Green facades for a resilient and liveable built environment

A holistic multi-criteria approach for selecting vertical greening systems

Royal HaskoningDHV

TU Delft

Master thesis

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Front page image: Green facade in Milan (own work)

Green facades for a resilient and liveable built environment: A holistic multi-criteria approach for selecting vertical greening systems

by

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Preface

In the streets of Milan, the green facade on the front page sparked my interest. Little did I know that this would be the beginning of a journey that would lead to this master thesis. Throughout the process, the role of green facades in creating more attractive and healthy cities kept me fascinated. In my opinion, this topic shows how nature-based building engineering solutions can have a lasting sustainable impact on society.

I want to thank my supervisors at TU Delft for their guidance. Henk Jonkers, Marc Ottelé and Hoessein Alkisaei, thank you for your valuable feedback, insights and enthusiasm. Thank you to Hester Thoen, for welcoming and mentoring me at Royal HaskoningDHV, and providing fresh perspectives throughout this project. I am also grateful to the interviewees and other colleagues at RHDHV who have inspired me. Lastly, to my family, friends, and partner, your unwavering support propelled me.

My aspiration for this research is to help transform grey cities into green ones, and resonate with those who, like me, are fascinated by the complex beauty of green facades.

Hugo van Reeuwijk
Delft, August 2023

Abstract

Vertical greening systems (VGS), i.e. vegetated building facades, can harness the benefits of nature to contribute to resilient and healthy cities. A lack of guidelines for the early selection and design of VGS currently limits implementation. Based on a literature study and expert interviews, this thesis proposes a multi-criteria framework and tool to assist architects and engineers in the holistic selection of multi-purpose VGS. The research compares the performance of different system types on 18 impact criteria, ranging from urban noise reduction to installation costs. Depending on project-specific input about environmental conditions and building project objectives, the framework provides a ranking of the most suitable VGS. Design recommendations ensure a VGS that is fit for purpose. Subsequently, sensitivity analyses, a case study and testing on sample projects validate the usability and results of the tool. The thesis extends current perspectives on evaluating the impact of VGS on the built environment. The tool enables users to make holistic and justified decisions on the application of a VGS.

Executive summary

Introduction

Urban quality of life is under pressure from factors such as excessive heat, air pollution, noise hindrance, biodiversity loss, pressure on the urban water cycle and mental health issues. Nature-based solutions that bring more nature into cities can tackle these challenges, for example by regulating heat and reducing stress. At the same time, sustainable buildings need to reduce energy consumption for heating and cooling. Vegetated building facades, known as vertical greening systems (VGS), happen to be a remedy for these challenges at building and city level, especially in dense cities with little space for parks and trees.

Although the multiple benefits of VGS demonstrated in research have attracted the interest of investors and policymakers, widespread implementation of VGS is lagging behind. The selection and design of VGS is not straightforward due to the variety of systems and purposes. An important barrier to implementation is the lack of guidelines on how to select and design the most suitable system for different purposes.

Therefore, this master thesis aims to develop a multi-criteria decision framework for the early selection and design of multi-purpose urban VGS. The resulting guide should enable architects and engineers of building projects to holistically compare the impacts of different VGS design options and to make justified decisions about the application of a VGS.

Methodology

The study uses a multi-criteria decision-making approach because it allows to evaluate multiple alternatives against a set of criteria. Through an extensive literature study, expert interviews and a case study, two products have been developed: a conceptual framework (figure 2) and a numerical Excel tool.

Framework and tool

The starting point of the framework structures the decision problem - finding the most suitable VGS for a specific project - by introducing design alternatives and criteria. Explorative literature research identifies seven main VGS typologies among two groups: green facades and living wall systems. Green facades consist of climbing plants in ground soil with or without climbing aids, such as steel cables. Living wall systems grow at height in pockets, trays or boxes filled with a substrate.

To compare the various typologies, the framework adopts a holistic set of 18 evaluation criteria grouped into five themes: biodiversity, social value, health and well-being, climate adaptation and mitigation, and costs and benefits. Based on a systematic literature review and expert interviews, these criteria include benefits (e.g. reducing air pollution) and burdens (e.g. installation costs) at the building and urban environment level. As such, the criteria reflect a broad range of sustainable construction aspects that contribute to more liveable and climate-resilient cities.

The central part of the framework focuses on assigning and processing scores on the evaluation criteria. Since no building project is the same, performances are partly based on project-specific inputs. Following a deductive approach, the research assigns each VGS type a score per criterion, specifically adapted to the Dutch climate. Some criteria are expressed on a quantitative scale, such as noise reduction in dB, while more intangible benefits, such as aesthetic value, are expressed on a 7-point qualitative scale. For most criteria, the tool considers a fixed score per system, which reflects the potential performance a system can deliver. For example, past experimental studies show that a living wall system made of felt pockets reduces traffic noise by 8.4 dB, while a green facade with a climbing aid delivers a 6.5 dB reduction. Additionally, the tool calculates a specific score based on environmental conditions (such as street morphology) for urban heat island and particulate matter reduction, as well as real estate value enhancement. Urban heat island mitigation by VGS, for example, is the largest in neighbourhoods with narrow streets and tall buildings.

The scores are globally standardised between 0 (worst) and 100 (best) to homogenize the multidimensional scores. Afterwards, criteria are weighted according to the importance of criteria to the selection decision. To do so, this study uses a combined weighting method. On the one hand, a relevance weight accounts for the relevance of mitigating the issue at the specific location. For example, traffic noise reduction is more relevant when street noise levels are high. Users of the tool can fill in these location characteristics from online databases. On the other hand, a priority weight allows the user to express client objectives. The total weight is the multiplication of the relevance and priority weight.

The final part of the framework presents a ranking of the most suitable VGS types. A weighted linear combination of the scores per criterion provides the user with a dimensionless, overall value per system. Besides ranking the alternatives, the tool presents different figures that show how criteria, themes and levels (building/urban) contribute to the overall value. It also shows the effect of the client's priorities on the ranking and scores per criterion. This allows users to understand why a particular system is considered more suitable than others and what the arguments are in favour of a certain system choice.

The design details of VGS can affect their performance. For example, a VGS on a south-facing facade us more effective in lowering indoor summer temperatures, and a wide range of native plant species adds more biodiversity value. Similarly, building coverage, vegetation density, substrate and supporting structure all have a considerable effect on the performance. To take this into account, the framework concludes with qualitative design recommendations per criterion, based on research findings. In this way, the user can detail the chosen type of VGS so that its full potential is realised.

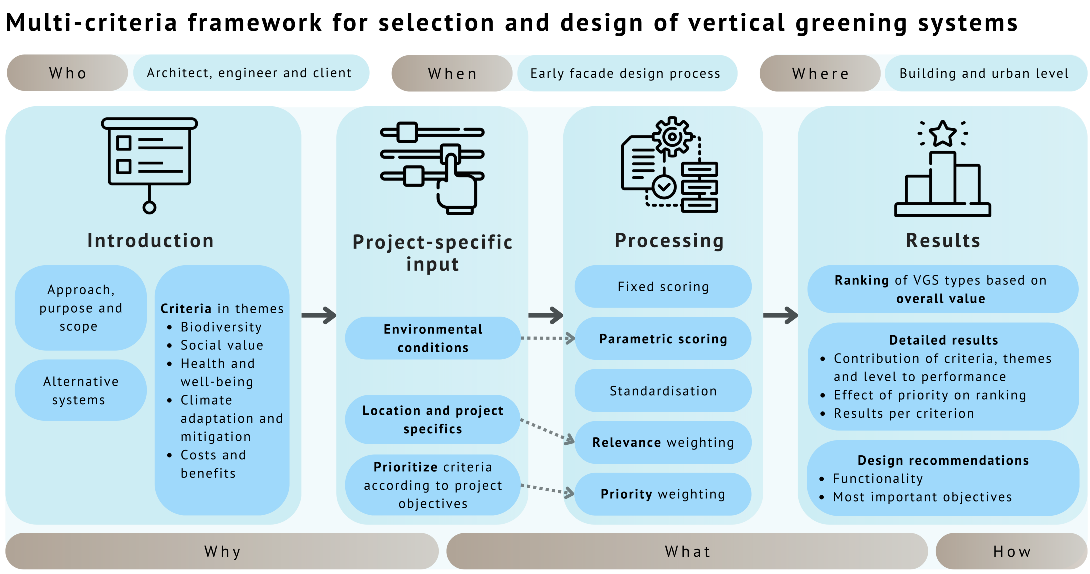


Figure 2: Multi-criteria decision-making framework

Validation

Sensitivity analyses show that the ranking of VGS is particularly sensitive to changes in client priorities, and less so to changes in environmental conditions. This demonstrates how a combination of location and project conditions can change the preferred VGS.

