50, max. u.c. floors = 0,72
Beams, façade secondary	HE100A	max. u.c. roof = 0,05, max. u.c. floors = 0,06
Columns	HE240A	max. u.c. = 0,79
Foundation piles	Fundex pile ∅540	28 piles with capacity 2000 kN
Element types	**Total mass or volume**	**ECI class**
Roof and floors	879,98 m^3	Precast concrete hollowcore slab, ECI = 81,18 €/m^3
Beams and columns	221,65 kg	Steel rolled profiles, ECI = 0,47 €/kg
Foundation piles	208,41 m^3	In-situ concrete C30/37 CEM I reinf. 200 kg/m^3, ECI = 72,51 €/m^3
ECI value	**€190813,94**	**Increase: 0%**

C.10. Indirect green façade with modular trellis, indirect green façade with continuous guides

Table C.10: Inputted loads and outputted information for a steel building with IGFT or IGFC

	INPUT	
Load type	**Value**	**Notes**
Roof, dead load	1,5 kN/m^2	1,5 kN/m^2 roof finishing
Roof, live load	1,0 kN/m^2	Category H: inaccessible roof
Roof, snow load	0,56 kN/m^2	
Roof, façade beam, dead load	0,46 kN/m	
Roof, façade beam, live load	0 kN/m	
Floors, dead load	1,8 kN/m^2	1,8 kN/m^2 floor finishing
Floors, live load	2,95 kN/m^2	1,75 kN/m^2 Category A: private floors, 1,2 kN/m^2 walls
Floors, façade beam, dead load	0,90 kN/m	
Floors, façade beam, live load	0 kN/m	
	OUTPUT	
Location	**Element size**	**Notes**
Roof	Dycore K150-8	max. u.c. = 0,57
Floors	Dycore K150-8	max. u.c. = 0,57
Beams, internal primary	HE200A	max. u.c. roof = 0,58, max. u.c. floors = 0,86
Beams, internal secondary	HE100A	max. u.c. roof = 0,03, max. u.c. floors = 0,03
Beams, façade primary	HE160A	max. u.c. roof = 0,52, max. u.c. floors = 0,76
Beams, façade secondary	HE100A	max. u.c. roof = 0,13, max. u.c. floors = 0,21
Columns	HE240A	max. u.c. = 0,79
Foundation piles	Fundex pile ∅540	29 piles with capacity 2000 kN
Element types	**Total mass or volume**	**ECI class**
Roof and floors	879,98 m^3	Precast concrete hollowcore slab, ECI = 81,18 €/m^3
Beams and columns	221,65 kg	Steel rolled profiles, ECI = 0,47 €/kg
Foundation piles	215,85 m^3	In-situ concrete C30/37 CEM I reinf. 200 kg/m^3, ECI = 72,51 €/m^3
ECI value	**€191353,62**	**Increase: 0,28%**

C.11. Continuous living wall system, modular living wall system with modular framed boxes, modular living wall system with modular trays

Table C.11: Inputted loads and outputted information for a steel building with LWSC, LWSMB or LWSMT

	INPUT	
Load type	**Value**	**Notes**
Roof, dead load	1,5 kN/m^2	1,5 kN/m^2 roof finishing
Roof, live load	1,0 kN/m^2	Category H: inaccessible roof
Roof, snow load	0,56 kN/m^2	
Roof, façade beam, dead load	0,77 kN/m	
Roof, façade beam, live load	0 kN/m	
Floors, dead load	1,8 kN/m^2	1,8 kN/m^2 floor finishing
Floors, live load	2,95 kN/m^2	1,75 kN/m^2 Category A: private floors, 1,2 kN/m^2 walls
Floors, façade beam, dead load	1,51 kN/m	
Floors, façade beam, live load	0 kN/m	
	OUTPUT	
Location	**Element size**	**Notes**
Roof	Dycore K150-8	max. u.c. = 0,57
Floors	Dycore K150-8	max. u.c. = 0,57
Beams, internal primary	HE200A	max. u.c. roof = 0,58, max. u.c. floors = 0,86
Beams, internal secondary	HE100A	max. u.c. roof = 0,03, max. u.c. floors = 0,03
Beams, façade primary	HE160A	max. u.c. roof = 0,54, max. u.c. floors = 0,80
Beams, façade secondary	HE100A	max. u.c. roof = 0,19, max. u.c. floors = 0,33
Columns	HE240A	max. u.c. = 0,79
Foundation piles	Fundex pile ∅540	29 piles with capacity 2000 kN
Element types	**Total mass or volume**	**ECI class**
Roof and floors	879,98 m^3	Precast concrete hollowcore slab, ECI = 81,18 €/m^3
Beams and columns	221,65 kg	Steel rolled profiles, ECI = 0,47 €/kg
Foundation piles	215,85 m^3	In-situ concrete C30/37 CEM I reinf. 200 kg/m^3, ECI = 72,51 €/m^3
ECI value	**€191353,62**	**Increase: 0,28%**

C.12. Linear living wall system

Table C.12: Inputted loads and outputted information for a steel building with LWSL

INPUT		
Load type	**Value**	**Notes**
Roof, dead load	1,5 kN/m^2	1,5 kN/m^2 roof finishing
Roof, live load	1,0 kN/m^2	Category H: inaccessible roof
Roof, snow load	0,56 kN/m^2	
Roof, façade beam, dead load	0,92 kN/m	
Roof, façade beam, live load	0 kN/m	
Floors, dead load	1,8 kN/m^2	1,8 kN/m^2 floor finishing
Floors, live load	2,95 kN/m^2	1,75 kN/m^2 Category A: private floors, 1,2 kN/m^2 walls
Floors, façade beam, dead load	1,81 kN/m	
Floors, façade beam, live load	0 kN/m	
OUTPUT		
Location	**Element size**	**Notes**
Roof	Dycore K150-8	max. u.c. = 0,57
Floors	Dycore K150-8	max. u.c. = 0,57
Beams, internal primary	HE200A	max. u.c. roof = 0,58, max. u.c. floors = 0,86
Beams, internal secondary	HE100A	max. u.c. roof = 0,03, max. u.c. floors = 0,03
Beams, façade primary	HE160A	max. u.c. roof = 0,54, max. u.c. floors = 0,81
Beams, façade secondary	HE100A	max. u.c. roof = 0,22, max. u.c. floors = 0,39
Columns	HE240A	max. u.c. = 0,79
Foundation piles	Fundex pile ∅540	29 piles with capacity 2000 kN
Element types	**Total mass or volume**	**ECI class**
Roof and floors	879,98 m^3	Precast concrete hollowcore slab, ECI = 81,18 €/m^3
Beams and columns	221,65 kg	Steel rolled profiles, ECI = 0,47 €/kg
Foundation piles	215,85 m^3	In-situ concrete C30/37 CEM I reinf. 200 kg/m^3, ECI = 72,51 €/m^3
ECI value	**€191353,62**	**Increase: 0,28%**

C.13. Vertical forest

Table C.13: Inputted loads and outputted information for a steel building with VF

INPUT		
Load type	**Value**	**Notes**
Roof, dead load	1,5 kN/m^2	1,5 kN/m^2 roof finishing
Roof, live load	1,0 kN/m^2	Category H: inaccessible roof
Roof, snow load	0,56 kN/m^2	
Roof, façade beam, dead load	3,0 kN/m	
Roof, façade beam, live load	1,25 kN/m	Category A: private floors
Floors, dead load	1,8 kN/m^2	1,8 kN/m^2 floor finishing
Floors, live load	2,95 kN/m^2	1,75 kN/m^2 Category A: private floors, 1,2 kN/m^2 walls
Floors, façade beam, dead load	6,0 kN/m	
Floors, façade beam, live load	2,5 kN/m	Category A: private balconies
OUTPUT		
Location	**Element size**	**Notes**
Roof	Dycore K150-8	max. u.c. = 0,57
Floors	Dycore K150-8	max. u.c. = 0,57
Beams, internal primary	HE200A	max. u.c. roof = 0,58, max. u.c. floors = 0,86
Beams, internal secondary	HE100A	max. u.c. roof = 0,03, max. u.c. floors = 0,03
Beams, façade primary	HE180A	max. u.c. roof = 0,52, max. u.c. floors = 0,85
Beams, façade secondary	HE140A	max. u.c. roof = 0,40, max. u.c. floors = 0,78
Columns	HE240A	max. u.c. = 0,79
Foundation piles	Fundex pile ∅540	33 piles with capacity 2000 kN
Element types	**Total mass or volume**	**ECI class**
Roof and floors	879,98 m^3	Precast concrete hollowcore slab, ECI = 81,18 €/m^3
Beams and columns	228,42 kg	Steel rolled profiles, ECI = 0,47 €/kg
Foundation piles	245,63 m^3	In-situ concrete C30/37 CEM I reinf. 200 kg/m^3, ECI = 72,51 €/m^3
ECI value	**€196696,93**	**Increase: 3,08%**

C.14. Combination: intensive retention blue roof and vertical forest

Table C.14: Inputted loads and outputted information for a steel building with IGRR+VF

	INPUT	
Load type	**Value**	**Notes**
Roof, dead load	8,3 kN/m^2	1,5 kN/m^2 roof finishing, 3,1 kN/m^2 green roof, 3,7 kN/m^2 water storage
Roof, live load	3,0 kN/m^2	Category A: communal floors, stairs and balconies
Roof, snow load	0,56 kN/m^2	
Roof, façade beam, dead load	3,0 kN/m	
Roof, façade beam, live load	1,25 kN/m	Category A: private floors
Floors, dead load	1,8 kN/m^2	1,8 kN/m^2 floor finishing
Floors, live load	2,95 kN/m^2	1,75 kN/m^2 Category A: private floors, 1,2 kN/m^2 walls
Floors, façade beam, dead load	6,0 kN/m	
Floors, façade beam, live load	2,5 kN/m	Category A: private balconies
	OUTPUT	
Location	**Element size**	**Notes**
Roof	One-way slab t=160 mm	max. u.c. = 0,9
Floors	Dycore K150-8	max. u.c. = 0,57
Beams, internal primary	HE260A	max. u.c. roof = 0,76, max. u.c. floors = 0,36
Beams, internal secondary	HE100A	max. u.c. roof = 0,03, max. u.c. floors = 0,03
Beams, façade primary	HE200A	max. u.c. roof = 0,74, max. u.c. floors = 0,62
Beams, façade secondary	HE140A	max. u.c. roof = 0,40, max. u.c. floors = 0,78
Columns	HE240A	max. u.c. = 0,90
Foundation piles	Fundex pile ∅540	37 piles with capacity 2000 kN
Element types	**Total mass or volume**	**ECI class**
Roof	93,86 m^3	In-situ concrete, ECI = 57,61 €/m^3
Floors	791,98 m^3	Precast concrete hollowcore slab, ECI = 81,18 €/m^3
Beams and columns	266,71	Steel rolled profiles, ECI = 0,47 €/kg
Foundation piles	275,40 m^3	In-situ concrete C30/37 CEM I reinf. 200 kg/m^3, ECI = 72,51 €/m^3
ECI value	**€215130,58**	**Increase: 12,74%**

D
Concrete variant

This appendix gives a more elaborate overview of the loads that were used as input for for the BSDT and gives an overview of the outputted unity checks, member cross sections and ECI value as well. The structure consists of concrete beams and columns. The beams support the floors and the roof, which consist of hollow-core elements or solid reinforced concrete slabs. As mentioned before the BSDT does not implement a stability system such as a concrete core or braces. As introduced in Chapter 7, the spans of the beams are between 2,25 and 4,10 meters. The columns parts have a minimum length of 3,04 meters and a maximum length of 3,25 meters. The foundation consists of Fundex pile with a diameter of 540 mm reaching down to -32,5 meters NAP. The number of piles needed is calculated by dividing the total weight of the building by the capacity of one pile, which is 2000 kN.

Figure D.1 shows a top view of the building Urban Woods as modelled in the BSDT. The grid sizes can be seen and the different types of beams are shown. The beams are split in four categories because the floors transfer load in one direction only. This leads to primary and secondary beams, where the primary beams are the ones that take up the load transferred by the floor. The secondary beams are not loaded by the floors. A sub categorization is made between beams along the façade and the ones that are not placed at the façade, which are called internal beams. The different types of beams can be seen in Figure D.1. The load transfer direction of the floors is indicated in this figure as well. Even though the secondary beams do not cary any of the load it is not possible to remove them in the BSDT.

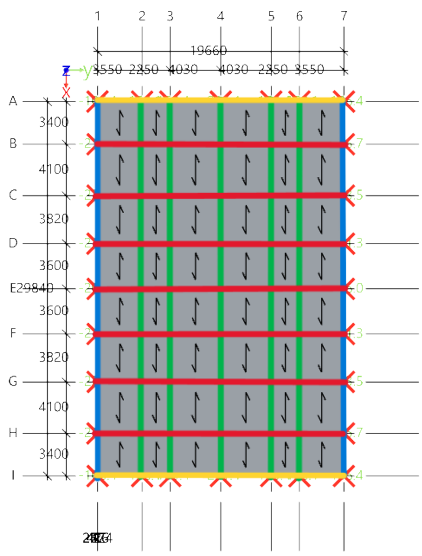

Figure D.1: Primary internal beams (red), primary façade beams (yellow), secondary internal beams (green) and secondary façade beams (blue)

D.1. Standard building

Table D.1: Inputted loads and outputted information for a concrete building without greenery system

INPUT		
Load type	**Value**	**Notes**
Roof, dead load	1,5 kN/m^2	1,5 kN/m^2 roof finishing
Roof, live load	1,0 kN/m^2	Category H: inaccessible roof
Roof, snow load	0,56 kN/m^2	
Roof, façade beam, dead load	0 kN/m	
Roof, façade beam, live load	0 kN/m	
Floors, dead load	1,8 kN/m^2	1,8 kN/m^2 floor finishing
Floors, live load	2,95 kN/m^2	1,75 kN/m^2 Category A: private floors, 1,2 kN/m^2 walls
Floors, façade beam, dead load	0 kN/m	
Floors, façade beam, live load	0 kN/m	
OUTPUT		
Location	**Element size**	**Notes**
Roof	Dycore K150-8	max. u.c. = 0,57
Floors	Dycore K150-8	max. u.c. = 0,57
Beams, internal primary	200x400	max. u.c. roof = 0,74, max. u.c. floors = 0,77
Beams, internal secondary	200x400	max. u.c. roof = 0,76, max. u.c. floors = 0,76
Beams, façade primary	300x600	max. u.c. roof = 0,56, max. u.c. floors = 0,73
Beams, façade secondary	200x400	max. u.c. roof = 0,76, max. u.c. floors = 0,76
Columns	600x600	max. u.c. = 0,23
Foundation piles	Fundex pile ∅540	43 piles with capacity 2000 kN
Element types	**Total mass or volume**	**ECI class**
Roof and floors	879,98 m^3	Precast concrete hollowcore slab, ECI = 81,18 €/m^3
Beams and columns	517,26 m^3	In-situ concrete C30/37 CEM I reinf. 100 kg/m^3, ECI = 57,61 €/m^3
Foundation piles	320,06 m^3	In-situ concrete C30/37 CEM I reinf. 200 kg/m^3, ECI = 72,51 €/m^3
ECI value	**€143353,02**	

D.2. Standard roof terrace

Table D.2: Inputted loads and outputted information for a concrete building with a standard roof terrace