A case study of Venlo city hall was carried out using desk research and interviewing the project manager. The most suitable system from the tool was the same as the one chosen, mainly because of the client's emphasis on particulate matter removal and greywater treatment. The use of the tool could have extended this focus to multiple relevant VGS functions, such as the reduction of traffic noise. The design recommendations given in the tool are also consistent with the design choices made. Therefore, the case study validates the results and usability of the tool.

At the same time, the tool is more of an aid to decision-making than the sole decision-maker. The tool was tested on three Dutch example projects with different functions and locations. The projects have applied VGS that were second or third most suitable according to the tool. This suggests that other aspects, such as the outward view from a building, might play a role in finalizing the VGS choice in later project phases. More importantly, it shows that the practical value of the tool lies in its purpose as a conversation tool that helps the design team to holistically compare VGS and to substantiate their choice.

Conclusion

The thesis concludes that the framework is one of the first guides for a holistic and universal process to select and design VGS in early project phases. It allows system types to be compared in terms of their multi-dimensional and multi-level impacts and provides arguments for selecting the suitable system. The location- and project-specific scoring and design recommendations take into account the complex influences of the environment, project type and design detailing. In this way, the framework contributes to academic and practical understanding of selecting and designing fit-for-purpose VGS that contribute to resilient and liveable cities.

Nomenclature

Abbreviation	Term
AV	Aesthetic value
BD	Biodiversity
CBA	Cost-benefit analysis
CE	Cooling energy savings
CS	Carbon sequestration
DGF	Direct green facade
EB	Environmental burdens
ET	Evapotranspiration
GF	Green facades
GW	Greywater treatment
HE	Heating energy savings
HS	Indoor heat stress reduction
IGFC	Indirect green facade with continuous guides
IGFT	Indirect green facade with modular trellis
LCA	Life-cycle analysis
LWS	Living wall systems
LWSC	Continuous living wall system with cloth or felt system
LWSL	Linear living wall system with planter boxes at every floor level
LWSMB	Modular living wall system with modular boxes
LWSMT	Modular living wall system with modular trays
MCDM	Multi-criteria decision-making
NBS	Nature-based solutions
PB-PR	Private benefits - Plaster renovation saving
PB-VI	Private benefits - Real estate value increase
PC-DC	Private costs - Disposal costs
PC-I	Private costs - Installation costs
PC-MO	Private costs - Maintenance and operation costs
PM	Particulate matter removal
RC	Rainfall runoff control
RE	Relaxation effects
RHDHV	Royal HaskoningDHV
TN	Traffic noise reduction
UGI	Urban green infrastructure
UHI	Urban heat island (reduction)
VGS	Vertical greening systems

Contents

Chapter 1

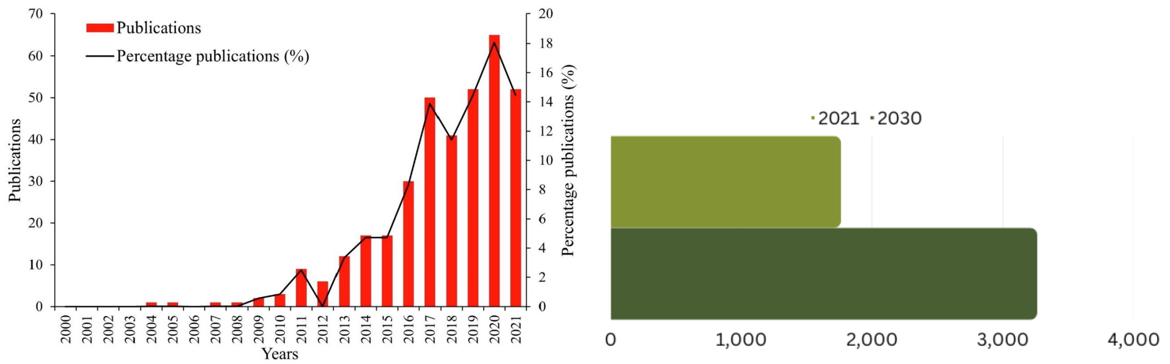
Introduction

1.1 Nature for resilient and liveable cities

The future development of cities is challenged by multiple pressures, including population growth, densification and the effects of climate change [1]. By 2030, 8 out of 10 Europeans will live in cities [2]. They will face hotter conditions due to heat waves and the urban heat island effect, along with air and noise pollution from traffic [3]. Excessive heat, air pollution and noise are major environmental causes of exacerbated health issues and premature mortality [2]. Last summer, for example, 61,000 Europeans lost their lives because of the heat [4]. Other factors that put the urban quality of life increasingly under stress include biodiversity loss, climate-induced pressure on the urban water cycle and mental health issues associated with urban living [5–8]. At the same time, buildings account for 40% of the world's total energy consumption, which makes it essential to reduce building-related energy consumption [9, 10]. As urbanisation and climate change endure, these challenges to the sustainability of buildings and cities will become more urgent [8].

As it turns out, integrating nature into cities is one promising way to address these challenges.[11]. Parks and greenery on streets, roofs and walls are examples of urban green infrastructure (UGI) [12], which falls under the umbrella of nature-based solutions (NBS) [13]. According to the European Commission, NBS are "solutions that are inspired and supported by nature, which are cost-effective, simultaneously provide environmental, social and economic benefits and help build resilience; such solutions bring more, and more diverse, nature and natural features and processes into cities, landscapes and seascapes" [14]. Urban green spaces, or UGIs, are a subset of NBS and have multiple benefits, such as improving air quality, cooling down ambient temperatures, providing recreational space and bringing more calmness through noise and stress reduction [15]; [16]. The multi-purpose values that UGI can deliver are referred to as "ecosystem services", i.e. the benefits of nature used by a city for its provisioning, regulating, cultural and habitat needs [3, 17]. Since these benefits contribute to climate adaptation and the physical and mental well-being of citizens [13, 18], the (re)introduction of urban greenery is crucial to ensure a resilient and liveable built environment [19–22].

Although cities initiate greening of public spaces [23], the open space for parks and green streets is becoming scarce in increasingly dense cities [15, 24]. Putting greenery on building roofs and facades saves this valuable space at ground level [25, 26]. Therefore, greening the building envelope is gaining interest in research and policy-making as a promising method of nature-inclusive construction [27, 28]. The recently proposed EU regulation on nature restoration would require countries to ensure "a net gain of urban green space that is integrated into existing and new buildings and infrastructure developments, in all cities, towns and suburbs" [29]. That acknowledges the need to integrate green onto buildings.



(a) Development of papers about VGS research [33] (b) Global green wall market forecast (million $) [34]

Figure 1.1: Growth of academic and commercial interest for VGS

1.2 Vertical greening systems

1.2.1 Potential

Whereas the application of green roofs is a much-established practice throughout the world, the potential of green building facades is not fully exploited [30, 31]. Compared to green roofs, VGS have potentially more effect on the built environment, as their surface can be significantly larger than the roof area – even up to 20 times for multi-story buildings [32]. The applicability of VGS on new-built and refurbishment projects also maximizes their potential impact, since Scheuermann et al. [5] estimate that at least 80% of the buildings in our cities will still be in use in 2050.

Moreover, vertical greening systems (VGS), i.e. vegetated building facades, have incited an advancing research field that has grown during the last 20 years (figure 1.1a). It has shown the multiple purposes of VGS. They can lower energy consumption for cooling and increase the real estate value of a building, whilst also mitigating outdoor polluted air, heat, noise and biodiversity loss [3, 15]. Hence, the ecosystem services delivered by VGS can enhance and restore the urban environment and improve building performance [35].

VGS have attracted the interest of policymakers and investors because of their potential and multiple benefits [21]. Some cities are introducing policies to promote the implementation of VGS [36]. For example, new building regulations in Vienna require 20% of facade area to be green [37]. German cities mandate facade greenery or subsidise the cost of installation [38]. And a scheme for high-rises in Singapore, which finances up to 50% of the installation costs of green roofs and VGS, has resulted in the greening of more than 110 existing buildings [39]. Globally, the global green wall market is expected to almost double - reaching a size of $3260 million by 2030, as shown in Figure 1.1b [34].

1.2.2 Implementation barriers

Although VGS play an important role in greening dense cities by improving resilience and livability, they are not widely used [37, 40]. How come? Researchers point to lack of affordability as a key barrier to large-scale adoption [36, 39, 41]. The perceived high costs for installation, green care and technical maintenance discourage decision-makers from opting for VGS [20, 37, 40]. Besides, uncertainties regarding the magnitude of VGS benefits during their lifetime exist among practitioners [30].

This research argues that applying a VGS to its full potential is complex and that the lack of guidance reflecting this is one of the main barriers to implementation. The diversity of alternative VGS and purposes complicate the decision to apply a VGS [15, 42].

Apart from reviews that have tried to synthesize the scattered state-of-the-art research about VGS [7, 43], there is no clear overview of the extent of benefits and burdens that different systems deliver, and how this is influenced by design (e.g. choice of plants) and environment (e.g. climate). As such, there is an academic need to holistically review the performances of different VGS relative to each other.

Previously developed guidelines for architects and engineers to evaluate VGS have a limited scope and often purely focus on quantifiable benefits [39, 44–46] (appendix 11.5). As such, there is a lack of practical guidance to compare the total impact of different VGS, choose the most suitable system and design for different purposes [47]. As a result, the choice of VGS in today's building projects is often poorly justified [35, 39].

1.3 Research approach

1.3.1 A multi-criteria decision-making framework

To enable better-substantiated choices for a VGS, this research aims to develop a multi-criteria decision-making framework for the early selection and design of the most suitable VGS. The thesis seeks an answer to the following main research question:

How can a multi-criteria design framework on early design decision-making for multi-purpose urban vertical greening systems be developed?

A multi-criteria framework that evaluates different VGS on all relevant impacts is the next step in harmonizing and enhancing VGS implementation. Academic novelty in this research lies in synthesizing fragmented research insights into a holistic perspective on VGS that can inform design decisions and in exploring the relations between environment, design detailing and performance. In practice, the framework should enable architects and engineers of building projects to holistically compare the impacts of different VGS design options and to make justified decisions about the application of a VGS. The framework will help them to identify VGS options and purposes and provide them with project-specific arguments to apply one system over the other.

The research focuses on the selection and design of VGS in early project phases. Taking VGS into account during early design phases can facilitate the planning of VGS, e.g. to coordinate the implications on the building structure and to enable green care and maintenance [37]. Moreover, identifying and formulating objectives for the VGS in early phases can improve justifying the choice of VGS and successfully implementing the VGS [48].

The research initially focuses on VGS in urban areas, because there is limited space for parks or street trees and VGS tackle challenges most prominent in cities, such as noise hindrance. Still, though, the resulting framework is applicable to non-urban areas as well.

The methodological approach of this study is based on multi-criteria decision-making (MCDM), because it allows to evaluate several alternatives in terms of a set of decision criteria. Through an extensive literature study, expert interviews and a case study, two products will be developed: a conceptual multi-criteria framework and a numerical application of this framework in an Excel tool. The background and suitability of an MCDM approach and detailed methodology are further discussed in chapter 2.

1.3.2 Sub-research questions and thesis outline

Following this introduction, chapter 2 discusses the MCDM approach and methods. Afterwards, the steps in the research flow diagram (figure 1.2) guide the research through 4 parts.

Part I: Problem structuring

Part I structures the decision problem in terms of the decision context and design alternatives. First, chapter 3 establishes the decision context by formulating the goal and decision-makers. Second, chapter 4 identifies the design alternatives to the decision problem in answer to sub-research question

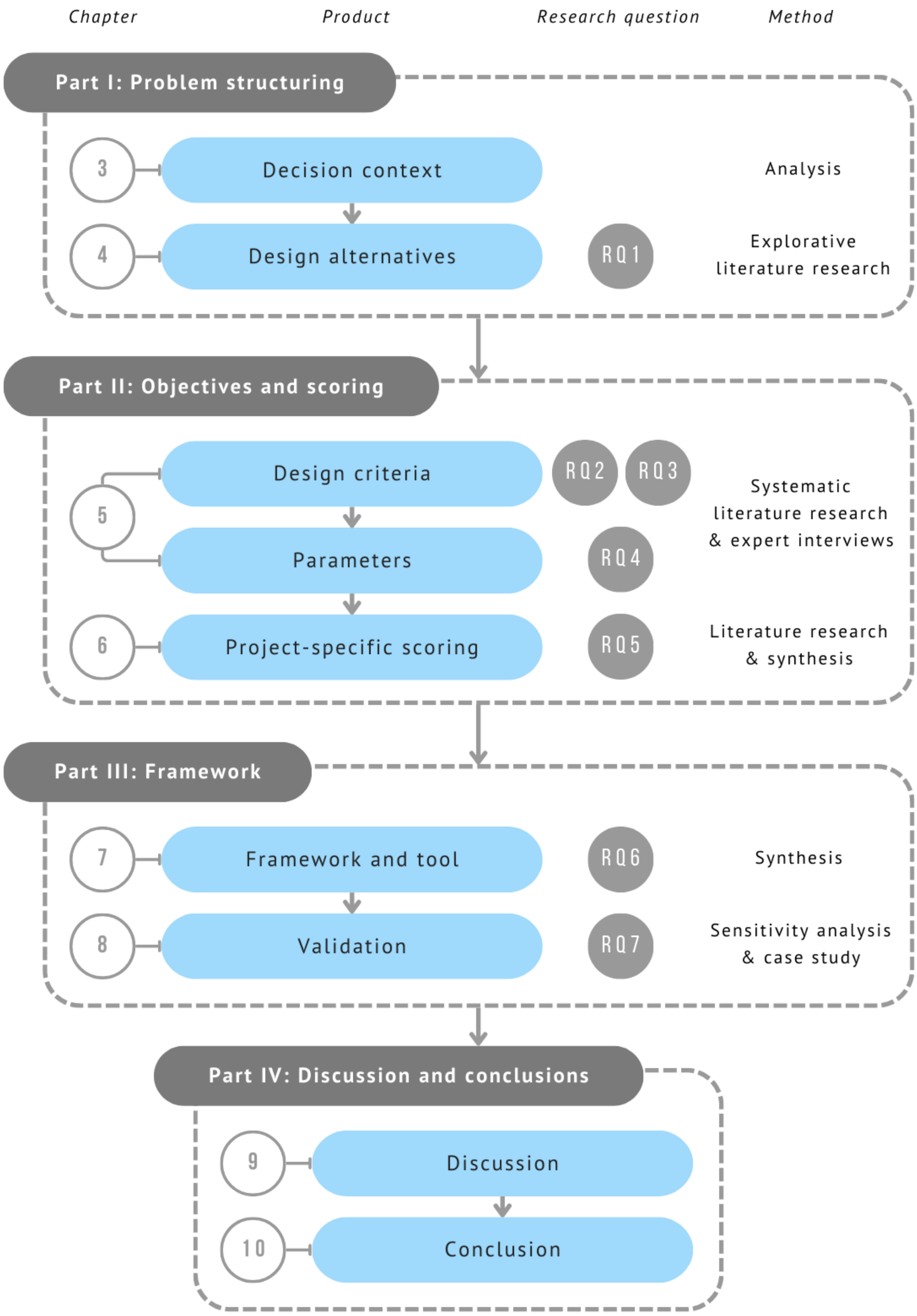


Figure 1.2: Research flow diagram

1 (RQ1). This question essentially refers to what the options are when it comes to VGS. The objective is to identify the main types of VGS that have a sufficient evidence base in research to be mature for widespread implementation. These options will serve as design alternatives in the framework.