	INPUT	
Load type	**Value**	**Notes**
Roof, dead load	2,75 kN/m^2	1,5 kN/m^2 roof finishing, 1,25 kN/m^2 concrete tiles
Roof, live load	3,0 kN/m^2	Category A: communal floors, stairs and balconies
Roof, snow load	0,56 kN/m^2	
Roof, façade beam, dead load	0 kN/m	
Roof, façade beam, live load	0 kN/m	
Floors, dead load	1,8 kN/m^2	1,8 kN/m^2 floor finishing
Floors, live load	2,95 kN/m^2	1,75 kN/m^2 Category A: private floors, 1,2 kN/m^2 walls
Floors, façade beam, dead load	0 kN/m	
Floors, façade beam, live load	0 kN/m	
	OUTPUT	
Location	**Element size**	**Notes**
Roof	Dycore K150-8	max. u.c. = 0,57
Floors	Dycore K150-8	max. u.c. = 0,57
Beams, internal primary	200x400	max. u.c. roof = 0,87, max. u.c. floors = 0,77
Beams, internal secondary	200x400	max. u.c. roof = 0,76, max. u.c. floors = 0,76
Beams, façade primary	300x600	max. u.c. roof = 0,82, max. u.c. floors = 0,73
Beams, façade secondary	200x400	max. u.c. roof = 0,76, max. u.c. floors = 0,76
Columns	600x600	max. u.c. = 0,24
Foundation piles	Fundex pile ∅540	44 piles with capacity 2000 kN
Element types	**Total mass or volume**	**ECI class**
Roof and floors	879,98 m^3	Precast concrete hollowcore slab, ECI = 81,18 €/m^3
Beams and columns	517,26 m^3	In-situ concrete C30/37, ECI = 57,61 €/m^3
Foundation piles	327,50 m^3	In-situ concrete C30/37 CEM I reinf. 200 kg/m^3, ECI = 72,51 €/m^3
ECI value	**€143892,70**	**Increase: 0,38%**

D.3. Lightweight green roof

Table D.3: Inputted loads and outputted information for a concrete building with EGRLW

INPUT		
Load type	**Value**	**Notes**
Roof, dead load	2,05 kN/m^2	1,5 kN/m^2 roof finishing, 0,55 kN/m^2 green roof
Roof, live load	1,0 kN/m^2	Category H: inaccessible roof
Roof, snow load	0,56 kN/m^2	
Roof, façade beam, dead load	0 kN/m	
Roof, façade beam, live load	0 kN/m	
Floors, dead load	1,8 kN/m^2	1,8 kN/m^2 floor finishing
Floors, live load	2,95 kN/m^2	1,75 kN/m^2 Category A: private floors, 1,2 kN/m^2 walls
Floors, façade beam, dead load	0 kN/m	
Floors, façade beam, live load	0 kN/m	
OUTPUT		
Location	**Element size**	**Notes**
Roof	Dycore K150-8	max. u.c. = 0,57
Floors	Dycore K150-8	max. u.c. = 0,57
Beams, internal primary	200x400	max. u.c. roof = 0,74, max. u.c. floors = 0,77
Beams, internal secondary	200x400	max. u.c. roof = 0,76, max. u.c. floors = 0,76
Beams, façade primary	300x600	max. u.c. roof = 0,60, max. u.c. floors = 0,73
Beams, façade secondary	200x400	max. u.c. roof = 0,76, max. u.c. floors = 0,76
Columns	600x600	max. u.c. = 0,23
Foundation piles	Fundex pile ∅540	43 piles with capacity 2000 kN
Element types	**Total mass or volume**	**ECI class**
Roof and floors	879,98 m^3	Precast concrete hollowcore slab, ECI = 81,18 €/m^3
Beams and columns	517,26 m^3	In-situ concrete C30/37 CEM I reinf. 100 kg/m^3, ECI = 57,61 €/m^3
Foundation piles	320,06 m^3	In-situ concrete C30/37 CEM I reinf. 200 kg/m^3, ECI = 72,51 €/m^3
ECI value	**€143353,02**	**Increase: 0%**

D.4. Biosolar green roof

Table D.4: Inputted loads and outputted information for a steel building with EGRBS

INPUT		
Load type	**Value**	**Notes**
Roof, dead load	2,7 kN/m^2	1,5 kN/m^2 roof finishing, 1,2 kN/m^2 green roof
Roof, live load	1,0 kN/m^2	Category H: inaccessible roof
Roof, snow load	1,2 kN/m^2	Increased value due to possible snow accumulation
Roof, façade beam, dead load	0 kN/m	
Roof, façade beam, live load	0 kN/m	
Floors, dead load	1,8 kN/m^2	1,8 kN/m^2 floor finishing
Floors, live load	2,95 kN/m^2	1,75 kN/m^2 Category A: private floors, 1,2 kN/m^2 walls
Floors, façade beam, dead load	0 kN/m	
Floors, façade beam, live load	0 kN/m	
OUTPUT		
Location	**Element size**	**Notes**
Roof	Dycore K150-8	max. u.c. = 0,57
Floors	Dycore K150-8	max. u.c. = 0,57
Beams, internal primary	200x400	max. u.c. roof = 0,74, max. u.c. floors = 0,77
Beams, internal secondary	200x400	max. u.c. roof = 0,76, max. u.c. floors = 0,76
Beams, façade primary	300x600	max. u.c. roof = 0,67, max. u.c. floors = 0,73
Beams, façade secondary	200x400	max. u.c. roof = 0,76, max. u.c. floors = 0,76
Columns	600x600	max. u.c. = 0,23
Foundation piles	Fundex pile ∅540	43 piles with capacity 2000 kN
Element types	**Total mass or volume**	**ECI class**
Roof and floors	879,98 m^3	Precast concrete hollowcore slab, ECI = 81,18 €/m^3
Beams and columns	517,26 m^3	In-situ concrete C30/37 CEM I reinf. 100 kg/m^3, ECI = 57,61 €/m^3
Foundation piles	320,06 m^3	In-situ concrete C30/37 CEM I reinf. 200 kg/m^3, ECI = 72,51 €/m^3
ECI value	**€143353,02**	**Increase: 0%**

D.5. Nature roof

Table D.5: Inputted loads and outputted information for a concrete building with EGRN

INPUT		
Load type	**Value**	**Notes**
Roof, dead load	2,45 kN/m^2	1,5 kN/m^2 roof finishing, 0,95 kN/m^2 green roof
Roof, live load	3,0 kN/m^2	Category A: communal floors, stairs and balconies
Roof, snow load	0,56 kN/m^2	
Roof, façade beam, dead load	0 kN/m	
Roof, façade beam, live load	0 kN/m	
Floors, dead load	1,8 kN/m^2	1,8 kN/m^2 floor finishing
Floors, live load	2,95 kN/m^2	1,75 kN/m^2 Category A: private floors, 1,2 kN/m^2 walls
Floors, façade beam, dead load	0 kN/m	
Floors, façade beam, live load	0 kN/m	
OUTPUT		
Location	**Element size**	**Notes**
Roof	Dycore K150-8	max. u.c. = 0,57
Floors	Dycore K150-8	max. u.c. = 0,57
Beams, internal primary	200x400	max. u.c. roof = 0,84, max. u.c. floors = 0,77
Beams, internal secondary	200x400	max. u.c. roof = 0,76, max. u.c. floors = 0,76
Beams, façade primary	300x600	max. u.c. roof = 0,79, max. u.c. floors = 0,73
Beams, façade secondary	200x400	max. u.c. roof = 0,76, max. u.c. floors = 0,76
Columns	600x600	max. u.c. = 0,24
Foundation piles	Fundex pile ∅540	44 piles with capacity 2000 kN
Element types	**Total mass or volume**	**ECI class**
Roof and floors	879,98 m^3	Precast concrete hollowcore slab, ECI = 81,18 €/m^3
Beams and columns	517,26 m^3	In-situ concrete C30/37, ECI = 57,61 €/m^3
Foundation piles	327,50 m^3	In-situ concrete C30/37 CEM I reinf. 200 kg/m^3, ECI = 72,51 €/m^3
ECI value	**€143892,70**	**Increase: 0,38%**

D.6. Extensive retention blue roof

Table D.6: Inputted loads and outputted information for a concrete building with EGRR

INPUT		
Load type	**Value**	**Notes**
Roof, dead load	4,0 kN/m^2	1,5 kN/m^2 roof finishing, 1,0 kN/m^2 green roof, 1,5 kN/m^2 water storage
Roof, live load	1,0 kN/m^2	Category H: inaccessible roof
Roof, snow load	0,56 kN/m^2	
Roof, façade beam, dead load	0 kN/m	
Roof, façade beam, live load	0 kN/m	
Floors, dead load	1,8 kN/m^2	1,8 kN/m^2 floor finishing
Floors, live load	2,95 kN/m^2	1,75 kN/m^2 Category A: private floors, 1,2 kN/m^2 walls
Floors, façade beam, dead load	0 kN/m	
Floors, façade beam, live load	0 kN/m	
OUTPUT		
Location	**Element size**	**Notes**
Roof	Dycore K150-8	max. u.c. = 0,61
Floors	Dycore K150-8	max. u.c. = 0,57
Beams, internal primary	200x400	max. u.c. roof = 0,78, max. u.c. floors = 0,77
Beams, internal secondary	200x400	max. u.c. roof = 0,76, max. u.c. floors = 0,76
Beams, façade primary	300x600	max. u.c. roof = 0,75, max. u.c. floors = 0,73
Beams, façade secondary	200x400	max. u.c. roof = 0,76, max. u.c. floors = 0,76
Columns	600x600	max. u.c. = 0,24
Foundation piles	Fundex pile ∅540	44 piles with capacity 2000 kN
Element types	**Total mass or volume**	**ECI class**
Roof and floors	879,98 m^3	Precast concrete hollow core slab, ECI = 81,18 €/m^3
Beams and columns	517,26 m^3	In-situ concrete C30/37, ECI = 57,61 €/m^3
Foundation piles	327,50 m^3	In-situ concrete C30/37 CEM I reinf. 200 kg/m^3, ECI = 72,51 €/m^3
ECI value	**€143892,70**	**Increase: 0,38%**

D.7. Intensive retention blue roof

Table D.7: Inputted loads and outputted information for a concrete building with IGRR

INPUT		
Load type	**Value**	**Notes**
Roof, dead load	8,3 kN/m^2	1,5 kN/m^2 roof finishing, 3,1 kN/m^2 green roof, 3,7 kN/m^2 water storage
Roof, live load	3,0 kN/m^2	Category A: communal floors, stairs and balconies
Roof, snow load	0,56 kN/m^2	
Roof, façade beam, dead load	0 kN/m	
Roof, façade beam, live load	0 kN/m	
Floors, dead load	1,8 kN/m^2	1,8 kN/m^2 floor finishing
Floors, live load	2,95 kN/m^2	1,75 kN/m^2 Category A: private floors, 1,2 kN/m^2 walls
Floors, façade beam, dead load	0 kN/m	
Floors, façade beam, live load	0 kN/m	
OUTPUT		
Location	**Element size**	**Notes**
Roof	One-way slab t=160 mm	max. u.c. = 0,90
Floors	Dycore K150-8	max. u.c. = 0,57
Beams, internal primary	300x500	max. u.c. roof = 0,84, max. u.c. floors = 0,90
Beams, internal secondary	200x400	max. u.c. roof = 0,76, max. u.c. floors = 0,76
Beams, façade primary	350x700	max. u.c. roof = 0,90, max. u.c. floors = 0,62
Beams, façade secondary	200x400	max. u.c. roof = 0,76, max. u.c. floors = 0,76
Columns	600x600	max. u.c. = 0,26
Foundation piles	Fundex pile ∅540	48 piles with capacity 2000 kN
Element types	**Total mass or volume**	**ECI class**
Roof	93,86 m^3	In-situ concrete, ECI = 57,61 €/m^3
Floors	791,98 m^3	Precast concrete hollowcore slab, ECI = 81,18 €/m^3
Beams and columns	639,16 m^3	In-situ concrete C30/37, ECI = 57,61 €/m^3
Foundation piles	357,27 m^3	In-situ concrete C30/37 CEM I reinf. 200 kg/m^3, ECI = 72,51 €/m^3
ECI value	**€151336,96**	**Increase: 5,57%**

D.8. Garden roof

Table D.8: Inputted loads and outputted information for a concrete building with IGRG

INPUT		
Load type	**Value**	**Notes**
Roof, dead load	7,5 kN/m^2	1,5 kN/m^2 roof finishing, 6 kN/m^2 green roof
Roof, live load	3,0 kN/m^2	Category A: communal floors, stairs and balconies
Roof, snow load	0,56 kN/m^2	
Roof, façade beam, dead load	0 kN/m	
Roof, façade beam, live load	0 kN/m	
Floors, dead load	1,8 kN/m^2	1,8 kN/m^2 floor finishing
Floors, live load	2,95 kN/m^2	1,75 kN/m^2 Category A: private floors, 1,2 kN/m^2 walls
Floors, façade beam, dead load	0 kN/m	
Floors, façade beam, live load	0 kN/m	

OUTPUT		
Location	**Element size**	**Notes**
Roof	One-way slab t=160 mm	max. u.c. = 0,9
Floors	Dycore K150-8	max. u.c. = 0,57
Beams, internal primary	300x500	max. u.c. roof = 0,80, max. u.c. floors = 0,90
Beams, internal secondary	200x400	max. u.c. roof = 0,76, max. u.c. floors = 0,76
Beams, façade primary	350x700	max. u.c. roof = 0,87, max. u.c. floors = 0,62
Beams, façade secondary	200x400	max. u.c. roof = 0,76, max. u.c. floors = 0,76
Columns	600x600	max. u.c. = 0,26
Foundation piles	Fundex pile ∅540	48 piles with capacity 2000 kN
Element types	**Total mass or volume**	**ECI class**
Roof	93,86 m^3	In-situ concrete, ECI = 57,61 €/m^3
Floors	791,98 m^3	Precast concrete hollowcore slab, ECI = 81,18 €/m^3
Beams and columns	639,16 m^3	In-situ concrete C30/37, ECI = 57,61 €/m^3
Foundation piles	357,27 m^3	In-situ concrete C30/37 CEM I reinf. 200 kg/m^3, ECI = 72,51 €/m^3
ECI value	**€151336,96**	**Increase: 5,57%**

D.9. Direct green façade

Table D.9: Inputted loads and outputted information for a concrete building with DGF

INPUT		
Load type	**Value**	**Notes**
Roof, dead load	1,5 kN/m^2	1,5 kN/m^2 roof finishing
Roof, live load	1,0 kN/m^2	Category H: inaccessible roof
Roof, snow load	0,56 kN/m^2	
Roof, façade beam, dead load	0,08 kN/m	
Roof, façade beam, live load	0 kN/m	
Floors, dead load	1,8 kN/m^2	1,8 kN/m^2 floor finishing
Floors, live load	2,95 kN/m^2	1,75 kN/m^2 Category A: private floors, 1,2 kN/m^2 walls
Floors, façade beam, dead load	0,15 kN/m	
Floors, façade beam, live load	0 kN/m	
OUTPUT		
Location	**Element size**	**Notes**
Roof	Dycore K150-8	max. u.c. = 0,57
Floors	Dycore K150-8	max. u.c. = 0,57
Beams, internal primary	200x400	max. u.c. roof = 0,86, max. u.c. floors = 0,77
Beams, internal secondary	200x400	max. u.c. roof = 0,76, max. u.c. floors = 0,76
Beams, façade primary	300x600	max. u.c. roof = 0,57, max. u.c. floors = 0,74
Beams, façade secondary	200x400	max. u.c. roof = 0,76, max. u.c. floors = 0,76
Columns	600x600	max. u.c. = 0,23
Foundation piles	Fundex pile ∅540	43 piles with capacity 2000 kN
Element types	**Total mass or volume**	**ECI class**
Roof and floors	879,98 m^3	Precast concrete hollowcore slab, ECI = 81,18 €/m^3
Beams and columns	517,26 m^3	In-situ concrete C30/37 CEM I reinf. 100 kg/m^3, ECI = 57,61 €/m^3
Foundation piles	320,06 m^3	In-situ concrete C30/37 CEM I reinf. 200 kg/m^3, ECI = 72,51 €/m^3
ECI value	**€143353,02**	**Increase: 0%**

D.10. Indirect green façade with modular trellis, indirect green façade with continuous guides

Table D.10: Inputted loads and outputted information for a concrete building with IGFT or IGFC