- *RQ1: What are the main design configurations for VGS?*

Part II: Objectives and scoring

Part II identifies objectives and scoring. Chapter 5 answers RQ2 and RQ3. These questions seek to provide an overview of the benefits and burdens delivered by VGS, translate them into evaluation criteria and gather performances of each system on these criteria.

- *RQ2: What are the ecosystem services delivered by VGS?*
- *RQ3: What are the environmental, economic and social impacts of VGS?*

Also, chapter 5 answers RQ4. This part determines parameters (such as environmental conditions or design detailing) that affect the performance of VGS on criteria. Also, it analyzes how different parameters relate, and whether they complement or conflict.

- *RQ4: What are the key parameters to optimize the performance of VGS and how do they complement or conflict each other?*

Chapter 6 explores ways to integrate project-specific parameters in an MCDM approach, answering RQ5. The objective of this question is to specify project-specific parameters relevant to early design decisions of VGS, such as location characteristics and client wishes. Also, this part analyses how they can be integrated into the framework, such as through the weighting of criteria.

- *RQ5: What are the project-specific characteristics that affect decision-making in early design phases of VGS?*

Part III: Framework

Next, part III introduces and validates the framework and tool. Chapter 7 answers RQ6. The objective is to establish an integrated multi-criteria design framework that can serve as a basis for architects and engineers to make well-informed decisions on whether to opt for a VGS, which VGS is most suitable and what should be taken into account in later design phases. Based on the knowledge base of the research phases before, this part proposes a multi-criteria framework to facilitate the decision-making in the multi-purpose design of VGS.

- *RQ6: How can design alternatives, design criteria, parameters and weighting be integrated in a multi-criteria design framework for the early design decisions of multi-purpose VGS?*

Chapter 8 answers RQ7. This part seeks to validate the results and usability of the framework through sensitivity analyses, a case study and testing on example projects.

- *RQ7: How can a multi-criteria design framework for the multi-purpose design of urban VGS be validated?*

Part IV: Discussion and conclusions

The concluding part IV consists of the discussion (chapter 9) and conclusions (chapter 10).

Chapter 2

Methodology

This chapter discusses the theoretical background of multi-criteria decision-making and the methods used in this research.

2.1 Multi-criteria decision-making

2.1.1 Characteristics

Multi-criteria decision-making (MCDM) is a non-monetary and quantitative evaluation approach [49]. It is also referred to as MCDA (multi-criteria decision analysis) and a comprehensive method within MCA (multi-criteria analysis) to aid decision-making.

In decision analysis, a decision problem occurs when there is a difference between the current and desired state, and there is more than one way to achieve the desired state [49]. The decision-making process is a set of actions undertaken to transform available information into an instruction to inform a choice. The aim of decision-making is to identify the alternative that is closest to the desired state [49].

MCDM is both an approach and a set of techniques, with the aim of providing an overall ordering of options, from the most preferred to the least preferred option [50]. The typical MCDM problem deals with the evaluation of several alternatives in terms of a set of decision criteria [51]. The plurality of options and criteria is a key characteristic of MCDM. A MCDM approach can guide designers and decision makers within such a multi-dimensional decision problem [52].

According to Dodgson et al. [50], "MCDA is a way of looking at complex problems that are characterised by any mixture of monetary and non-monetary objectives, of breaking the problem into more manageable pieces to allow data and judgements to be brought to bear on the pieces, and then of reassembling the pieces to present a coherent overall picture to decision makers."

In that way, an MCDM approach simplifies decisions by breaking them into parts but does not over-simplify by neglecting the complexities of decisions [49]. For example, it does not represent the performance of an option merely in one (monetary) value.

The results of an MCDM approach show that options may differ in the extent to which they achieve several objectives, and that not one option will be obviously best in achieving all objectives [50]. Even more so, the MCDM can indicate the trade-offs or conflicts usually evident amongst the criteria (e.g. between burdens and benefits).

The purpose of MCDM is to serve as an aid to thinking and decision-making, not to take the decision [50]. For example, it can be used to explore the reasons behind the ordering or ranking, which can lead to an increased understanding of relevant aspects [52].

2.1.2 Suitability to VGS

MCDM is a suitable methodological approach for this study, because of the complex VGS selection process, integration of intangible benefits and past applications.

Decisions for selecting and designing VGS in early phases are complex and multifaceted, and draw on multidisciplinary knowledge. The multiple purposes of VGS (e.g. budgetary requirements or a goal to enhance biodiversity) and heterogeneous alternatives (systems) fit an MCDM approach with a comparative assessment of different alternatives in terms of a set of criteria [40].

Next to that, MCDM allows to integrate intangible or 'soft' benefits, such as improving aesthetic value, and benefits for which quantified performances have not been found in research yet. This suits the quantitative and qualitative aspects associated with VGS, and the varying evidence bases for VGS effects. MCDM allows to express the degree of achievement of different objectives in different measurement units, and does not necessarily require monetization [53]. Purely monetary evaluation for a common scale is not always satisfactory because it requires a lot of assumptions [49]. Therefore, compared to other evaluation approaches, MCDM covers a full, comprehensive range of aspects related to the project (see section 5.1) [49]. Moreover, the MCDM approach makes choosing a VGS an explicit, justified and transparent decision, instead of an informal - possibly subjective or biased - choice.

The third reason for MCDM being a suitable approach is past application in the field. MCDM approaches are often adopted for socio-technical issues in both public and private sector organizations [50]. More specifically, recent research has applied MCDM approaches for the design of building facades, often sustainability-based [42, 54] or for the design of green roofs [52]).

Therefore, multi-criteria decision analysis is regarded as suitable decision support for the early selection and design process of VGS.

2.2 Methods

Figure 2.1 shows the steps of successfully setting up an MCDM approach [50]. These steps form the backbone of the research approach in this study.

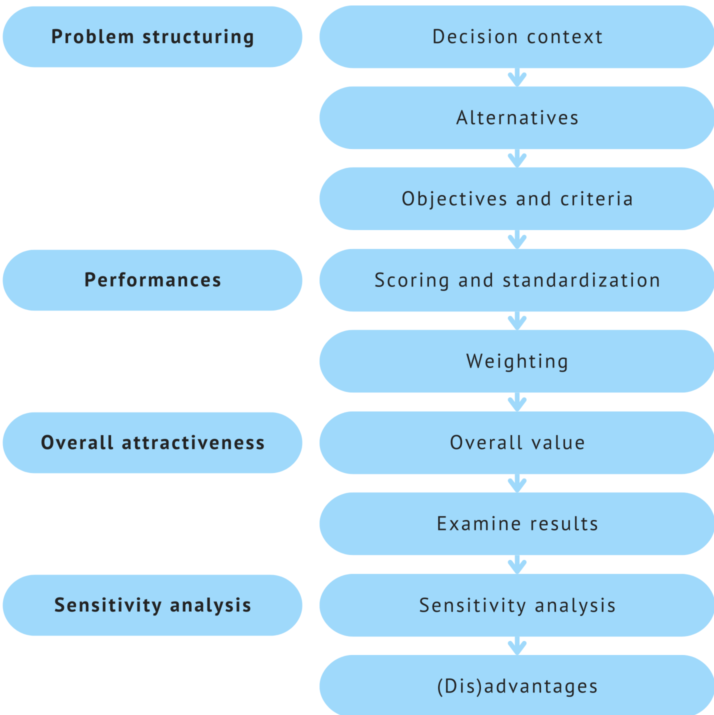


Figure 2.1: Steps of setting up a MCDM approach (based on [50])

First, chapter 3 establishes the decision context is established by formulating the goal and decision-makers.

Second, chapter 4 identifies the design alternatives to the decision problem in answer to RQ1. The design options that are ready to be implemented and well understood in research are deducted from an explorative literature research (see appendix 11.1).

Third, chapter 5 formulates design criteria that reflect the value associated with the consequences of each alternative. In researching RQ2 and RQ3, a systematic literature research ensures a comprehensive, transparent search that maximises credibility ([55]; appendix 11.3). Also, chapter 5 deducts performances of each system on the criteria.

Fourth, to answer RQ4 the parameters that affect VGS performance are researched through a mixed-methods approach. Parameters found in the systematic literature research are complemented with semi-structured expert interviews (chapter 5; appendix 11.4).

Fifth, chapter 6 explores ways to integrate project-specific parameters in an MCDM approach, based on the literature study, answering RQ5. This includes establishing standardization and weighting to obtain an overall value per alternative.

Sixth, the conceptual framework and ready-to-use Excel tool of RQ6 are the result of combining the result from previous sub-research questions (chapter 7).

Seventh, chapter 8 seeks validation of the results from the framework/tool through a sensitivity analysis, a case study and example projects (RQ7). For the case study, desk research is combined with a case-related interview to test the tool (appendix 11.9).

Part I

Problem structuring

Chapter 3

Decision context

The first step in multi-criteria decision analysis is to establish the decision context. This chapter discusses the goal and scope of the decision framework developed in this study.

3.1 Goal

The goals of the framework are to identify the most suitable design alternative for a specific building project, and to inform users about what design considerations play a role in the choice for a VGS type. This should result in an overall ranking of alternatives, from most preferred to least preferred [50].

The framework focuses on early design phases, as an early and holistic VGS selection can facilitate VGS planning [37]. Figure 3.1 shows the phases of the design process for complex facades. The linear visualisation is a simplification of the iterative process, where phases inform each other and overlap [56]. This study considers the early design process to start with defining and establishing enclosure goals (e.g. visual, performance and costs), followed by thematic enclosure concepts and information gathering.

The framework therefore covers design phases where much is still open, apart from the location and function of the building. The result of the framework can inform the subsequent schematic design phase.

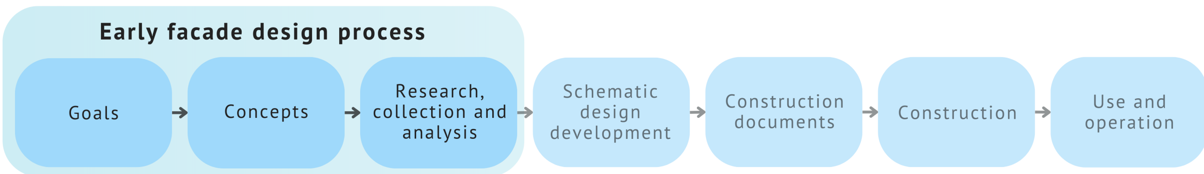


Figure 3.1: Simplified facade design process timeline, and a definition of the early process (adapted from Boswell [56])

3.2 Building types and key players

The framework is applicable for residential and non-residential building projects in the Netherlands (table 3.1). Depending on functional use and the type of client (public or private), different emphases in design considerations can be expected. For example, thermal insulation benefits of VGS can be considered less important for parking garages with occupants that spend little time there. As such, the influence of building typology can be expressed in the 'Priority' weighting (chapter 6).

The numerical scoring is specific to the Netherlands, especially for climate-dependent benefits. Nevertheless, the approach and conceptual steps of the framework are generic and remain widely

Table 3.1: Building project types, clients and occupants

	Residential		**Non-residential**	
Function	Residential		Offices	Other: schools, hospitals, data centres, stations, parking garages, etc.
Client/owner	Private home-owner	Housing cooperative, commercial	Commercial, governmental	Commercial, educational, governmental
Occupants	Residents	Tenants	Workers	Various

applicable.

Intended users of the framework are architects and engineers (such as structural, building services and building physics engineers) as participants in the early design process [56]. They can use the framework in cooperation with clients to determine the suitability of VGS in a project. The framework allows to present different design alternatives and their (dis)advantages to the client, who is the ultimate decision-maker.

Chapter 4

Design alternatives

This chapter identifies the system types that serve as design alternatives, as well as their distinctive characteristics. Appendix 11.1 presents the methodological details for the explorative literature research performed in answering RQ1.

4.1 Definition

Francis and Lorimer [57] clearly define vertical greening systems (VGS) as *"different forms of vegetated wall surfaces, based on the spreading of plant species across the wall surface by using vertical structures, which may or may not be fixed to an indoor wall or to a building facade"*. Other studies complement this definition by including all elements that support the growth of the vegetation [35, 40] as well as the deliberate planting and controlled fashion of growing [58]. A VGS is also often referred to as 'green wall', 'vegetated facade', 'vertical garden', 'vertical landscaping' or with nearly similar terms such as 'vertical green', 'green vertical system' or 'vertical greenery system' [58–61]. Because these are regarded as synonyms, this study consistently employs the term vertical greening systems (VGS), with reference to the above definition.

4.2 Classification

Although there is no consensus on a comprehensive classification for VGS, the majority of studies adopt a classification according to the growing method and supporting structure employed [32, 35, 59, 62, 63]. This results in an evident split in two major system types: green facades and living wall systems, as shown in figure 4.1 [15, 35, 59]. Likewise, other studies use a distinction between ground- and facade-bound greening [37, 43] or extensive and intensive systems [64].

Alternatively, more elaborate classifications are based on the main components and factors of VGS variants [65]. Wood, Bahrami, and Safarik [58] argue that the four key components in VGS are plants, planting media (e.g. substrate), the supporting structure which can hold plants (e.g. containers) and irrigation systems. The supporting structure provides the strength to VGS and carries and transfers safely all the loads that are caused by each component [36]. A fifth distinctive component is the presence of drainage and its features [35, 66].

In line with the most commonly used classifications, seven VGS types are defined as design alternatives in the multi-criteria approach. The taxonomy in figure 4.1 provides an overview. Systems excluded from this study, e.g. because they are not well embedded well in research, are listed in appendix 11.2.

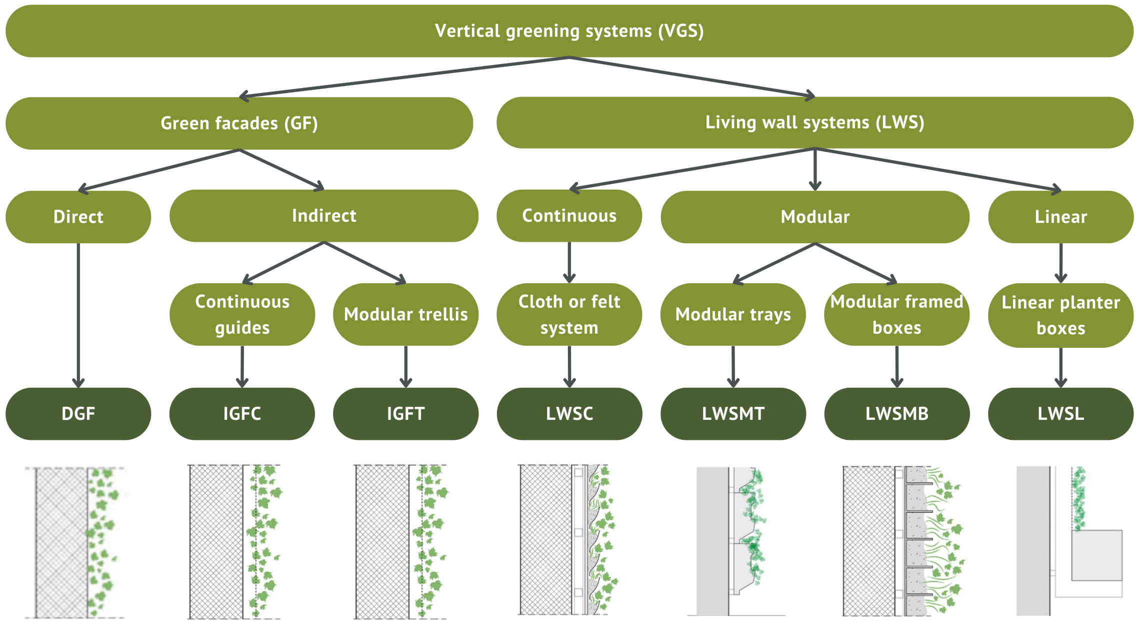


Figure 4.1: Taxonomy of VGS types (own work; cross sections from [62], [67])

4.3 Green facades

The distinctive feature of green facades (GF) is a vegetation cover formed by climbing or hanging plants, growing from ground level [62]. The plants are rooted into the soil at the base of the building [3]. Most studies divide green facades into a direct and indirect, or double-skin, category. Table 4.1 shows the system components and characteristics of the three types of green facade.