INPUT		
Load type	**Value**	**Notes**
Roof, dead load	1,5 kN/m^2	1,5 kN/m^2 roof finishing
Roof, live load	1,0 kN/m^2	Category H: inaccessible roof
Roof, snow load	0,56 kN/m^2	
Roof, façade beam, dead load	0,46 kN/m	
Roof, façade beam, live load	0 kN/m	
Floors, dead load	1,8 kN/m^2	1,8 kN/m^2 floor finishing
Floors, live load	2,95 kN/m^2	1,75 kN/m^2 Category A: private floors, 1,2 kN/m^2 walls
Floors, façade beam, dead load	0,90 kN/m	
Floors, façade beam, live load	0 kN/m	
OUTPUT		
Location	**Element size**	**Notes**
Roof	Dycore K150-8	max. u.c. = 0,57
Floors	Dycore K150-8	max. u.c. = 0,57
Beams, internal primary	200x400	max. u.c. roof = 0,86, max. u.c. floors = 0,77
Beams, internal secondary	200x400	max. u.c. roof = 0,76, max. u.c. floors = 0,76
Beams, façade primary	300x600	max. u.c. roof = 0,58, max. u.c. floors = 0,77
Beams, façade secondary	200x400	max. u.c. roof = 0,76, max. u.c. floors = 0,76
Columns	600x600	max. u.c. = 0,23
Foundation piles	Fundex pile ∅540	43 piles with capacity 2000 kN
Element types	**Total mass or volume**	**ECI class**
Roof and floors	879,98 m^3	Precast concrete hollowcore slab, ECI = 81,18 €/m^3
Beams and columns	517,26 m^3	In-situ concrete C30/37 CEM I reinf. 100 kg/m^3, ECI = 57,61 €/m^3
Foundation piles	320,06 m^3	In-situ concrete C30/37 CEM I reinf. 200 kg/m^3, ECI = 72,51 €/m^3
ECI value	**€143353,02**	**Increase: 0%**

D.11. Continuous living wall system, modular living wall system with modular framed boxes, modular living wall system with modular trays

Table D.11: Inputted loads and outputted information for a concrete building with LWSC, LWSMB or LWSMT

	INPUT	
Load type	**Value**	**Notes**
Roof, dead load	1,5 kN/m^2	1,5 kN/m^2 roof finishing
Roof, live load	1,0 kN/m^2	Category H: inaccessible roof
Roof, snow load	0,56 kN/m^2	
Roof, façade beam, dead load	0,77 kN/m	
Roof, façade beam, live load	0 kN/m	
Floors, dead load	1,8 kN/m^2	1,8 kN/m^2 floor finishing
Floors, live load	2,95 kN/m^2	1,75 kN/m^2 Category A: private floors, 1,2 kN/m^2 walls
Floors, façade beam, dead load	1,51 kN/m	
Floors, façade beam, live load	0 kN/m	
	OUTPUT	
Location	**Element size**	**Notes**
Roof	Dycore K150-8	max. u.c. = 0,57
Floors	Dycore K150-8	max. u.c. = 0,57
Beams, internal primary	200x400	max. u.c. roof = 0,86, max. u.c. floors = 0,77
Beams, internal secondary	200x400	max. u.c. roof = 0,76, max. u.c. floors = 0,76
Beams, façade primary	300x600	max. u.c. roof = 0,60, max. u.c. floors = 0,80
Beams, façade secondary	200x400	max. u.c. roof = 0,76, max. u.c. floors = 0,76
Columns	600x600	max. u.c. = 0,23
Foundation piles	Fundex pile ∅540	43 piles with capacity 2000 kN
Element types	**Total mass or volume**	**ECI class**
Roof and floors	879,98 m^3	Precast concrete hollowcore slab, ECI = 81,18 €/m^3
Beams and columns	517,26 m^3	In-situ concrete C30/37, ECI = 57,61 €/m^3
Foundation piles	320,06 m^3	In-situ concrete C30/37 CEM I reinf. 200 kg/m^3, ECI = 72,51 €/m^3
ECI value	**€143353,02**	**Increase: 0%**

D.12. Linear living wall system

Table D.12: Inputted loads and outputted information for a concrete building with LWSL

INPUT		
Load type	**Value**	**Notes**
Roof, dead load	1,5 kN/m^2	1,5 kN/m^2 roof finishing
Roof, live load	1,0 kN/m^2	Category H: inaccessible roof
Roof, snow load	0,56 kN/m^2	
Roof, façade beam, dead load	0,92 kN/m	
Roof, façade beam, live load	0 kN/m	
Floors, dead load	1,8 kN/m^2	1,8 kN/m^2 floor finishing
Floors, live load	2,95 kN/m^2	1,75 kN/m^2 Category A: private floors, 1,2 kN/m^2 walls
Floors, façade beam, dead load	1,81 kN/m	
Floors, façade beam, live load	0 kN/m	
OUTPUT		
Location	**Element size**	**Notes**
Roof	Dycore K150-8	max. u.c. = 0,57
Floors	Dycore K150-8	max. u.c. = 0,57
Beams, internal primary	200x400	max. u.c. roof = 0,86, max. u.c. floors = 0,77
Beams, internal secondary	200x400	max. u.c. roof = 0,76, max. u.c. floors = 0,76
Beams, façade primary	300x600	max. u.c. roof = 0,60, max. u.c. floors = 0,81
Beams, façade secondary	200x400	max. u.c. roof = 0,76, max. u.c. floors = 0,76
Columns	600x600	max. u.c. = 0,23
Foundation piles	Fundex pile ∅540	43 piles with capacity 2000 kN
Element types	**Total mass or volume**	**ECI class**
Roof and floors	879,98 m^3	Precast concrete hollowcore slab, ECI = 81,18 €/m^3
Beams and columns	517,26 m^3	In-situ concrete C30/37, ECI = 57,61 €/m^3
Foundation piles	320,06 m^3	In-situ concrete C30/37 CEM I reinf. 200 kg/m^3, ECI = 72,51 €/m^3
ECI value	**€143353,02**	**Increase: 0%**

D.13. Vertical forest

Table D.13: Inputted loads and outputted information for a concrete building with VF

INPUT		
Load type	**Value**	**Notes**
Roof, dead load	1,5 kN/m^2	1,5 kN/m^2 roof finishing
Roof, live load	1,0 kN/m^2	Category H: inaccessible roof
Roof, snow load	0,56 kN/m^2	
Roof, façade beam, dead load	3,0 kN/m	
Roof, façade beam, live load	1,25 kN/m	Category A: private floors
Floors, dead load	1,8 kN/m^2	1,8 kN/m^2 floor finishing
Floors, live load	2,95 kN/m^2	1,75 kN/m^2 Category A: private floors, 1,2 kN/m^2 walls
Floors, façade beam, dead load	6,0 kN/m	
Floors, façade beam, live load	2,5 kN/m	Category A: private balconies
OUTPUT		
Location	**Element size**	**Notes**
Roof	Dycore K150-8	max. u.c. = 0,57
Floors	Dycore K150-8	max. u.c. = 0,57
Beams, internal primary	200x400	max. u.c. roof = 0,86, max. u.c. floors = 0,77
Beams, internal secondary	200x400	max. u.c. roof = 0,76, max. u.c. floors = 0,76
Beams, façade primary	400x600	max. u.c. roof = 0,61, max. u.c. floors = 0,88
Beams, façade secondary	250x400	max. u.c. roof = 0,76, max. u.c. floors = 0,78
Columns	600x600	max. u.c. = 0,23
Foundation piles	Fundex pile ∅540	48 piles with capacity 2000 kN
Element types	**Total mass or volume**	**ECI class**
Roof and floors	879,98 m^3	Precast concrete hollowcore slab, ECI = 81,18 €/m^3
Beams and columns	552,79 m^3	In-situ concrete C30/37, ECI = 57,61 €/m^3
Foundation piles	357,27 m^3	In-situ concrete C30/37 CEM I reinf. 200 kg/m^3, ECI = 72,51 €/m^3
ECI value	**€148098,16**	**Increase: 3,31%**

D.14. Combination: intensive retention blue roof and vertical forest

Table D.14: Inputted loads and outputted information for a concrete building with IGRR+VF

INPUT		
Load type	**Value**	**Notes**
Roof, dead load	8,3 kN/m^2	1,5 kN/m^2 roof finishing, 3,1 kN/m^2 green roof, 3,7 kN/m^2 water storage
Roof, live load	3,0 kN/m^2	Category A: communal floors, stairs and balconies
Roof, snow load	0,56 kN/m^2	
Roof, façade beam, dead load	3,0 kN/m	
Roof, façade beam, live load	1,25 kN/m	Category A: private floors
Floors, dead load	1,8 kN/m^2	1,8 kN/m^2 floor finishing
Floors, live load	2,95 kN/m^2	1,75 kN/m^2 Category A: private floors, 1,2 kN/m^2 walls
Floors, façade beam, dead load	6,0 kN/m	
Floors, façade beam, live load	2,5 kN/m	Category A: private balconies
OUTPUT		
Location	**Element size**	**Notes**
Roof	One-way slab t=160 mm	max. u.c. = 0,9
Floors	Dycore K150-8	max. u.c. = 0,57
Beams, internal primary	300x500	max. u.c. roof = 0,70, max. u.c. floors = 0,90
Beams, internal secondary	200x400	max. u.c. roof = 0,76, max. u.c. floors = 0,76
Beams, façade primary	450x700	max. u.c. roof = 0,86, max. u.c. floors = 0,75
Beams, façade secondary	250x500	max. u.c. roof = 0,76, max. u.c. floors = 0,78
Columns	600x600	max. u.c. = 0,26
Foundation piles	Fundex pile ∅540	54 piles with capacity 2000 kN
Element types	**Total mass or volume**	**ECI class**
Roof	93,86 m^3	In-situ concrete, ECI = 57,61 €/m^3
Floors	791,98 m^3	Precast concrete hollowcore slab, ECI = 81,18 €/m^3
Beams and columns	678,62 m^3	In-situ concrete C30/37, ECI = 57,61 €/m^3
Foundation piles	401,93 m^3	In-situ concrete C30/37 CEM I reinf. 200 kg/m^3, ECI = 72,51 €/m^3
ECI value	**€156848,31**	**Increase: 9,41%**

D.15. Verification of column slenderness

The following verification is made for a concrete building without any greenery systems applied, using columns with a 600x600 mm cross section.

$$n = \frac{N_{Ed}}{A_c f_{cd}} = \frac{1915{,}43 \cdot 10^3}{600^2 \cdot 20} = 0{,}266 \tag{D.1}$$

$$\lambda_{lim} = 20 \cdot A \cdot B \cdot C/\sqrt{n} = 20 \cdot 0{,}7 \cdot 1{,}1 \cdot 0{,}7/\sqrt{0{,}266} = 20{,}90 \tag{D.2}$$

$$i = \sqrt{\frac{I}{A}} = \sqrt{\frac{\frac{1}{12} \cdot 600 \cdot 600^3}{600 \cdot 600}} = 0{,}173 \tag{D.3}$$

$$\lambda = \frac{l_0}{i} = \frac{1 \cdot 3{,}14}{0{,}173} = 18{,}13 \tag{D.4}$$

Since $\lambda < \lambda_{lim}$, this column can be seen as a short column and second order effects do not have to be taken into account.

The following verification is made for a concrete building with the application of an intensive retention blue roof (IGRR) and a vertical forest (VF), using columns with a 600x600 mm cross section.

$$n = \frac{N_{Ed}}{A_c f_{cd}} = \frac{2188{,}70 \cdot 10^3}{600^2 \cdot 20} = 0{,}304 \tag{D.5}$$

$$\lambda_{lim} = 20 \cdot A \cdot B \cdot C/\sqrt{n} = 20 \cdot 0{,}7 \cdot 1{,}1 \cdot 0{,}7/\sqrt{0{,}304} = 19{,}55 \tag{D.6}$$

The cross sections remains unchanged and therefore λ remains unchanged as well. Since $\lambda < \lambda_{lim}$, this column can be seen as a short column and second order effects do not have to be taken into account.

E
Timber variant

This appendix gives a more elaborate overview of the loads that were used as input for for the RFEM model and gives an overview of the outputted unity checks, member cross sections and ECI value as well. The finishing of the roofs and floors includes insulation, a cement screed and filling layer. The calculation results from the Calculatis tool by Stora Enso can also be found in this appendix placed behind the overview table of the appropriate situation. The structure consists of glued laminated timber (GLT) beams and columns. The beams support the floors and the roof, which consist of cross laminated timber (CLT) elements. This model did include a stability system in the form of diagonal elements and a CLT core. These elements have not been counted towards the ECI value because in the other two variants a stability system was lacking. As introduced in Chapter 8, the spans in this model all have a width of 3,60 meters. The columns parts all have a length of 3 meters. The foundation consists of Fundex pile with a diameter of 540 mm reaching down to -32,5 meters NAP. The number of piles needed is calculated by dividing the total weight of the building by the capacity of one pile, which is 2000 kN. Figure E.1 to E.3 show the different views of the timber model.

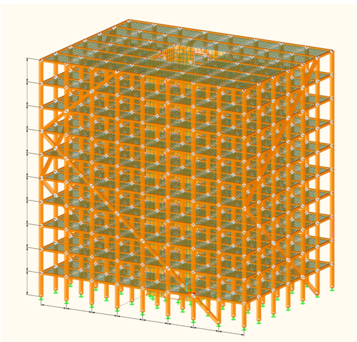

Figure E.1: 3D view of the timber model of Urban Woods

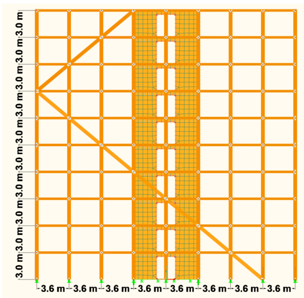

Figure E.2: Side view 1 of the timber model of Urban Woods

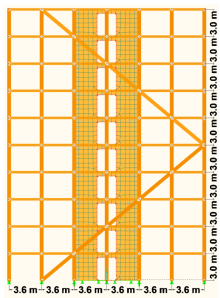

Figure E.3: Side view 2 of the timber model of Urban Woods

E.1. Standard building

Table E.1: Inputted loads and outputted information for a timber building without greenery system

INPUT		
Load type	**Value**	**Notes**
Roof, dead load	1,5 kN/m^2	1,5 kN/m^2 roof finishing
Roof, live load	1,0 kN/m^2	Category H: inaccessible roof
Roof, snow load	0,56 kN/m^2	
Roof, façade beam, dead load	0 kN/m	
Roof, façade beam, live load	0 kN/m	
Floors, dead load	2,75 kN/m^2	2,75 kN/m^2 floor finishing
Floors, live load	2,55 kN/m^2	1,75 kN/m^2 Category A: private floors, 0,8 kN/m^2 walls
Floors, façade beam, dead load	0 kN/m	
Floors, façade beam, live load	0 kN/m	
OUTPUT		
Location	**Element size**	**Notes**
Roof	CLT, t=180 mm	max. u.c. = 0,89
Floors	CLT, t=180 mm	max. u.c. = 0,76
Beams, roof	HB 280x280	max. u.c. = 0,16
Beams, floors	HB 280x280	max. u.c. = 0,34
Columns	HB 400x400	max. u.c. = 0,35
Foundation piles	Fundex pile ∅540	23 piles with capacity 2000 kN
Element types	**Total mass or volume**	**ECI class**
Roof and floors	1026,43 m^3	Timber CLT, ECI = 38,78 €/m^3
Beams and columns	182359,30	Timber GLT confifeous, ECI = 0,12 €/kg
Foundation piles	171,19 m^3	In-situ concrete C30/37 CEM I reinf. 200 kg/m^3, ECI = 72,51 €/m^3
ECI value	**€74263,74**	