4.3.1 Direct green facades

Traditional direct GF systems (DGF) consist of plants directly attached to the wall and have no additional growing support (figure 4.2). The self-clinging climbers adhere to external walls through adventitious roots or self-adhesive pads [68]. Although some reviews of the VGS market did not consider direct GF [15, 36] this study includes them because they are deliberately planted and thus an option for designers.

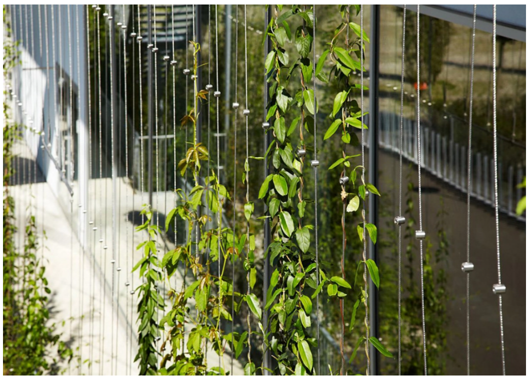
4.3.2 Indirect green facades

Nowadays, GF systems are usually indirect. Indirect green facades contain a lightweight support structure upon which plants climb, are guided and spread out [62]. The climbing aid is placed at a small distance from the building facade, creating an air gap. For indirect GF, the two available system types are continuous guides (IGFC) and modular trellis (IGFT), which differ in the integrality of their supporting structure [35, 48, 66]. In a market review by Ogut, Tzortzi, and Bertolin [36], 75% of indirect GF had modular trellis.

According to Manso and Castro-Gomes [35], continuous guides (IGFC) are based on a single support structure that directs the development of plants along the entire surface. Similarly, Ogut, Tzortzi, and Bertolin [36] identify systems with vertical cables, horizontal cables and/or rods, and Pérez et al. [64] describes wired structures that consist of steel cables, anchorages, separators and other features. Figures 4.3a and 4.4 show the linear cables of IGFC systems.

Indirect GF with modular trellis (IGFT) result from the installation of several modular supporting elements along the surface (figure 4.3b) [35]. The supporting structure is constituted by modular

Figure 4.2: Direct green facade (DGF) in Munich (own work)



(a) Indirect green facade with continuous guides (IGFC) [69]

(b) Indirect green facade with modular trellis (IGFT) [69]

Figure 4.3: Indirect green facades

trellis (also referred to as 3D trellis), a grid system (2D trellis, nets) or a mesh structure, mounted to the building wall or independent structures [15, 36, 64].

The light-weight supporting structure indirect GF have in common prevents the falling of vegetation, creates an air gap between the building surface and vegetation – beneficial for insulation and maintenance – and increases the system resistance to rain, wind and snow [66]. A choice for supports made of steel (stainless, coated or galvanized), wood, aluminium or plastic changes the aesthetic and functional properties, because of different weights, profile thicknesses, durability and costs [70, 71].

4.3.3 Green facades characteristics

Compared to other VGS, green facades are characterized by a straightforward installation and design, and are relatively cost-effective and easy to maintain, due to the simplicity of the system and because tasks related to the irrigation or fertilizing can be performed at ground level [48, 62, 67]. Watering of GF needs to be done manually, periodically depending on the environment, and more often when

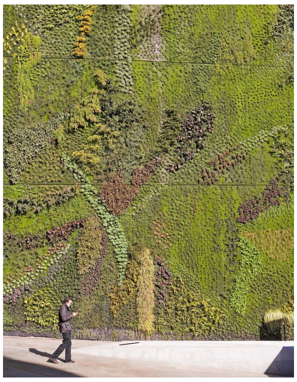
Figure 4.4: Attachment of climber plant on climbing aid [69]

Table 4.1: Components and characteristics of green facades (* = Detailed cost overview in section 5.13)

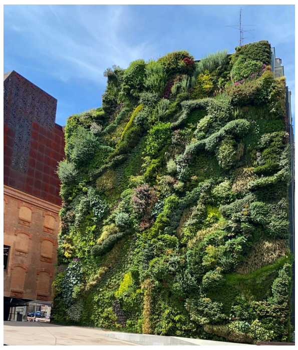
System type	**Green facades (GF)**		
Category	Direct	Indirect	
Subcategory		Continuous guides	Modular trellis
Code	DGF	IFGC	IGFT
Similar designations	Traditional green facade	Cable wire system, IGFC – cable/rope, Wired, Cable and wire net system	Double-skin green facade, 3D modular trellis, 2D grid system, Mesh system IGFT – trellis/mesh, Modular trellis, Mesh structure, Modular trellis panels
System components			
Supporting structure		Lightweight support structure of steel, wood, plastic or aluminium: cables, ropes, rods	Lightweight support structure of steel, wood, plastic or aluminium: nets, trellis, meshes
Growing method	Soil-based		
Cultivation	Ground soil		
Vegetation	Mostly self-clinging climbers or hanging plants (e.g. English Ivy, Boston Ivy)		
Irrigation	Manually, periodically depending on plants and climate		
Drainage	-	-	-
Characteristics			
Growing speed	Slow	Medium-slow	
Weight (kg/m^2)	5	20-30	
Installation costs* (€/m^2)	Low (22-39)	Medium (127-270)	
Maintenance costs* (€/m^2/y)	Low (205)		

planted in the 'rain-shadow' of the facade (Interview A). Green facades are relatively light, having a structural weight between 5 and 30 kg/m2 (table 4.1).

However, GF systems imply extra work in case of damages and maintenance of the facade itself, because it is difficult to remove part of the planting [67]. It is also important to consider that it can take years for vegetation to cover the desired surface [72] (Interview A), for example, climbers



(a) LWSC at Caixa Forum short after construction in 2014 [73]



(b) LWSC at Caixa Forum in full bloom in 2021 [73]

Figure 4.5: Living wall system with continuous felt system (LWSC) in Madrid

can grow between 3 and 10 meters in their first 4 years [63]. The growing speed depends on the orientation [5] and the plant species – as different climbing plants can grow up to between 5 and 25 meters high [32]. When the size and thickness of the vegetation need to be controlled, pruning is necessary (Interview A).

4.4 Living wall systems

The second category of VGS concerns living wall systems (LWS) which involve a supporting structure and at-height growing medium adapted to different cultivation systems, fixated to the building facade ([39, 57, 62]). As opposed to GF, plants are not in contact with the soil at ground level, but the entire habitat of the plants is located on the facade itself ([37, 59, 63]. Because of the many variations in living wall systems, LWS products make up 83% of the list of VGS products on the market. Medl, Stangl, and Florineth [43] categorize LWS according to the integrality of the application method, being continuous, modular or linear.

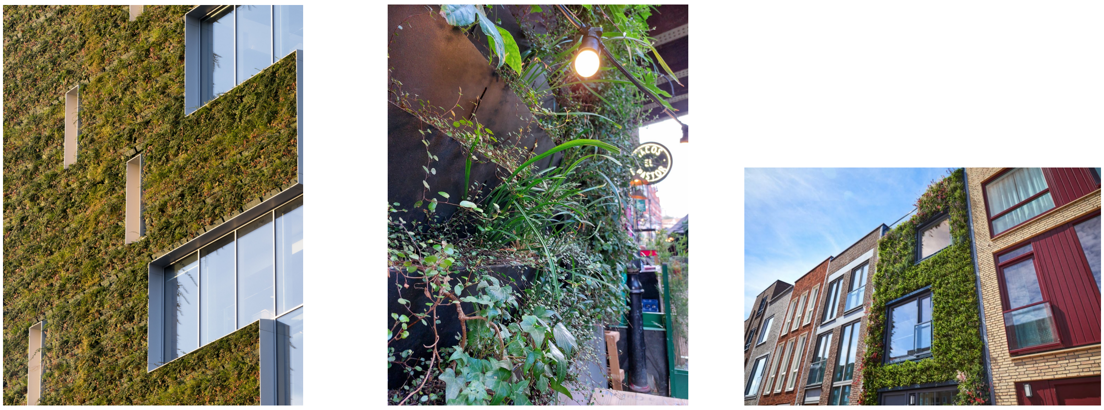
4.4.1 Continuous LWS

Continuous LWS (LWSC) are based on the application of lightweight, permeable, flexible and root-proof screens (such as a fabric layer), which form small pockets to insert plants individually [35, 66, 67]. Figure 4.5 shows an application of LWSC at the Caixa Forum in Madrid. The single support structure of continuous LWS consists of the screen attached to a waterproof base panel, in turn held by a supporting frame indirectly fixed to the wall [43]. Therefore, continuous LWS have a reduced width compared to other LWS [62].