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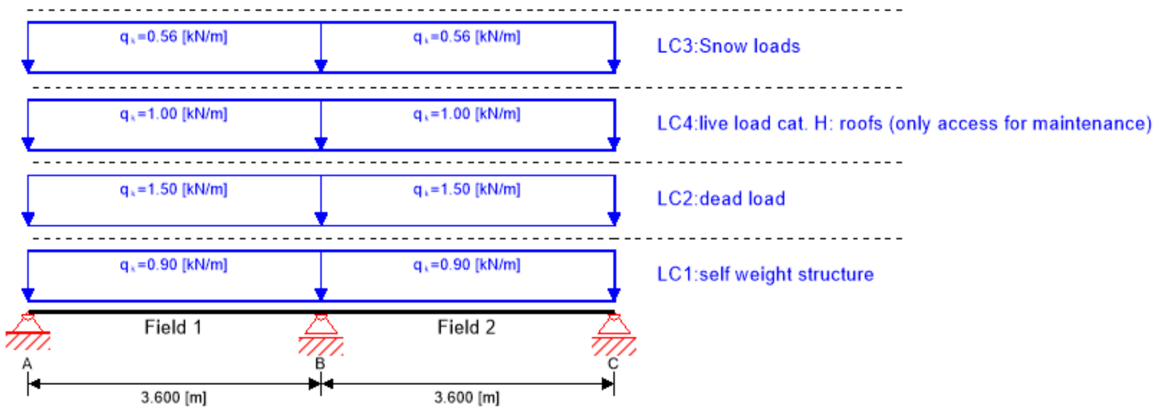
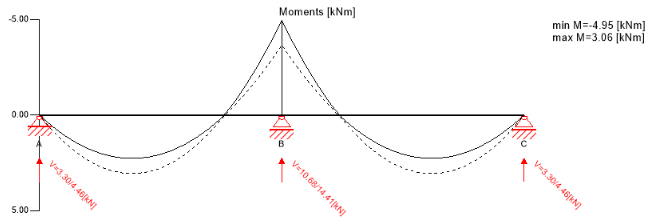
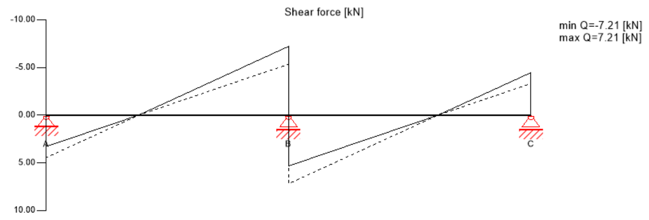
System



Section: CLT 180 L7s; **Material**: C24 spruce ETA (2022); **Service class**: service class 1; **Fire resistance class**: R 120

Utilization 89 %





Flexural stress analysis 9%

$M_{y,d}$ =	-4.95	kNm		$f_{m,k}$ =	24.00	N/mm²	
$M_{z,d}$ =	0.00	kNm		$f_{m,k,z}$ =	24.00	N/mm²	
$N_{t,d}$ =	0.00	kN		$f_{t,0,k}$ =	0.00	N/mm²	
$\sigma_{t,d}$ =	0.00	N/mm²		$f_{t,0,d}$ =	6.72	N/mm²	
$\sigma_{m,y,d}$ =	-1.16	N/mm²		$f_{m,y,d}$ =	12.67	N/mm²	
$\sigma_{m,z,d}$ =	0.00	N/mm²	<	$f_{m,z,d}$ =	0.00	N/mm²	✓

Shear stress analysis 3%

V_d =	-7.21	kN		$f_{v,k}$ =	4.00	N/mm²	
$\tau_{v,d}$ =	0.06	N/mm²	<	$f_{v,d}$ =	1.92	N/mm²	✓

Rolling shear analysis 9%

V_d =	-7.21	kN		$f_{r,k}$ =	1.25	N/mm²	
$\tau_{r,d}$ =	0.06	N/mm²	<	$f_{r,d}$ =	0.60	N/mm²	✓

w_{inst} = w[char] 9%

Field	K_{def}	Limit	w_{limit}	$w_{calc.}$	Ratio
		[-]	[mm]	[mm]	
1	0.8	L/250	14.4	1.2	8%
2	0.8	L/250	14.4	1.2	9%

w_{fin} = w[char] + w[q.p.]*kdef 13%

Field	K_{def}	Limit	w_{limit}	$w_{calc.}$	Ratio
		[-]	[mm]	[mm]	
1	0.8	L/250	14.4	1.8	13%
2	0.8	L/250	14.4	1.9	13%

$w_{net,fin}$ = w[frq] - w[D.L] + w[q.p.]*kdef 6%

Field	K_{def}	Limit	w_{limit}	$w_{calc.}$	Ratio
		[-]	[mm]	[mm]	
1	0.8	L/333	10.8	0.7	6%
2	0.8	L/333	10.8	0.7	6%

Flexural stress analysis Fire							**89%**
$M_{y,d}$ =	-4.07	kNm		$f_{m,k}$ =	24.00	N/mm²	
$M_{z,d}$ =	0.00	kNm		$f_{m,k,z}$ =	24.00	N/mm²	
$N_{t,d}$ =	0.00	kN		$f_{t,0,k}$ =	0.00	N/mm²	
$\sigma_{t,d}$ =	0.00	N/mm²		$f_{t,0,d}$ =	16.10	N/mm²	
$\sigma_{m,y,d}$ =	27.12	N/mm²		$f_{m,y,d}$ =	30.36	N/mm²	
$\sigma_{m,z,d}$ =	0.00	N/mm²	$<$	$f_{m,z,d}$ =	0.00	N/mm²	✓

Shear stress analysis Fire							**6%**
V_d =	-5.65	kN		$f_{v,k}$ =	4.00	N/mm²	
$\tau_{v,d}$ =	0.28	N/mm²	$<$	$f_{v,d}$ =	4.60	N/mm²	✓

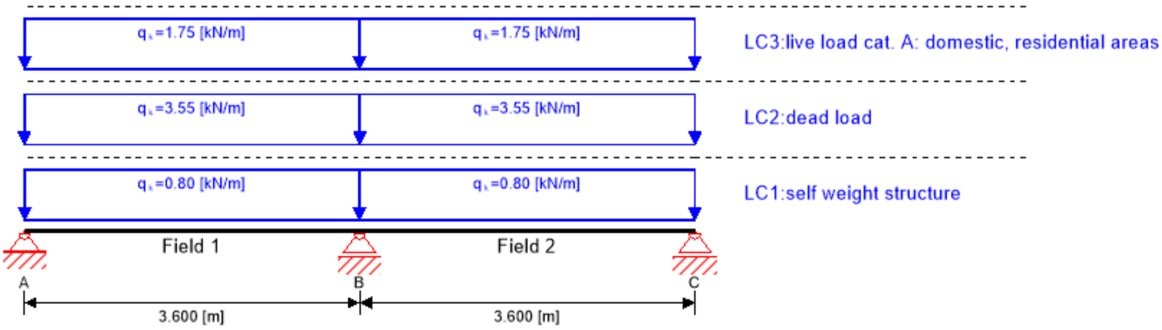
Rolling shear analysis Fire							**0%**
V_d =	-5.40	kN		$f_{r,k}$ =	1.25	N/mm²	
$\tau_{r,d}$ =	0.00	N/mm²	$<$	$f_{r,d}$ =	1.44	N/mm²	✓

Support reaction

Load case category	k_{mod}	A_V	B_V	C_V
			[kN]	
self weight structure	0.6	1.24	4.00	1.24
		1.24	4.00	1.24
dead load	0.6	2.06	6.67	2.06
		2.06	6.67	2.06
Snow loads	0.9	0.77	2.49	0.77
		0.00	0.00	0.00
live load cat. H: roofs (only access for maintenance)	0.9	1.59	4.45	1.59
		-0.21	0.00	-0.21

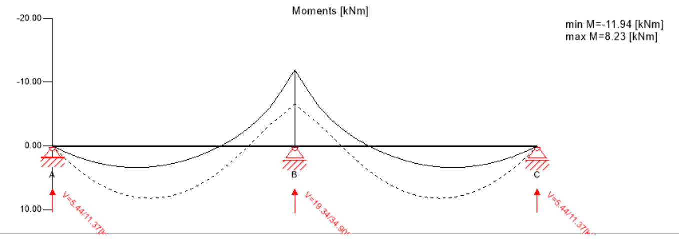
Disclaimer

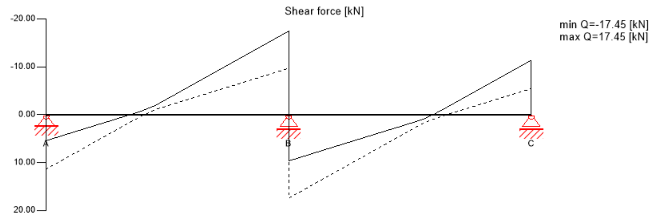
System



Section: CLT 160 L5s - 2; **Material**: C24 spruce ETA (2022); **Service class**: service class 1; **Fire resistance class**: R 120

Utilization 76 %





Flexural stress analysis 17%

$M_{y,d}$ =	-11.94	kNm		$f_{m,k}$ =	24.00	N/mm²
$M_{z,d}$ =	0.00	kNm		$f_{m,k,z}$ =	24.00	N/mm²
$N_{t,d}$ =	0.00	kN		$f_{t,0,k}$ =	0.00	N/mm²
$\sigma_{t,d}$ =	0.00	N/mm²		$f_{t,0,d}$ =	8.96	N/mm²
$\sigma_{m,y,d}$ =	-2.84	N/mm²		$f_{m,y,d}$ =	16.90	N/mm²
$\sigma_{m,z,d}$ =	0.00	N/mm²	<	$f_{m,z,d}$ =	0.00	N/mm² ✓

Shear stress analysis 6%

V_d =	-17.45	kN		$f_{v,k}$ =	4.00	N/mm²
$\tau_{v,d}$ =	0.16	N/mm²	<	$f_{v,d}$ =	2.56	N/mm² ✓

Rolling shear analysis 23%

V_d =	17.45	kN		$f_{r,k}$ =	1.05	N/mm²
$\tau_{r,d}$ =	0.16	N/mm²	<	$f_{r,d}$ =	0.67	N/mm² ✓

w_{inst} = w[char] 18%

Field	K_{def}	Limit	w_{limit}	$w_{calc.}$	Ratio
		[-]	[mm]	[mm]	
1	0.8	L/250	14.4	2.5	18%
2	0.8	L/250	14.4	2.6	18%

w_{fin} = w[char] + w[q.p.]*kdef 29%

Field	K_{def}	Limit	w_{limit}	$w_{calc.}$	Ratio
		[-]	[mm]	[mm]	
1	0.8	L/250	14.4	4.1	28%
2	0.8	L/250	14.4	4.1	29%

$w_{net,fin}$ = w[frq] - w[D.L] + w[q.p.]*kdef 19%

Field	K_{def}	Limit	w_{limit}	$w_{calc.}$	Ratio
		[-]	[mm]	[mm]	
1	0.8	L/333	10.8	2.0	18%
2	0.8	L/333	10.8	2.0	19%

Flexural stress analysis Fire — 76%

$M_{y,d}$ =	-8.46	kNm		$f_{m,k}$ =	24.00	N/mm²	
$M_{z,d}$ =	0.00	kNm		$f_{m,k,z}$ =	24.00	N/mm²	
$N_{t,d}$ =	0.00	kN		$f_{t,0,k}$ =	0.00	N/mm²	
$\sigma_{t,d}$ =	0.00	N/mm²		$f_{t,0,d}$ =	16.10	N/mm²	
$\sigma_{m,y,d}$ =	-22.97	N/mm²		$f_{m,y,d}$ =	30.36	N/mm²	
$\sigma_{m,z,d}$ =	0.00	N/mm²	<	$f_{m,z,d}$ =	0.00	N/mm²	✓

Shear stress analysis Fire — 8%

V_d =	-11.75	kN		$f_{v,k}$ =	4.00	N/mm²	
$\tau_{v,d}$ =	0.38	N/mm²	<	$f_{v,d}$ =	4.60	N/mm²	✓

Rolling shear analysis Fire — 0%

V_d =	-11.75	kN		$f_{r,k}$ =	1.25	N/mm²	
$\tau_{r,d}$ =	0.00	N/mm²	<	$f_{r,d}$ =	1.44	N/mm²	✓

Support reaction

Load case category	k_{mod}	A_V	B_V [kN]	C_V
self weight structure	0.6	1.10	3.56	1.10
		1.10	3.56	1.10
dead load	0.6	4.89	15.78	4.89
		4.89	15.78	4.89
live load cat. A: domestic, residential areas	0.8	2.78	7.78	2.78
		-0.37	0.00	-0.37

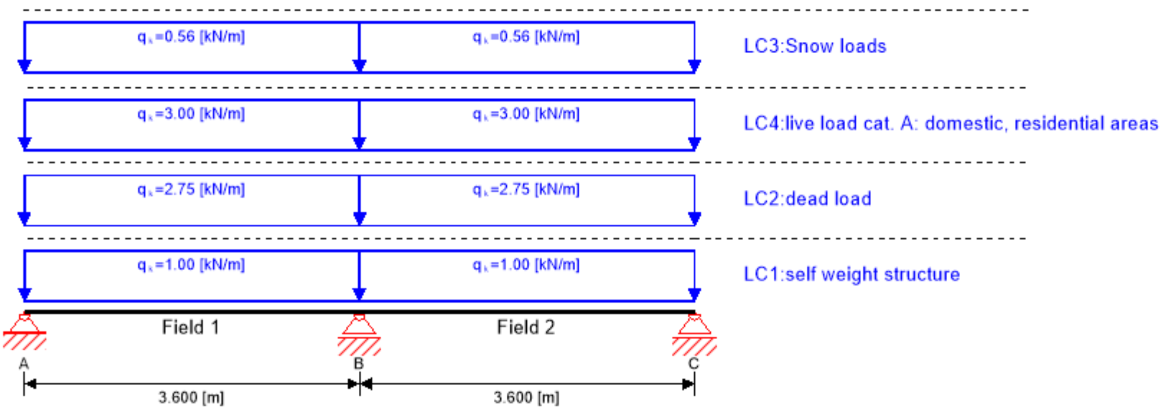
Disclaimer

E.2. Standard roof terrace

Table E.2: Inputted loads and outputted information for a timber building with a standard roof terrace

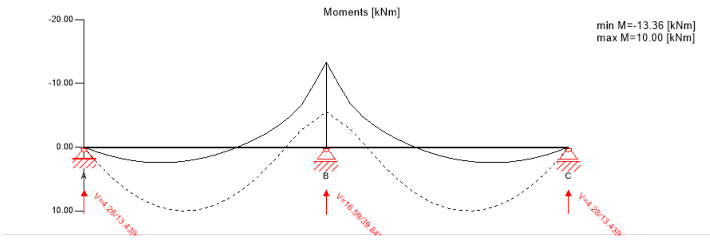
INPUT		
Load type	**Value**	**Notes**
Roof, dead load	2,75 kN/m^2	1,5 kN/m^2 roof finishing, 1,25 kN/m^2 concrete tiles
Roof, live load	3,0 kN/m^2	Category A: communal floors, stairs and balconies
Roof, snow load	0,56 kN/m^2	
Roof, façade beam, dead load	0 kN/m	
Roof, façade beam, live load	0 kN/m	
Floors, dead load	2,75 kN/m^2	2,75 kN/m^2 floor finishing
Floors, live load	2,55 kN/m^2	1,75 kN/m^2 Category A: private floors, 0,8 kN/m^2 walls
Floors, façade beam, dead load	0 kN/m	
Floors, façade beam, live load	0 kN/m	
OUTPUT		
Location	**Element size**	**Notes**
Roof	CLT, t=200 mm	max. u.c. = 0,34
Floors	CLT, t=180 mm	max. u.c. = 0,76
Beams, roof	HB 280x280	max. u.c. = 0,34
Beams, floors	HB 280x280	max. u.c. = 0,34
Columns	HB 420x420	max. u.c. = 0,33
Foundation piles	Fundex pile ∅540	24 piles with capacity 2000 kN
Element types	**Total mass or volume**	**ECI class**
Roof and floors	1037,84 m^3	Timber CLT, ECI = 38,78 €/m^3
Beams and columns	193517,86	Timber GLT confifeous, ECI = 0,12 €/kg
Foundation piles	178,64 m^3	In-situ concrete C30/37 CEM I reinf. 200 kg/m^3, ECI = 72,51 €/m^3
ECI value	**€76594,81**	**Increase: 3,14%**

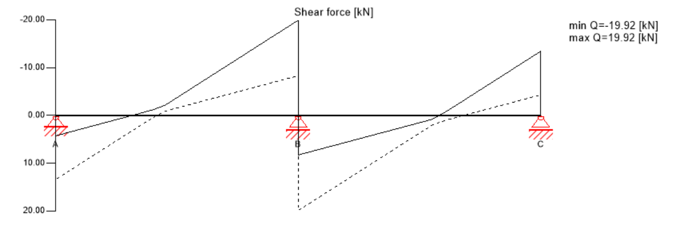
System



Section: CLT 200 L5s; **Material**: C24 spruce ETA (2022); **Service class**: service class 1; **Fire resistance class**: R 120