Typically, the fabric layer is made up out of several felt or textile layers, hence this system is also referred to as a cloth or felt system, or geo-textile felt system [15, 62]. The felt can be cut on-site or prefab modules with already prepared pockets can be used [62]. The absorbent fabric layer also serves as drainage [43, 66].

The growing method of LWS is either hydroponic, i.e. soil-less (76% of products), or soil-based [36]. Hydroponic cultivation involves a growing medium, i.e. the place where the roots of plants thrive, which can be an organic fibrous medium (e.g. sphagnum moss) or mineral-based fibrous or granular media (e.g. foam) [36]) A permeable layer ensures the uniform distribution of water and nutrients received from the irrigation system [35].

Continuous LWS are mainly based on hydroponic cultures, with the geo-textile layered pockets serving as growing medium, and thus require no soil substrate [43, 66]. The irrigation system of continuous LWS usually consists of a drip line at the top of the wall and works as a closed circuit, based on gravity and capillarity [36].



(a) LWS with modular trays (LWSMT) at Venlo city hall [74]
(b) LWS with modular trays (LWSMT) in London (own work)
(c) LWS with modular boxes (LWSMB) in Delft [75]

Figure 4.6: Modular living wall systems

4.4.2 Modular LWS

Otherwise, the more recently developed modular living wall systems are based on several elements with a specific dimension, designed to include growing media where plants can grow [32, 35]. The modules are supported by a complementary structure or directly fixed to the wall [35].

Differences in composition, weight and assembly determine a further classification. Firstly, modular trays (LWSMT), also referred to as modular panels, employ rigid containers or linear pots made of plastic or steel, attachable to each other, that hold the plants and substrate (figure 4.6a and 4.6b) [35, 48]. Secondly, modular framed boxes incorporate smaller elements, such as planter tiles, flexible bags or vessels (figure 4.6c) [15]. Planter tiles are designed as modular facade cladding with insertions for plants. Flexible bags include lightweight materials and a growing medium that allow application on curved or sloped surfaces [35]. A key difference is that modular trays (LWSMT) employ vertically growing plants, while modular framed boxes (LWSMB) often have more horizontally growing vegetation.

The growing medium of modular LWS can be inorganic (e.g. foam, rock wool) or organic (e.g. soil, sphagnum moss, coconut fibre) substrate [15, 66, 67]. The drip lines for irrigation are generally installed on top of each module.

4.4.3 Linear LWS

A system that combines linear planter boxes (e.g. aluminium or plastic) at intermediate heights (e.g. every floor level) with a climbing aid structure is referred to as a linear living wall system (LWSL). The system can be useful in case of very tall buildings (since it provides faster coverage than GF) or in case of a lack of space at the base of the building [36, 37, 66, 76]. Some studies refer to it as an indirect green facade with planter boxes [3], but this study regards it LWSL because of its at-height rooting and extensive characteristics.

A variation of LWSL are perimeter pots, which consist of planter boxes around the perimeter of the building, with numerous possible plant species (e.g. hanging shrubs) but without climbers on a climbing aid [61]. The characteristics of perimeter pots are regarded similar to LWSL in this study.

4.4.4 LWS characteristics

Different types of VGS, and especially LWS, have been developed over the last years as designs are optimized and new types are developed [77, 78]. Table 4.2 provides the system components and characteristics of LWS. Planting of LWS can be performed on site, by placing small plants into perforations, or through pre-planted modules [62]. The latter is often the case for modular LWS

Figure 4.7: Linear living wall system (LWSL) in Milan (own work)

and involves planting of pre-cultivated vegetation, creating pre-vegetated modules, and subsequent suspension and fixing to the building structure [59, 66]. Even though LWS usually employ evergreen plants, the choice of plant species is influenced by the characteristics of the type of VGS, climate and environmental conditions [62, 67]. The design considerations in selecting plant species are elaborated in section 5.14.

The structure supporting the plants in LWS can be constructed directly to the wall with uprights and brackets, or indirectly through an auxiliary substructure [36]. Most common is the galvanized steel grid, but other options are stainless steel, aluminium or plastic as structural support [36]. For continuous and modular LWS, a waterproof membrane protects the structure from moisture [40, 43].

Table 4.2: Components and characteristics of living wall systems (* = Detailed cost overview in section 5.13)

System type	**Living wall systems (LWS)**			
Category	Continuous	Modular		Linear
Subcategory	Cloth or felt system	Modular trays	Modular framed boxes	Linear plant boxes
Code	LWSC	LWSMT	LWSMB	LWSL
Similar designations	Geotextile felt system, Felt layers, Pocket (felt) system, Geotextile felts, Felt pockets vertical garden, Lightweight screens, LWFL - geo-textile layers, Continuous GW, Felt system	Modular trays, Rigid containers, Panels, Vertical panel, Modular panel system, Modular trays, LWFS – foam substrate	Pocket system, Hanging pocket, Horizontal felt system, Grid panel, Foam substrates, Planter tiles, Flexible bags, Modular vessels	Trough planters, Carrir system, Planter box-based planting, Trellis and container system, Flower pots, IGFB – planter boxes, LWS based on planter boxes, Indirect with Planter boxes
System components				
Supporting structure	Textile or nonwoven felt with pockets, supported by back layer and optional substructure	Container elements of galvanized steel, polyethylene or recycled plastic, optional substructure	Galvanized steel, polyethylene, or recycled plastic panels, optional substructure	Planter boxes at different intermediate heights, combined with climbing aid, connected by means of light supporting structure
Growing method	Hydroponic cultures with(out) organic substrate	Hydroponics or soil-based, modules with (in)organic substrate	Hydroponics or soil-based, modules with (in)organic substrate	Soil-based
Cultivation	Geo-textile layers	Containers with (in)organic substrate	Modules with (in)organic substrate	Planter boxes with soil or (in)organic substrate
Vegetation	Wide range of species	Wide range of species	Wide range of species	Mostly climbers, hanging plants and shrubs
Irrigation	Computerized irrigation (1-5 l/m^2/day), drip line at top of the wall	Computerized irrigation (1-5 l/m^2/day), drip line on top of each module	Computerized irrigation (1-5 l/m^2/day), drip line on top of each module	Periodically depending on plants and climate
Drainage	Absorbent fabric layer	Lateral and inferior holes		Planter boxes with inferior holes
Characteristics				
Growing speed	Fast			Medium-fast
Weight (kg/m^2)	> 50			25-60
Installation costs* (€/m^2)	High (210-590)			Medium (190-365)
Maintenance costs* (€/m^2/y)	High (40-100)			Low-medium (5-7.5)

Design of the irrigation system is essential to guarantee proper watering of the plants (Interview A). It consists of horizontal hoses with drippers (drip lines) that drain the entire facade or modules, after which excess water leaves through a drainage system, which can be containers perforated on the side or a gutter system [36]. For LWS, an automated watering system supplies the right amount of water, which can vary between 1 and 5 l/m2/day [48]. An optional feature, especially in the case of inorganic substrates, is application of fertilisers (fertigation) to supply nutrition, e.g. through the drip lines [36, 62].

LWS often weigh more than 50 kg/m2, making them heavier than GF. The load-bearing capacity of the primary structure can often handle this load, which is elaborated in section 5.14.

In comparison to green facades, living wall systems demand a functionally more complex design and construction, because there are more variables to be considered, including the layers involved, supporting materials and control of water and nutrients [67]. This implies higher installation and maintenance costs, e.g. due to different lifetimes (and replacements) of components (table4.2) [32].

Still though, LWS offer the opportunity to plant a wide range of suitable plant species – creating more aesthetical potential – and to cover a (high) façade rapidly or even instantly when installing pre-vegetated panels [5, 67]. Also, pre-vegetated LWS can be exploited to obtain environmental benefits from the moment of installation [62].