Utilization — 34 %





Flexural stress analysis — 15%

$M_{y,d}$ =	-13.36	kNm		$f_{m,k}$ =	24.00	N/mm²	
$M_{z,d}$ =	0.00	kNm		$f_{m,k,z}$ =	24.00	N/mm²	
$N_{t,d}$ =	0.00	kN		$f_{t,0,k}$ =	0.00	N/mm²	
$\sigma_{t,d}$ =	0.00	N/mm²		$f_{t,0,d}$ =	8.96	N/mm²	
$\sigma_{m,y,d}$ =	2.53	N/mm²		$f_{m,y,d}$ =	16.90	N/mm²	
$\sigma_{m,z,d}$ =	0.00	N/mm²	<	$f_{m,z,d}$ =	0.00	N/mm²	✓

Shear stress analysis — 5%

V_d =	-19.92	kN		$f_{v,k}$ =	4.00	N/mm²	
$\tau_{v,d}$ =	0.13	N/mm²	<	$f_{v,d}$ =	2.56	N/mm²	✓

Rolling shear analysis — 18%

V_d =	-19.92	kN		$f_{r,k}$ =	1.05	N/mm²	
$\tau_{r,d}$ =	0.12	N/mm²	<	$f_{r,d}$ =	0.67	N/mm²	✓

w_{inst} = w[char] — 15%

Field	K_{def}	Limit	w_{limit}	$w_{calc.}$	Ratio
		[-]	[mm]	[mm]	
1	0.8	L/250	14.4	2.2	15%
2	0.8	L/250	14.4	2.2	15%

w_{fin} = w[char] + w[q.p.]*kdef — 23%

Field	K_{def}	Limit	w_{limit}	$w_{calc.}$	Ratio
		[-]	[mm]	[mm]	
1	0.8	L/250	14.4	3.3	23%
2	0.8	L/250	14.4	3.3	23%

$w_{net,fin}$ = w[frq] - w[D.L] + w[q.p.]*kdef — 15%

Field	K_{def}	Limit	w_{limit}	$w_{calc.}$	Ratio
		[-]	[mm]	[mm]	
1	0.8	L/333	10.8	1.7	15%
2	0.8	L/333	10.8	1.7	15%

Flexural stress analysis Fire							**34%**
$M_{y,d}$ =	-8.35	kNm		$f_{m,k}$ =	24.00	N/mm²	
$M_{z,d}$ =	0.00	kNm		$f_{m,k,z}$ =	24.00	N/mm²	
$N_{t,d}$ =	0.00	kN		$f_{t,0,k}$ =	0.00	N/mm²	
$\sigma_{t,d}$ =	0.00	N/mm²		$f_{t,0,d}$ =	16.10	N/mm²	
$\sigma_{m,y,d}$ =	-10.37	N/mm²		$f_{m,y,d}$ =	30.36	N/mm²	
$\sigma_{m,z,d}$ =	0.00	N/mm²	$<$	$f_{m,z,d}$ =	0.00	N/mm²	✓
Shear stress analysis Fire							**3%**
V_d =	-11.77	kN		$f_{v,k}$ =	4.00	N/mm²	
$\tau_{v,d}$ =	0.16	N/mm²	$<$	$f_{v,d}$ =	4.60	N/mm²	✓
Rolling shear analysis Fire							**13%**
V_d =	-11.77	kN		$f_{r,k}$ =	1.05	N/mm²	
$\tau_{r,d}$ =	0.16	N/mm²	$<$	$f_{r,d}$ =	1.21	N/mm²	✓

Support reaction

Load case category	k_{mod}	A_V	B_V	C_V
			[kN]	
self weight structure	0.6	1.39	4.42	1.39
		1.39	4.42	1.39
dead load	0.6	3.82	12.17	3.82
		3.82	12.17	3.82
Snow loads	0.9	0.78	2.48	0.78
		0.00	0.00	0.00
live load cat. A: domestic, residential areas	0.8	4.78	13.27	4.78
		-0.62	0.00	-0.62

Disclaimer

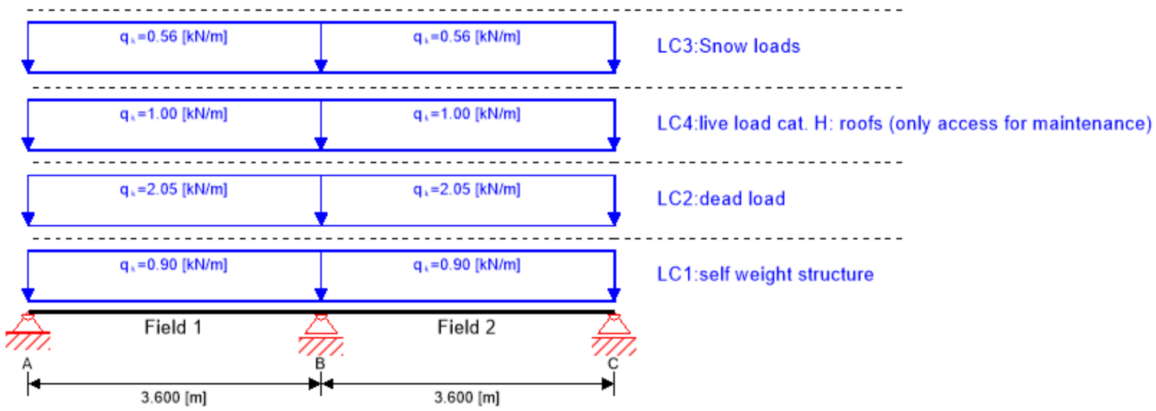
E.3. Lightweight green roof

Table E.3: Inputted loads and outputted information for a timber building with EGRLW

INPUT		
Load type	**Value**	**Notes**
Roof, dead load	2,05 kN/m^2	1,5 kN/m^2 roof finishing, 0,55 kN/m^2 green roof
Roof, live load	1,0 kN/m^2	Category H: inaccessible roof
Roof, snow load	0,56 kN/m^2	
Roof, façade beam, dead load	0 kN/m	
Roof, façade beam, live load	0 kN/m	
Floors, dead load	2,75 kN/m^2	2,75 kN/m^2 floor finishing
Floors, live load	2,55 kN/m^2	1,75 kN/m^2 Category A: private floors, 0,8 kN/m^2 walls
Floors, façade beam, dead load	0 kN/m	
Floors, façade beam, live load	0 kN/m	
OUTPUT		
Location	**Element size**	**Notes**
Roof	CLT, t=180 mm	max. u.c. = 0,61
Floors	CLT, t=180 mm	max. u.c. = 0,76
Beams, roof	HB 280x280	max. u.c. = 0,19
Beams, floors	HB 280x280	max. u.c. = 0,34
Columns	HB 400x400	max. u.c. = 0,35
Foundation piles	Fundex pile ∅540	23 piles with capacity 2000 kN
Element types	**Total mass or volume**	**ECI class**
Roof and floors	1026,43 m^3	Timber CLT, ECI = 38,78 €/m^3
Beams and columns	182359,30 kg	Timber GLT confifeous, ECI = 0,12 €/kg
Foundation piles	171,19 m^3	In-situ concrete C30/37 CEM I reinf. 200 kg/m^3, ECI = 72,51 €/m^3
ECI value	**€74263,74**	**Increase: 0%**

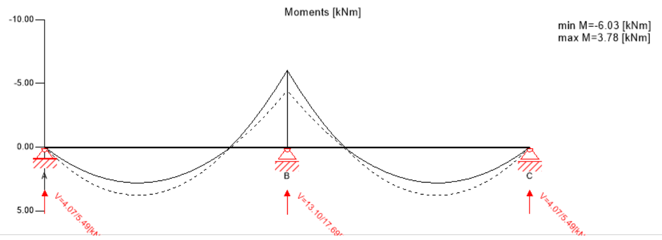
Hout vloeren UW		**1**	1/2
Roof lightweight		Netherlands	21/04/2024
BSc Joris Dekker	Delft University of Technology	Checker	

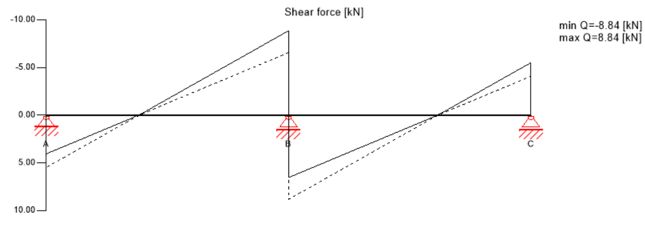
System



Section: CLT 180 L5s; **Material**: C24 spruce ETA (2022); **Service class**: service class 1; **Fire resistance class**: R 120

Utilization 61 %





Flexural stress analysis 10%

$M_{y,d}$ =	-6.03	kNm		$f_{m,k}$ =	24.00	N/mm²
$M_{z,d}$ =	0.00	kNm		$f_{m,k,z}$ =	24.00	N/mm²
$N_{t,d}$ =	0.00	kN		$f_{t,0,k}$ =	0.00	N/mm²
$\sigma_{t,d}$ =	0.00	N/mm²		$f_{t,0,d}$ =	6.72	N/mm²
$\sigma_{m,y,d}$ =	1.33	N/mm²		$f_{m,y,d}$ =	12.67	N/mm²
$\sigma_{m,z,d}$ =	0.00	N/mm²	<	$f_{m,z,d}$ =	0.00	N/mm² ✓

Shear stress analysis 3%

V_d =	-8.84	kN		$f_{v,k}$ =	4.00	N/mm²
$\tau_{v,d}$ =	0.07	N/mm²	<	$f_{v,d}$ =	1.92	N/mm² ✓

Rolling shear analysis 11%

V_d =	-8.84	kN		$f_{r,k}$ =	1.15	N/mm²
$\tau_{r,d}$ =	0.06	N/mm²	<	$f_{r,d}$ =	0.55	N/mm² ✓

w_{inst} = w[char] 10%

Field	K_{def}	Limit	w_{limit}	$w_{calc.}$	Ratio
		[-]	[mm]	[mm]	
1	0.8	L/250	14.4	1.4	10%
2	0.8	L/250	14.4	1.4	10%

w_{fin} = w[char] + w[q.p.]*kdef 15%

Field	K_{def}	Limit	w_{limit}	$w_{calc.}$	Ratio
		[-]	[mm]	[mm]	
1	0.8	L/250	14.4	2.1	15%
2	0.8	L/250	14.4	2.2	15%

$w_{net,fin}$ = w[frq] - w[D.L] + w[q.p.]*kdef 7%

Field	K_{def}	Limit	w_{limit}	$w_{calc.}$	Ratio
		[-]	[mm]	[mm]	
1	0.8	L/333	10.8	0.8	7%
2	0.8	L/333	10.8	0.8	7%

Flexural stress analysis Fire — 61%

$M_{y,d}$ =	-4.96	kNm		$f_{m,k}$ =	24.00	N/mm²	
$M_{z,d}$ =	0.00	kNm		$f_{m,k,z}$ =	24.00	N/mm²	
$N_{t,d}$ =	0.00	kN		$f_{t,0,k}$ =	0.00	N/mm²	
$\sigma_{t,d}$ =	0.00	N/mm²		$f_{t,0,d}$ =	16.10	N/mm²	
$\sigma_{m,y,d}$ =	18.59	N/mm²		$f_{m,y,d}$ =	30.36	N/mm²	
$\sigma_{m,z,d}$ =	0.00	N/mm²	<	$f_{m,z,d}$ =	0.00	N/mm²	✓

Shear stress analysis Fire — 6%

V_d =	-6.89	kN		$f_{v,k}$ =	4.00	N/mm²	
$\tau_{v,d}$ =	0.26	N/mm²	<	$f_{v,d}$ =	4.60	N/mm²	✓

Rolling shear analysis Fire — 0%

V_d =	-6.64	kN		$f_{r,k}$ =	1.15	N/mm²	
$\tau_{r,d}$ =	0.00	N/mm²	<	$f_{r,d}$ =	1.32	N/mm²	✓

Support reaction

Load case category	k_{mod}	A_V	B_V [kN]	C_V
self weight structure	0.6	1.24	4.00	1.24
		1.24	4.00	1.24
dead load	0.6	2.83	9.10	2.83
		2.83	9.10	2.83
Snow loads	0.9	0.77	2.49	0.77
		0.00	0.00	0.00
live load cat. H: roofs (only access for maintenance)	0.9	1.59	4.44	1.59
		-0.21	0.00	-0.21

Disclaimer

E.4. Biosolar green roof

Table E.4: Inputted loads and outputted information for a timber building with EGRBS

INPUT		
Load type	**Value**	**Notes**
Roof, dead load	2,7 kN/m^2	1,5 kN/m^2 roof finishing, 1,2 kN/m^2 green roof
Roof, live load	1,0 kN/m^2	Category H: inaccessible roof
Roof, snow load	1,2 kN/m^2	Increased value due to possible snow accumulation
Roof, façade beam, dead load	0 kN/m	
Roof, façade beam, live load	0 kN/m	
Floors, dead load	2,75 kN/m^2	2,75 kN/m^2 floor finishing
Floors, live load	2,55 kN/m^2	1,75 kN/m^2 Category A: private floors, 0,8 kN/m^2 walls
Floors, façade beam, dead load	0 kN/m	
Floors, façade beam, live load	0 kN/m	
OUTPUT		
Location	**Element size**	**Notes**
Roof	CLT, t=180 mm	max. u.c. = 0,77
Floors	CLT, t=180 mm	max. u.c. = 0,76
Beams, roof	HB 280x280	max. u.c. = 0,23
Beams, floors	HB 280x280	max. u.c. = 0,34
Columns	HB 420x420	max. u.c. = 0,32
Foundation piles	Fundex pile ∅540	23 piles with capacity 2000 kN
Element types	**Total mass or volume**	**ECI class**
Roof and floors	1026,43 m^3	Timber CLT, ECI = 38,78 €/m^3
Beams and columns	193517,86 kg	Timber GLT confifeous, ECI = 0,12 €/kg
Foundation piles	171,19 m^3	In-situ concrete C30/37 CEM I reinf. 200 kg/m^3, ECI = 72,51 €/m^3
ECI value	**€75612,88**	**Increase: 1,82%**

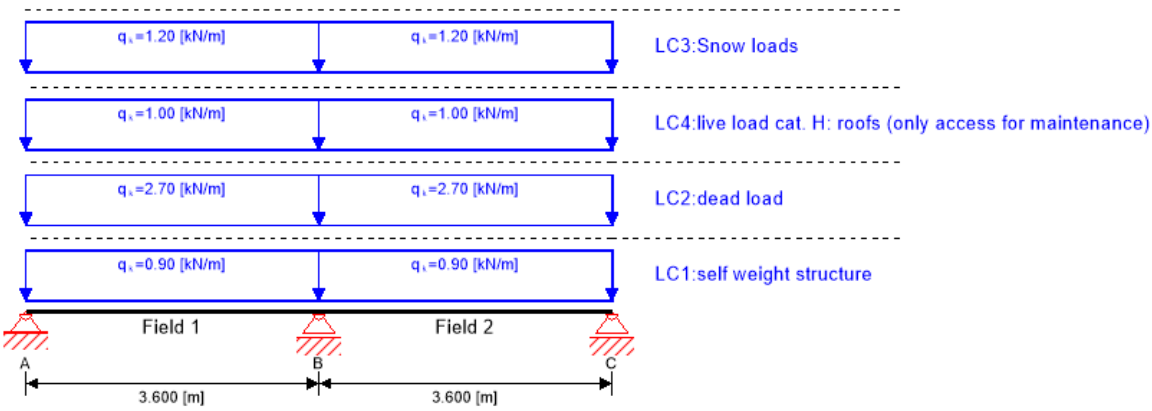
Hout vloeren UW
Roof biosolar

BSc Joris Dekker — Delft University of Technology

1
Netherlands
Checker

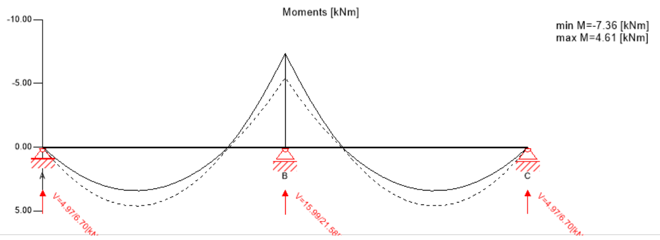
21/04/2024

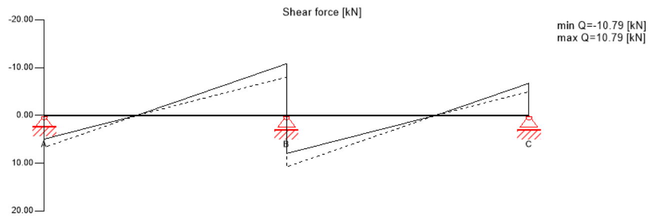
System



Section: CLT 180 L5s; **Material**: C24 spruce ETA (2022); **Service class**: service class 1; **Fire resistance class**: R 120

Utilization — 77 %





Flexural stress analysis — 13%

$M_{y,d}$ =	-7.36	kNm		$f_{m,k}$ =	24.00	N/mm²
$M_{z,d}$ =	0.00	kNm		$f_{m,k,z}$ =	24.00	N/mm²
$N_{t,d}$ =	0.00	kN		$f_{t,0,k}$ =	0.00	N/mm²
$\sigma_{t,d}$ =	0.00	N/mm²		$f_{t,0,d}$ =	6.72	N/mm²
$\sigma_{m,y,d}$ =	1.62	N/mm²		$f_{m,y,d}$ =	12.67	N/mm²
$\sigma_{m,z,d}$ =	0.00	N/mm²	<	$f_{m,z,d}$ =	0.00	N/mm² ✓

Shear stress analysis — 4%

V_d =	-10.79	kN		$f_{v,k}$ =	4.00	N/mm²
$\tau_{v,d}$ =	0.08	N/mm²	<	$f_{v,d}$ =	1.92	N/mm² ✓

Rolling shear analysis — 13%

V_d =	-10.79	kN		$f_{r,k}$ =	1.15	N/mm²
$\tau_{r,d}$ =	0.07	N/mm²	<	$f_{r,d}$ =	0.55	N/mm² ✓

w_{inst} = w[char] — 11%

Field	K_{def}	Limit	w_{limit}	$w_{calc.}$	Ratio
		[-]	[mm]	[mm]	
1	0.8	L/250	14.4	1.6	11%
2	0.8	L/250	14.4	1.6	11%

w_{fin} = w[char] + w[q.p.]*kdef — 18%

Field	K_{def}	Limit	w_{limit}	$w_{calc.}$	Ratio
		[-]	[mm]	[mm]	
1	0.8	L/250	14.4	2.5	17%
2	0.8	L/250	14.4	2.5	18%

$w_{net,fin}$ = w[frq] - w[D.L] + w[q.p.]*kdef — 9%

Field	K_{def}	Limit	w_{limit}	$w_{calc.}$	Ratio
		[-]	[mm]	[mm]	
1	0.8	L/333	10.8	1.0	9%
2	0.8	L/333	10.8	1.0	9%

Flexural stress analysis Fire 77%

$M_{y,d}$ =	-6.22	kNm		$f_{m,k}$ =	24.00	N/mm²	
$M_{z,d}$ =	0.00	kNm		$f_{m,k,z}$ =	24.00	N/mm²	
$N_{t,d}$ =	0.00	kN		$f_{t,0,k}$ =	0.00	N/mm²	
$\sigma_{t,d}$ =	0.00	N/mm²		$f_{t,0,d}$ =	16.10	N/mm²	
$\sigma_{m,y,d}$ =	23.31	N/mm²		$f_{m,y,d}$ =	30.36	N/mm²	
$\sigma_{m,z,d}$ =	0.00	N/mm²	<	$f_{m,z,d}$ =	0.00	N/mm²	✓

Shear stress analysis Fire 7%

V_d =	-8.64	kN		$f_{v,k}$ =	4.00	N/mm²	
$\tau_{v,d}$ =	0.32	N/mm²	<	$f_{v,d}$ =	4.60	N/mm²	✓

Rolling shear analysis Fire 0%

V_d =	-8.10	kN		$f_{r,k}$ =	1.15	N/mm²	
$\tau_{r,d}$ =	0.00	N/mm²	<	$f_{r,d}$ =	1.32	N/mm²	✓

Support reaction

Load case category	k_{mod}	A_V	B_V [kN]	C_V
self weight structure	0.6	1.24	4.00	1.24
		1.24	4.00	1.24
dead load	0.6	3.72	11.99	3.72
		3.72	11.99	3.72
Snow loads	0.9	1.66	5.33	1.66
		0.00	0.00	0.00
live load cat. H: roofs (only access for maintenance)	0.9	1.59	4.44	1.59
		-0.21	0.00	-0.21

Disclaimer

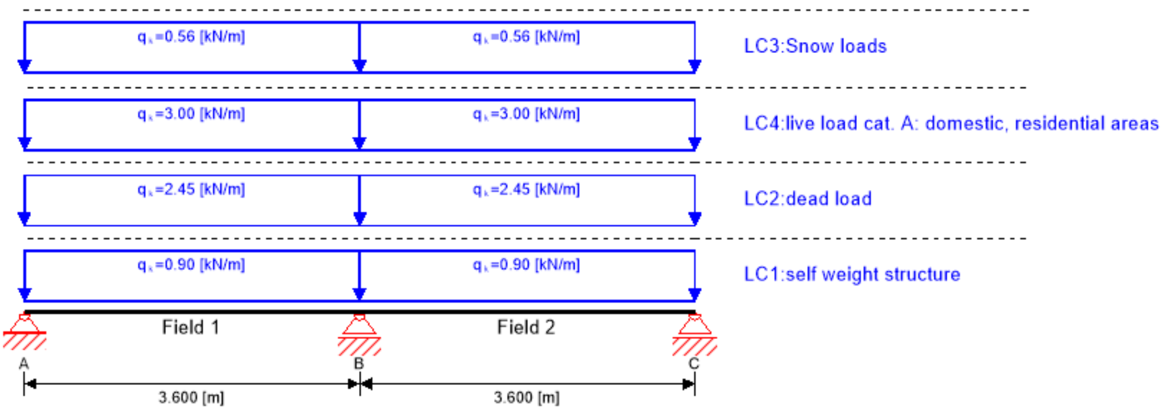
E.5. Nature roof

Table E.5: Inputted loads and outputted information for a timber building with EGRN

INPUT		
Load type	**Value**	**Notes**
Roof, dead load	2,45 kN/m^2	1,5 kN/m^2 roof finishing, 0,95 kN/m^2 green roof
Roof, live load	3,0 kN/m^2	Category A: communal floors, stairs and balconies
Roof, snow load	0,56 kN/m^2	
Roof, façade beam, dead load	0 kN/m	
Roof, façade beam, live load	0 kN/m	
Floors, dead load	2,75 kN/m^2	2,75 kN/m^2 floor finishing
Floors, live load	2,55 kN/m^2	1,75 kN/m^2 Category A: private floors, 0,8 kN/m^2 walls
Floors, façade beam, dead load	0 kN/m	
Floors, façade beam, live load	0 kN/m	
OUTPUT		
Location	**Element size**	**Notes**
Roof	CLT, t=180 mm	max. u.c. = 0,97
Floors	CLT, t=180 mm	max. u.c. = 0,76
Beams, roof	HB 300x300	max. u.c. = 0,35
Beams, floors	HB 280x280	max. u.c. = 0,34
Columns	HB 420x420	max. u.c. = 0,33
Foundation piles	Fundex pile ∅540	24 piles with capacity 2000 kN
Element types	**Total mass or volume**	**ECI class**
Roof and floors	1026,43 m^3	Timber CLT, ECI = 38,78 €/m^3
Beams and columns	194605,29 kg	Timber GLT confifeous, ECI = 0,12 €/kg
Foundation piles	178,64 m^3	In-situ concrete C30/37 CEM I reinf. 200 kg/m^3, ECI = 72,51 €/m^3
ECI value	**€76284,04**	**Increase: 2,72%**

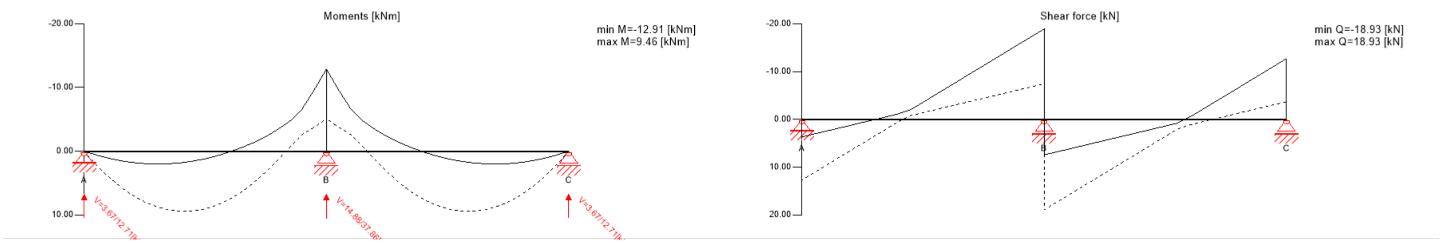
Hout vloeren UW		**1**	1/2
Roof nature		Netherlands	21/04/2024
BSc Joris Dekker	Delft University of Technology	Checker	

System



Section: CLT 180 L5s; **Material**: C24 spruce ETA (2022); **Service class**: service class 1; **Fire resistance class**: R 120

Utilization 97 %



Flexural stress analysis 17%

$M_{y,d}$ =	-12.91	kNm		$f_{m,k}$ =	24.00	N/mm²	
$M_{z,d}$ =	0.00	kNm		$f_{m,k,z}$ =	24.00	N/mm²	
$N_{t,d}$ =	0.00	kN		$f_{t,0,k}$ =	0.00	N/mm²	
$\sigma_{t,d}$ =	0.00	N/mm²		$f_{t,0,d}$ =	8.96	N/mm²	
$\sigma_{m,y,d}$ =	2.85	N/mm²		$f_{m,y,d}$ =	16.90	N/mm²	
$\sigma_{m,z,d}$ =	0.00	N/mm²	<	$f_{m,z,d}$ =	0.00	N/mm²	✓

Shear stress analysis 5%

V_d =	-18.93	kN		$f_{v,k}$ =	4.00	N/mm²	
$\tau_{v,d}$ =	0.14	N/mm²	<	$f_{v,d}$ =	2.56	N/mm²	✓

Rolling shear analysis 18%

V_d =	-18.93	kN		$f_{r,k}$ =	1.15	N/mm²	
$\tau_{r,d}$ =	0.13	N/mm²	<	$f_{r,d}$ =	0.74	N/mm²	✓

w_{inst} = w[char] 17%

Field	K_{def}	Limit	w_{limit}	$w_{calc.}$	Ratio
		[-]	[mm]	[mm]	
1	0.8	L/250	14.4	2.4	17%
2	0.8	L/250	14.4	2.4	17%

w_{fin} = w[char] + w[q.p.]*kdef 25%

Field	K_{def}	Limit	w_{limit}	$w_{calc.}$	Ratio
		[-]	[mm]	[mm]	
1	0.8	L/250	14.4	3.5	25%
2	0.8	L/250	14.4	3.6	25%

$w_{net,fin}$ = w[frq] - w[D.L] + w[q.p.]*kdef 17%

Field	K_{def}	Limit	w_{limit}	$w_{calc.}$	Ratio
		[-]	[mm]	[mm]	
1	0.8	L/333	10.8	1.8	17%
2	0.8	L/333	10.8	1.8	17%

Flexural stress analysis Fire							**97%**
$M_{y,d}$ =	-7.85	kNm		$f_{m,k}$ =	24.00	N/mm²	
$M_{z,d}$ =	0.00	kNm		$f_{m,k,z}$ =	24.00	N/mm²	
$N_{t,d}$ =	0.00	kN		$f_{t,0,k}$ =	0.00	N/mm²	
$\sigma_{t,d}$ =	0.00	N/mm²		$f_{t,0,d}$ =	16.10	N/mm²	
$\sigma_{m,y,d}$ =	29.44	N/mm²		$f_{m,y,d}$ =	30.36	N/mm²	
$\sigma_{m,z,d}$ =	0.00	N/mm²	<	$f_{m,z,d}$ =	0.00	N/mm²	✓

Shear stress analysis Fire							**9%**
V_d =	-10.91	kN		$f_{v,k}$ =	4.00	N/mm²	
$\tau_{v,d}$ =	0.41	N/mm²	<	$f_{v,d}$ =	4.60	N/mm²	✓

Rolling shear analysis Fire							**0%**
V_d =	-10.91	kN		$f_{r,k}$ =	1.15	N/mm²	
$\tau_{r,d}$ =	0.00	N/mm²	<	$f_{r,d}$ =	1.32	N/mm²	✓

Support reaction

Load case category	k_{mod}	A_V	B_V [kN]	C_V
self weight structure	0.6	1.24	4.00	1.24
		1.24	4.00	1.24
dead load	0.6	3.38	10.88	3.38
		3.38	10.88	3.38
Snow loads	0.9	0.77	2.49	0.77
		0.00	0.00	0.00
live load cat. A: domestic, residential areas	0.8	4.77	13.32	4.77
		-0.63	0.00	-0.63

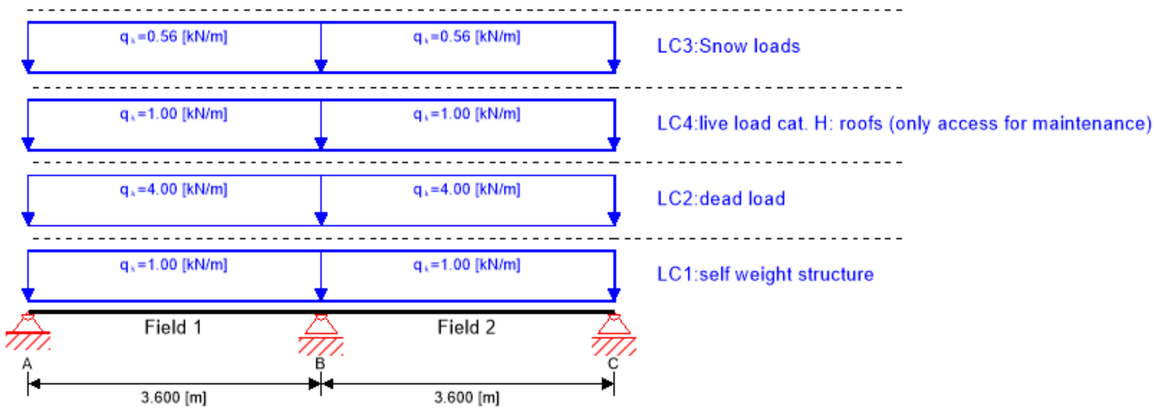
Disclaimer

E.6. Extensive retention blue roof

Table E.6: Inputted loads and outputted information for a timber building with EGRR

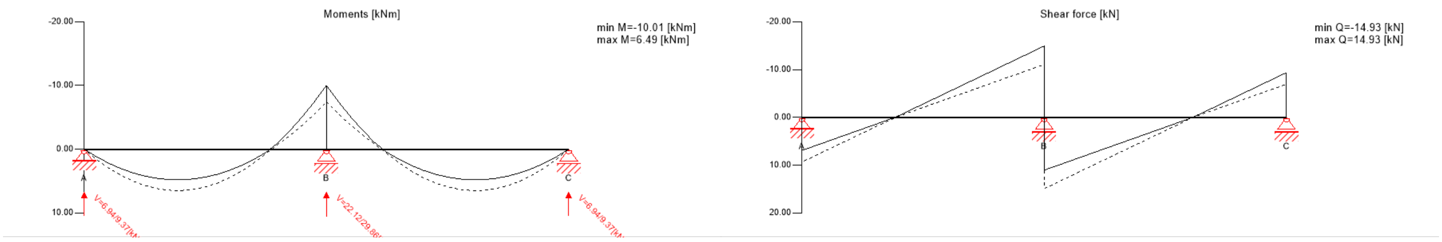
INPUT		
Load type	**Value**	**Notes**
Roof, dead load	4,0 kN/m^2	1,5 kN/m^2 roof finishing, 1,0 kN/m^2 green roof, 1,5 kN/m^2 water storage
Roof, live load	1,0 kN/m^2	Category H: inaccessible roof
Roof, snow load	0,56 kN/m^2	
Roof, façade beam, dead load	0 kN/m	
Roof, façade beam, live load	0 kN/m	
Floors, dead load	2,75 kN/m^2	2,75 kN/m^2 floor finishing
Floors, live load	2,55 kN/m^2	1,75 kN/m^2 Category A: private floors, 0,8 kN/m^2 walls
Floors, façade beam, dead load	0 kN/m	
Floors, façade beam, live load	0 kN/m	
OUTPUT		
Location	**Element size**	**Notes**
Roof	CLT, t=200 mm	max. u.c. = 0,33
Floors	CLT, t=180 mm	max. u.c. = 0,76
Beams, roof	HB 280x280	max. u.c. = 0,30
Beams, floors	HB 280x280	max. u.c. = 0,34
Columns	HB 420x420	max. u.c. = 0,33
Foundation piles	Fundex pile ∅540	24 piles with capacity 2000 kN
Element types	**Total mass or volume**	**ECI class**
Roof and floors	1037,84 m^3	Timber CLT, ECI = 38,78 €/m^3
Beams and columns	193517,86	Timber GLT confifeous, ECI = 0,12 €/kg
Foundation piles	178,64 m^3	In-situ concrete C30/37 CEM I reinf. 200 kg/m^3, ECI = 72,51 €/m^3
ECI value	**€76594,81**	**Increase: 3,14%**

System



Section: CLT 200 L5s; **Material**: C24 spruce ETA (2022); **Service class**: service class 1; **Fire resistance class**: R 120

Utilization 33 %



Flexural stress analysis 15%

$M_{y,d}$ =	-10.01	kNm		$f_{m,k}$ =	24.00	N/mm²
$M_{z,d}$ =	0.00	kNm		$f_{m,k,z}$ =	24.00	N/mm²
$N_{t,d}$ =	0.00	kN		$f_{t,0,k}$ =	0.00	N/mm²
$\sigma_{t,d}$ =	0.00	N/mm²		$f_{t,0,d}$ =	6.72	N/mm²
$\sigma_{m,y,d}$ =	1.90	N/mm²		$f_{m,y,d}$ =	12.67	N/mm²
$\sigma_{m,z,d}$ =	0.00	N/mm²	<	$f_{m,z,d}$ =	0.00	N/mm² ✓

Shear stress analysis 5%

V_d =	-14.93	kN		$f_{v,k}$ =	4.00	N/mm²
$\tau_{v,d}$ =	0.10	N/mm²	<	$f_{v,d}$ =	1.92	N/mm² ✓

Rolling shear analysis 18%

V_d =	-14.93	kN		$f_{r,k}$ =	1.05	N/mm²
$\tau_{r,d}$ =	0.09	N/mm²	<	$f_{r,d}$ =	0.50	N/mm² ✓

w_{inst} = w[char] 12%

Field	K_{def}	Limit	w_{limit}	$w_{calc.}$	Ratio
		[-]	[mm]	[mm]	
1	0.8	L/250	14.4	1.8	12%
2	0.8	L/250	14.4	1.8	12%

w_{fin} = w[char] + w[q.p.]*kdef 20%

Field	K_{def}	Limit	w_{limit}	$w_{calc.}$	Ratio
		[-]	[mm]	[mm]	
1	0.8	L/250	14.4	2.9	20%
2	0.8	L/250	14.4	2.9	20%

$w_{net,fin}$ = w[frq] - w[D.L] + w[q.p.]*kdef 11%

Field	K_{def}	Limit	w_{limit}	$w_{calc.}$	Ratio
		[-]	[mm]	[mm]	
1	0.8	L/333	10.8	1.1	11%
2	0.8	L/333	10.8	1.2	11%

Flexural stress analysis Fire 33%

$M_{y,d}$ =	-8.13	kNm		$f_{m,k}$ =	24.00	N/mm²	
$M_{z,d}$ =	0.00	kNm		$f_{m,k,z}$ =	24.00	N/mm²	
$N_{t,d}$ =	0.00	kN		$f_{t,0,k}$ =	0.00	N/mm²	
$\sigma_{t,d}$ =	0.00	N/mm²		$f_{t,0,d}$ =	16.10	N/mm²	
$\sigma_{m,y,d}$ =	-10.10	N/mm²		$f_{m,y,d}$ =	30.36	N/mm²	
$\sigma_{m,z,d}$ =	0.00	N/mm²	<	$f_{m,z,d}$ =	0.00	N/mm²	✓

Shear stress analysis Fire 3%

V_d =	-11.46	kN		$f_{v,k}$ =	4.00	N/mm²	
$\tau_{v,d}$ =	0.16	N/mm²	<	$f_{v,d}$ =	4.60	N/mm²	✓

Rolling shear analysis Fire 13%

V_d =	-11.46	kN		$f_{r,k}$ =	1.05	N/mm²	
$\tau_{r,d}$ =	0.15	N/mm²	<	$f_{r,d}$ =	1.21	N/mm²	✓

Support reaction

Load case category	k_{mod}	A_V	B_V [kN]	C_V
self weight structure	0.6	1.39	4.42	1.39
		1.39	4.42	1.39
dead load	0.6	5.55	17.70	5.55
		5.55	17.70	5.55
Snow loads	0.9	0.78	2.48	0.78
		0.00	0.00	0.00
live load cat. H: roofs (only access for maintenance)	0.9	1.59	4.42	1.59
		-0.21	0.00	-0.21

Disclaimer

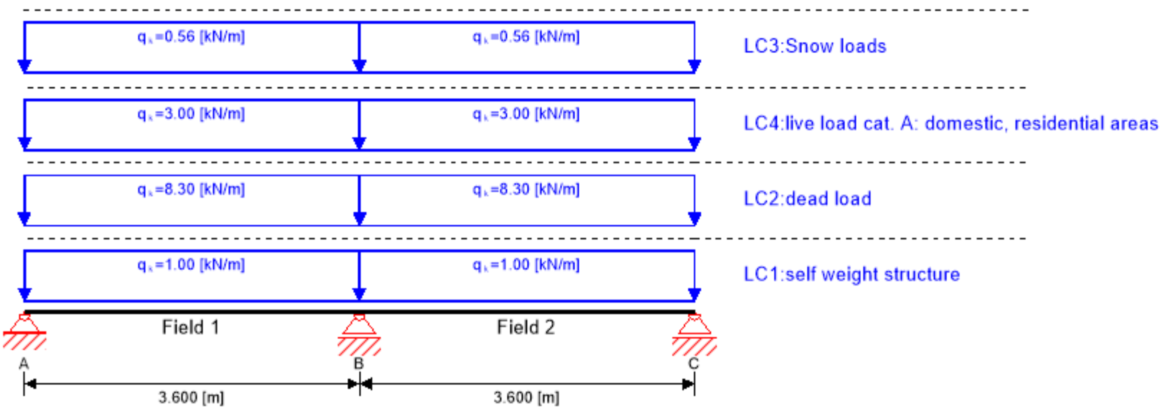
E.7. Intensive retention blue roof

Table E.7: Inputted loads and outputted information for a timber building with IGRR

INPUT		
Load type	**Value**	**Notes**
Roof, dead load	8,3 kN/m^2	1,5 kN/m^2 roof finishing, 3,1 kN/m^2 green roof, 3,7 kN/m^2 water storage
Roof, live load	3,0 kN/m^2	Category A: communal floors, stairs and balconies
Roof, snow load	0,56 kN/m^2	
Roof, façade beam, dead load	0 kN/m	
Roof, façade beam, live load	0 kN/m	
Floors, dead load	2,75 kN/m^2	2,75 kN/m^2 floor finishing
Floors, live load	2,55 kN/m^2	1,75 kN/m^2 Category A: private floors, 0,8 kN/m^2 walls
Floors, façade beam, dead load	0 kN/m	
Floors, façade beam, live load	0 kN/m	
OUTPUT		
Location	**Element size**	**Notes**
Roof	CLT, t=200 mm	max. u.c. = 0,70
Floors	CLT, t=180 mm	max. u.c. = 0,76
Beams, roof	HB 550x550	max. u.c. = 0,34
Beams, floors	HB 280x280	max. u.c. = 0,34
Columns	HB 450x450	max. u.c. = 0,34
Foundation piles	Fundex pile ∅540	26 piles with capacity 2000 kN
Element types	**Total mass or volume**	**ECI class**
Roof and floors	1037,84 m^3	Timber CLT, ECI = 38,78 €/m^3
Beams and columns	232284,33 kg	Timber GLT confifeous, ECI = 0,12 €/kg
Foundation piles	193,52 m^3	In-situ concrete C30/37 CEM I reinf. 200 kg/m^3, ECI = 72,51 €/m^3
ECI value	**€82361,27**	**Increase: 10,90%**

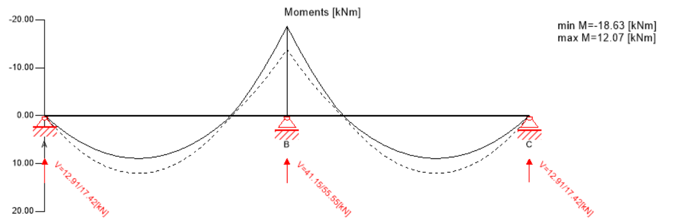
Hout vloeren UW		**1**	1/2
Roof intensive retention		Netherlands	13/05/2024
BSc Joris Dekker	Delft University of Technology	Checker	

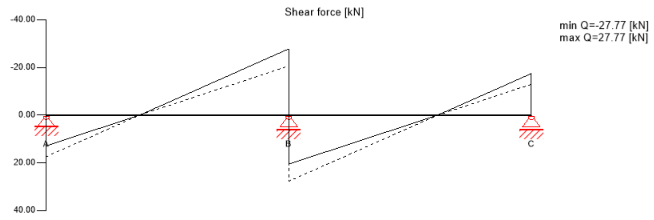
System



Section: CLT 200 L5s; **Material**: C24 spruce ETA (2022); **Service class**: service class 1; **Fire resistance class**: R 120

Utilization — 70 %





Flexural stress analysis — 28%

$M_{y,d}$ =	-18.63	kNm		$f_{m,k}$ =	24.00	N/mm²	
$M_{z,d}$ =	0.00	kNm		$f_{m,k,z}$ =	24.00	N/mm²	
$N_{t,d}$ =	0.00	kN		$f_{t,0,k}$ =	0.00	N/mm²	
$\sigma_{t,d}$ =	0.00	N/mm²		$f_{t,0,d}$ =	6.72	N/mm²	
$\sigma_{m,y,d}$ =	3.53	N/mm²		$f_{m,y,d}$ =	12.67	N/mm²	
$\sigma_{m,z,d}$ =	0.00	N/mm²	<	$f_{m,z,d}$ =	0.00	N/mm²	✓

Shear stress analysis — 9%

V_d =	-27.77	kN		$f_{v,k}$ =	4.00	N/mm²	
$\tau_{v,d}$ =	0.18	N/mm²	<	$f_{v,d}$ =	1.92	N/mm²	✓

Rolling shear analysis — 33%

V_d =	-27.77	kN		$f_{r,k}$ =	1.05	N/mm²	
$\tau_{r,d}$ =	0.17	N/mm²	<	$f_{r,d}$ =	0.50	N/mm²	✓

w_{inst} = w[char] — 26%

Field	K_{def}	Limit [-]	w_{limit} [mm]	$w_{calc.}$ [mm]	Ratio
1	0.8	L/250	14.4	3.7	26%
2	0.8	L/250	14.4	3.7	26%

w_{fin} = w[char] + w[q.p.]*kdef — 42%

Field	K_{def}	Limit [-]	w_{limit} [mm]	$w_{calc.}$ [mm]	Ratio
1	0.8	L/250	14.4	6.0	42%
2	0.8	L/250	14.4	6.1	42%

$w_{net,fin}$ = w[frq] - w[D.L] + w[q.p.]*kdef — 27%

Field	K_{def}	Limit [-]	w_{limit} [mm]	$w_{calc.}$ [mm]	Ratio
1	0.8	L/333	10.8	2.9	27%
2	0.8	L/333	10.8	2.9	27%

Flexural stress analysis Fire 70%

$M_{y,d}$ =	-17.17	kNm		$f_{m,k}$ =	24.00	N/mm²	
$M_{z,d}$ =	0.00	kNm		$f_{m,k,z}$ =	24.00	N/mm²	
$N_{t,d}$ =	0.00	kN		$f_{t,0,k}$ =	0.00	N/mm²	
$\sigma_{t,d}$ =	0.00	N/mm²		$f_{t,0,d}$ =	16.10	N/mm²	
$\sigma_{m,y,d}$ =	-21.34	N/mm²		$f_{m,y,d}$ =	30.36	N/mm²	
$\sigma_{m,z,d}$ =	0.00	N/mm²	<	$f_{m,z,d}$ =	0.00	N/mm²	✓

Shear stress analysis Fire 7%

V_d =	-24.21	kN		$f_{v,k}$ =	4.00	N/mm²	
$\tau_{v,d}$ =	0.33	N/mm²	<	$f_{v,d}$ =	4.60	N/mm²	✓

Rolling shear analysis Fire 27%

V_d =	-24.21	kN		$f_{r,k}$ =	1.05	N/mm²	
$\tau_{r,d}$ =	0.32	N/mm²	<	$f_{r,d}$ =	1.21	N/mm²	✓

Support reaction

Load case category	k_{mod}	A_V	B_V [kN]	C_V
self weight structure	0.6	1.39	4.42	1.39
		1.39	4.42	1.39
dead load	0.6	11.52	36.72	11.52
		11.52	36.72	11.52
Snow loads	0.9	0.78	2.48	0.78
		0.00	0.00	0.00
live load cat. A: domestic, residential areas	0.8	4.78	13.27	4.78
		-0.62	0.00	-0.62

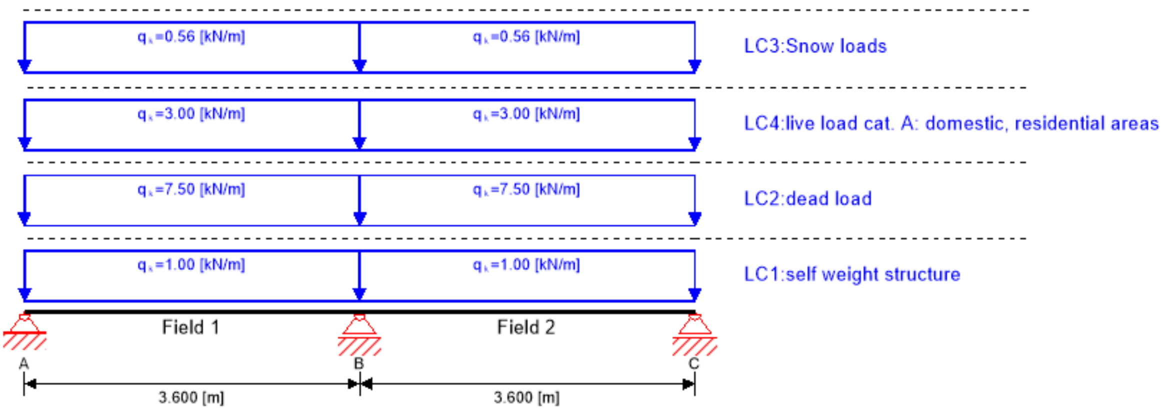
Disclaimer

E.8. Garden roof

Table E.8: Inputted loads and outputted information for a timber building with IGRG

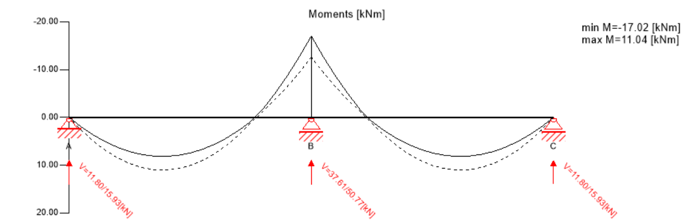
INPUT		
Load type	**Value**	**Notes**
Roof, dead load	7,5 kN/m^2	1,5 kN/m^2 roof finishing, 6 kN/m^2 green roof
Roof, live load	3,0 kN/m^2	Category A: communal floors, stairs and balconies
Roof, snow load	0,56 kN/m^2	
Roof, façade beam, dead load	0 kN/m	
Roof, façade beam, live load	0 kN/m	
Floors, dead load	2,75 kN/m^2	2,75 kN/m^2 floor finishing
Floors, live load	2,55 kN/m^2	1,75 kN/m^2 Category A: private floors, 0,8 kN/m^2 walls
Floors, façade beam, dead load	0 kN/m	
Floors, façade beam, live load	0 kN/m	
OUTPUT		
Location	**Element size**	**Notes**
Roof	CLT, t=200 mm	max. u.c. = 0,65
Floors	CLT, t=180 mm	max. u.c. = 0,76
Beams, roof	HB 550x550	max. u.c. = 0,16
Beams, floors	HB 280x280	max. u.c. = 0,34
Columns	HB 450x450	max. u.c. = 0,35
Foundation piles	Fundex pile ∅540	26 piles with capacity 2000 kN
Element types	**Total mass or volume**	**ECI class**
Roof and floors	1037,84 m^3	Timber CLT, ECI = 38,78 €/m^3
Beams and columns	232284,33 kg	Timber GLT confifeous, ECI = 0,12 €/kg
Foundation piles	193,52 m^3	In-situ concrete C30/37 CEM I reinf. 200 kg/m^3, ECI = 72,51 €/m^3
ECI value	**€82361,27**	**Increase: 10,90%**

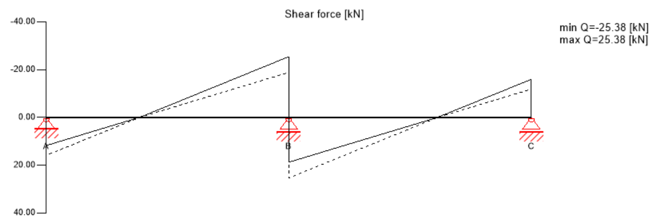
System



Section: CLT 200 L5s; **Material**: C24 spruce ETA (2022); **Service class**: service class 1; **Fire resistance class**: R 120

Utilization — 65 %





Flexural stress analysis — 25%

$M_{y,d}$ =	-17.02	kNm		$f_{m,k}$ =	24.00	N/mm²	
$M_{z,d}$ =	0.00	kNm		$f_{m,k,z}$ =	24.00	N/mm²	
$N_{t,d}$ =	0.00	kN		$f_{t,0,k}$ =	0.00	N/mm²	
$\sigma_{t,d}$ =	0.00	N/mm²		$f_{t,0,d}$ =	6.72	N/mm²	
$\sigma_{m,y,d}$ =	3.22	N/mm²		$f_{m,y,d}$ =	12.67	N/mm²	
$\sigma_{m,z,d}$ =	0.00	N/mm²	<	$f_{m,z,d}$ =	0.00	N/mm²	✓

Shear stress analysis — 9%

V_d =	-25.38	kN		$f_{v,k}$ =	4.00	N/mm²	
$\tau_{v,d}$ =	0.16	N/mm²	<	$f_{v,d}$ =	1.92	N/mm²	✓

Rolling shear analysis — 31%

V_d =	-25.38	kN		$f_{r,k}$ =	1.05	N/mm²	
$\tau_{r,d}$ =	0.15	N/mm²	<	$f_{r,d}$ =	0.50	N/mm²	✓

w_{inst} = w[char] — 24%

Field	K_{def}	Limit [-]	w_{limit} [mm]	$w_{calc.}$ [mm]	Ratio
1	0.8	L/250	14.4	3.5	24%
2	0.8	L/250	14.4	3.5	24%

w_{fin} = w[char] + w[q.p.]*kdef — 40%

Field	K_{def}	Limit [-]	w_{limit} [mm]	$w_{calc.}$ [mm]	Ratio
1	0.8	L/250	14.4	5.6	39%
2	0.8	L/250	14.4	5.7	40%

$w_{net,fin}$ = w[frq] - w[D.L] + w[q.p.]*kdef — 25%

Field	K_{def}	Limit [-]	w_{limit} [mm]	$w_{calc.}$ [mm]	Ratio
1	0.8	L/333	10.8	2.7	25%
2	0.8	L/333	10.8	2.7	25%

Flexural stress analysis Fire							**65%**
$M_{y,d}$ =	-15.90	kNm		$f_{m,k}$ =	24.00	N/mm²	
$M_{z,d}$ =	0.00	kNm		$f_{m,k,z}$ =	24.00	N/mm²	
$N_{t,d}$ =	0.00	kN		$f_{t,0,k}$ =	0.00	N/mm²	
$\sigma_{t,d}$ =	0.00	N/mm²		$f_{t,0,d}$ =	16.10	N/mm²	
$\sigma_{m,y,d}$ =	-19.75	N/mm²		$f_{m,y,d}$ =	30.36	N/mm²	
$\sigma_{m,z,d}$ =	0.00	N/mm²	<	$f_{m,z,d}$ =	0.00	N/mm²	✓

Shear stress analysis Fire							**7%**
V_d =	-22.42	kN		$f_{v,k}$ =	4.00	N/mm²	
$\tau_{v,d}$ =	0.30	N/mm²	<	$f_{v,d}$ =	4.60	N/mm²	✓

Rolling shear analysis Fire							**25%**
V_d =	-22.42	kN		$f_{r,k}$ =	1.05	N/mm²	
$\tau_{r,d}$ =	0.30	N/mm²	<	$f_{r,d}$ =	1.21	N/mm²	✓

Support reaction

Load case category	k_{mod}	A_V	B_V [kN]	C_V
self weight structure	0.6	1.39	4.42	1.39
		1.39	4.42	1.39
dead load	0.6	10.41	33.18	10.41
		10.41	33.18	10.41
Snow loads	0.9	0.78	2.48	0.78
		0.00	0.00	0.00
live load cat. A: domestic, residential areas	0.8	4.78	13.27	4.78
		-0.62	0.00	-0.62

Disclaimer

E.9. Direct green façade

Table E.9: Inputted loads and outputted information for a timber building with DGF

INPUT		
Load type	**Value**	**Notes**
Roof, dead load	1,5 kN/m^2	1,5 kN/m^2 roof finishing
Roof, live load	1,0 kN/m^2	Category H: inaccessible roof
Roof, snow load	0,56 kN/m^2	
Roof, façade beam, dead load	0,08 kN/m	
Roof, façade beam, live load	0 kN/m	
Floors, dead load	2,75 kN/m^2	2,75 kN/m^2 floor finishing
Floors, live load	2,55 kN/m^2	1,75 kN/m^2 Category A: private floors, 0,8 kN/m^2 walls
Floors, façade beam, dead load	0,15 kN/m	
Floors, façade beam, live load	0 kN/m	
OUTPUT		
Location	**Element size**	**Notes**
Roof	CLT, t=200 mm	max. u.c. = 0,89
Floors	CLT, t=180 mm	max. u.c. = 0,76
Beams, roof	HB 280x280	max. u.c. = 0,16
Beams, floors	HB 280x280	max. u.c. = 0,34
Columns	HB 400x400	max. u.c. = 0,35
Foundation piles	Fundex pile ∅540	23 piles with capacity 2000 kN
Element types	**Total mass or volume**	**ECI class**
Roof and floors	1026,43 m^3	Timber CLT, ECI = 38,78 €/m^3
Beams and columns	182359,30 kg	Timber GLT confifeous, ECI = 0,12 €/kg
Foundation piles	171,19 m^3	In-situ concrete C30/37 CEM I reinf. 200 kg/m^3, ECI = 72,51 €/m^3
ECI value	**€74263,74**	**Increase: 0%**

E.10. Indirect green façade with modular trellis, indirect green façade with continuous guides

Table E.10: Inputted loads and outputted information for a timber building with IGFT or IGFC

INPUT		
Load type	**Value**	**Notes**
Roof, dead load	1,5 kN/m^2	1,5 kN/m^2 roof finishing
Roof, live load	1,0 kN/m^2	Category H: inaccessible roof
Roof, snow load	0,56 kN/m^2	
Roof, façade beam, dead load	0,46 kN/m	
Roof, façade beam, live load	0 kN/m	
Floors, dead load	2,75 kN/m^2	2,75 kN/m^2 floor finishing
Floors, live load	2,55 kN/m^2	1,75 kN/m^2 Category A: private floors, 0,8 kN/m^2 walls
Floors, façade beam, dead load	0,90 kN/m	
Floors, façade beam, live load	0 kN/m	
OUTPUT		
Location	**Element size**	**Notes**
Roof	CLT, t=180 mm	max. u.c. = 0,89
Floors	CLT, t=180 mm	max. u.c. = 0,76
Beams, roof	HB 280x280	max. u.c. = 0,16
Beams, floors	HB 280x280	max. u.c. = 0,34
Columns	HB 400x400	max. u.c. = 0,35
Foundation piles	Fundex pile ∅540	23 piles with capacity 2000 kN
Element types	**Total mass or volume**	**ECI class**
Roof and floors	1026,43 m^3	Timber CLT, ECI = 38,78 €/m^3
Beams and columns	182359,30 kg	Timber GLT confifeous, ECI = 0,12 €/kg
Foundation piles	171,19 m^3	In-situ concrete C30/37 CEM I reinf. 200 kg/m^3, ECI = 72,51 €/m^3
ECI value	**€74263,74**	**Increase: 0%**

E.11. Continuous living wall system, modular living wall system with modular framed boxes, modular living wall system with modular trays

Table E.11: Inputted loads and outputted information for a timber building with LWSC, LWSMB or LWSMT

	INPUT	
Load type	**Value**	**Notes**
Roof, dead load	1,5 kN/m^2	1,5 kN/m^2 roof finishing
Roof, live load	1,0 kN/m^2	Category H: inaccessible roof
Roof, snow load	0,56 kN/m^2	
Roof, façade beam, dead load	0,77 kN/m	
Roof, façade beam, live load	0 kN/m	
Floors, dead load	2,75 kN/m^2	2,75 kN/m^2 floor finishing
Floors, live load	2,55 kN/m^2	1,75 kN/m^2 Category A: private floors, 0,8 kN/m^2 walls
Floors, façade beam, dead load	1,51 kN/m	
Floors, façade beam, live load	0 kN/m	
	OUTPUT	
Location	**Element size**	**Notes**
Roof	CLT, t=180 mm	max. u.c. = 0,89
Floors	CLT, t=180 mm	max. u.c. = 0,76
Beams, roof	HB 280x280	max. u.c. = 0,16
Beams, floors	HB 280x280	max. u.c. = 0,34
Columns	HB 400x400	max. u.c. = 0,35
Foundation piles	Fundex pile ∅540	24 piles with capacity 2000 kN
Element types	**Total mass or volume**	**ECI class**
Roof and floors	1026,43 m^3	Timber CLT, ECI = 38,78 €/m^3
Beams and columns	182359,30 kg	Timber GLT confifeous, ECI = 0,12 €/kg
Foundation piles	178,64 m^3	In-situ concrete C30/37 CEM I reinf. 200 kg/m^3, ECI = 72,51 €/m^3
ECI value	**€74803,43**	**Increase: 0,73%**

E.12. Linear living wall system

Table E.12: Inputted loads and outputted information for a timber building with LWSL

INPUT		
Load type	**Value**	**Notes**
Roof, dead load	1,5 kN/m^2	1,5 kN/m^2 roof finishing
Roof, live load	1,0 kN/m^2	Category H: inaccessible roof
Roof, snow load	0,56 kN/m^2	
Roof, façade beam, dead load	0,92 kN/m	
Roof, façade beam, live load	0 kN/m	
Floors, dead load	2,75 kN/m^2	2,75 kN/m^2 floor finishing
Floors, live load	2,55 kN/m^2	1,75 kN/m^2 Category A: private floors, 0,8 kN/m^2 walls
Floors, façade beam, dead load	1,81 kN/m	
Floors, façade beam, live load	0 kN/m	
OUTPUT		
Location	**Element size**	**Notes**
Roof	CLT, t=180 mm	max. u.c. = 0,89
Floors	CLT, t=180 mm	max. u.c. = 0,76
Beams, roof	HB 280x280	max. u.c. = 0,16
Beams, floors	HB 280x280	max. u.c. = 0,34
Columns	HB 400x400	max. u.c. = 0,35
Foundation piles	Fundex pile ∅540	23 piles with capacity 2000 kN
Element types	**Total mass or volume**	**ECI class**
Roof and floors	1026,43 m^3	Timber CLT, ECI = 38,78 €/m^3
Beams and columns	182359,30 kg	Timber GLT confifeous, ECI = 0,12 €/kg
Foundation piles	171,19 m^3	In-situ concrete C30/37 CEM I reinf. 200 kg/m^3, ECI = 72,51 €/m^3
ECI value	**€74263,74**	**Increase: 0%**

E.13. Vertical forest

Table E.13: Inputted loads and outputted information for a timber building with VF

INPUT		
Load type	**Value**	**Notes**
Roof, dead load	1,5 kN/m^2	1,5 kN/m^2 roof finishing
Roof, live load	1,0 kN/m^2	Category H: inaccessible roof
Roof, snow load	0,56 kN/m^2	
Roof, façade beam, dead load	3,0 kN/m	
Roof, façade beam, live load	1,25 kN/m	Category A: private floors
Floors, dead load	2,75 kN/m^2	2,75 kN/m^2 floor finishing
Floors, live load	2,55 kN/m^2	1,75 kN/m^2 Category A: private floors, 0,8 kN/m^2 walls
Floors, façade beam, dead load	6,0 kN/m	
Floors, façade beam, live load	2,5 kN/m	Category A: private balconies
OUTPUT		
Location	**Element size**	**Notes**
Roof	CLT, t=180 mm	max. u.c. = 0,89
Floors	CLT, t=180 mm	max. u.c. = 0,76
Beams, roof	HB 280x280	max. u.c. = 0,18
Beams, floors internal	HB 280x280	max. u.c. = 0,34
Beams, floors façade	HB 340x340	max. u.c. = 0,34
Columns	HB 400x400	max. u.c. = 0,35
Foundation piles	Fundex pile ∅540	28 piles with capacity 2000 kN
Element types	**Total mass or volume**	**ECI class**
Roof and floors	1026,43 m^3	Timber CLT, ECI = 38,78 €/m^3
Beams and columns	196533,39 kg	Timber GLT confifeous, ECI = 0,12 €/kg
Foundation piles	208,41 m^3	In-situ concrete C30/37 CEM I reinf. 200 kg/m^3, ECI = 72,51 €/m^3
ECI value	**€78675,89**	**Increase: 5,94%**

E.14. Combination: intensive retention blue roof and vertical forest

Table E.14: Inputted loads and outputted information for a timber building with IGRR+VF

INPUT		
Load type	**Value**	**Notes**
Roof, dead load	8,3 kN/m^2	1,5 kN/m^2 roof finishing, 3,1 kN/m^2 green roof, 3,7 kN/m^2 water storage
Roof, live load	3,0 kN/m^2	Category A: communal floors, stairs and balconies
Roof, snow load	0,56 kN/m^2	
Roof, façade beam, dead load	3,0 kN/m	
Roof, façade beam, live load	1,25 kN/m	Category A: private floors
Floors, dead load	2,75 kN/m^2	2,75 kN/m^2 floor finishing
Floors, live load	2,55 kN/m^2	1,75 kN/m^2 Category A: private floors, 0,8 kN/m^2 walls
Floors, façade beam, dead load	6,0 kN/m	
Floors, façade beam, live load	2,5 kN/m	Category A: private balconies
OUTPUT		
Location	**Element size**	**Notes**
Roof	CLT, t=200 mm	max. u.c. = 0,65
Floors	CLT, t=180 mm	max. u.c. = 0,76
Beams, roof	HB 550x550	max. u.c. = 0,34
Beams, floors internal	HB 280x280	max. u.c. = 0,35
Beams, floors façade	HB 340x340	max. u.c. = 0,31
Columns	HB 400x400	max. u.c. = 0,31
Foundation piles	Fundex pile ∅540	30 piles with capacity 2000 kN
Element types	**Total mass or volume**	**ECI class**
Roof and floors	1140,48 m^3	Timber CLT, ECI = 38,78 €/m^3
Beams and columns	246458,42 kg	Timber GLT confifeous, ECI = 0,12 €/kg
Foundation piles	223,30 m^3	In-situ concrete C30/37 CEM I reinf. 200 kg/m^3, ECI = 72,51 €/m^3
ECI value	**€86233,74**	**Increase: 16,12%**