4.5 Conclusion: seven alternatives

This study identifies seven types of VGS as the main system typologies (table 4.3), in answer to RQ1. These systems serve as design alternatives, i.e. options, in the MCDM approach. The range of systems creates a decision problem: what system is most suitable to apply in a building project? The following chapters elaborate on ways to solve this issue according to the multi-criteria decision-making approach.

System type	Abbreviation
Direct green facade	DGF
Indirect green facade with continuous guides	IGFC
Indirect green facade with modular trellis	IGFT
Continuous living wall system with cloth or felt system	LWSC
Modular living wall system with modular trays	LWSMT
Modular living wall system with modular boxes	LWSMB
Linear living wall system with planter boxes at every floor level	LWSL

Table 4.3: System types and abbreviations

Part II

Objectives and scoring

Chapter 5

Criteria, performances and parameters

The next step in constructing a MCDM framework is to identify objectives and criteria that reflect the value associated with the consequences of each alternative [49]. To evaluate the VGS alternatives, this chapter:

- Discusses existing evaluation approaches
- Identifies benefits and burdens of VGS that serve as evaluation criteria in the MCDM approach
- Identifies suitable indicators to express the performance of VGS
- Derives performances of VGS alternatives
- Identifies environmental and systems design parameters that affect performances

5.1 Evaluation approaches

Ways to assess VGS, in order to select and design them, have already been developed to some extent in literature and practice. Appendix 11.5 thoroughly analyzes the scope and limitations of existing design guidelines. This section discusses some of the concepts, perspectives and approaches to evaluating VGS.

Some evaluation approaches focus purely on the potential ecosystem services that different types of VGS can deliver ([45]). Ecosystem services can be defined as nature's benefits to society and economy (Perini, 2021). They can used by a city for its provisioning (e.g. energy), regulating (e.g. of air quality, noise, climate), cultural (e.g. recreation) and habitat needs ([17]; [3]). Dover [8] has depicted a non-exhaustive overview of the ecosystem services which can be provided by green infrastructure in urban areas, as shown in Figure 5.1.

Approaches to evaluate sustainability of VGS include life cycle assessment (LCA) methodology, which can be used effectively to demonstrate if a VGS can be considered environmentally sustainable or not (Perini, 2021). However, research has not been able to capture all environmental benefits of VGS in LCA methods (section 5.12).

A social cost-benefit approach (SCBA) focuses the added value of VGS to environment and society expressed in monetary values [46, 79]. Although this economic perspective is useful for decision-makers, this research adopts the MCDM approach to also include values that cannot be readily be quantified against a monetary scale, but that can be expressed in a qualitative indicator (see chapter 2) [50].

To holistically evaluate VGS, this study adopts a multi-criteria decision-making approach integrating ecosystem services, economic costs and benefits, and environmental impacts associated with VGS.

Figure 5.1: Ecosystem services provided by green infrastructure [8]

5.1.1 Impact on building and urban level

Although the application of VGS is a measure at the building level, the impact of VGS is felt at the building and urban level (figure 5.2). Some benefits affect the building occupants and/or the owner, such as provision of thermal indoor comfort. Whereas the client (building level) often bears the costs, the public or pedestrians (urban level) are beneficiaries of ecosystem services such as mitigation of air pollution or urban heat islands. Therefore, the framework also aims to indicate whether aspects affect building or urban level.

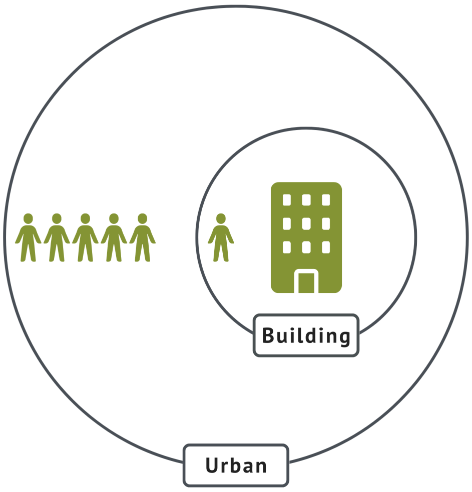


Figure 5.2: Building and urban impact levels of VGS (own figure)

5.2 Chapter outline

This chapter reviews the ecosystem services and other effects delivered by VGS, their mechanisms and potential to mitigate urban sustainability issues. Through an explorative literature study (appendix 11.3) complemented with semi-structured expert interviews (appendix 11.4), an integrated set of criteria was found. Some aspects associated with VGS are excluded from the set of criteria due to a lack of evidence (appendix 11.6).

It turns out that VGS can be vital to improvements in thermal performance on a building scale, as well as regulation of urban heat islands, air quality, noise, urban biodiversity and sustainable water management. In a softer way, VGS contribute to aesthetics and human health and well-being. In addition, economic and environmental impacts and functionality aspects are discussed. For every evaluation criterion, its mechanisms, performances of different VGS, parameters affecting that performance and key takeaways are discussed.

5.3 Thermal performance and energy savings

The contribution to thermal comfort is the most dominant and well understood benefit in VGS research. On the one hand, the improved thermal performance makes VGS a passive tool for indoor heating and cooling energy savings at the building scale. On the other hand, the reduction of outdoor ambient air temperatures can mitigate the urban heat island effect (UHI) at the city scale [80]. This section covers the building thermal performance and energy savings, while urban UHI mitigation is covered in section 5.4.

5.3.1 Issue

Two issues play a role when looking at thermal performance of buildings.

First of all, indoor thermal comfort in buildings is essential for a comfortable indoor climate for the people working or living in them [81]. When ambient conditions are hot, associated heat stress can increase mortality and morbidity, as well as increase adverse pregnancy outcomes and negatively affect mental health [82]. Since half of the global population and more than 1 billion workers are exposed to high heat episodes and about a third of all exposed workers have negative health effects, creating a healthy working environment is essential and improves users' well-being and productivity [82]. Mitigating heat stress is a priority in the Dutch built environment as well [83].

Secondly, buildings account for 40% of the world's total energy consumption, a significant substantial proportion of which is used by commercial buildings for heating, cooling and lighting. This accounts for around 10% of greenhouse gas emissions [9, 84]. Dover [8] explains how this significant energy consumption is linked to climate change. Directly, using energy from non-sustainable sources for heating and cooling increases CO2 emissions. More indirectly, air conditioning increases urban heat islands as hot air is released into the local environment. In addition, for a typical building in hot and warm climates, the rise in urban temperatures will further increase the building's cooling energy by 23% [85]. Therefore, reducing the energy consumption of buildings is essential to prevent the negative impact of buildings on the environment [9].

5.3.2 Mechanisms

Four main energetic effects established by Pérez et al. [64] alter heat transfer pathways and the thermal micro-climate in and around buildings with a VGS.

Firstly, the shading provided by vegetation intercepts incoming solar radiation before it reaches the building facade. This prevents the underlying surfaces from heating up by absorbing and reflecting a fraction of the radiation [26]. The shadow effect is the most studied and is considered to be the most important driver for cooling at building level [26, 80] (Interview A).

The second effect is the absorption of latent heat through evapotranspiration from plants and substrate [86]. Transpiration refers to the release of water by plants which cools the surrounding air. Evaporation refers to the transfer of water to the air from the substrate, or from water captured by the plant during precipitation or dew [26].

Thirdly, the VGS construction layers such as plants, substrate, panels and air gap bring along additional thermal insulation capacity. The heat resistance of these construction parts (R_c) adds to the total heat resistance of the facade (R_T), according to the formula:

$$R_T = R_{si} + R_c + R_{se}$$

Heat resistance is expressed in m^2K/W, and R_{si} and R_{se} are the heat transfer resistance at inside and outer surface [81].

Fourth, the plants and supporting structure can enable evaporative cooling by acting as a wind barrier. The presence of a VGS results in wind speed reductions within the foliage, and higher wind speeds on the outside of the foliage [67, 87]. The enlarged wind speed difference along the edge of the vegetation enhances evaporative cooling.

In other words, the shading, cooling, insulation and wind barrier effect play a role in the thermal behaviour of VGS [3], as shown in Figure 5.3.

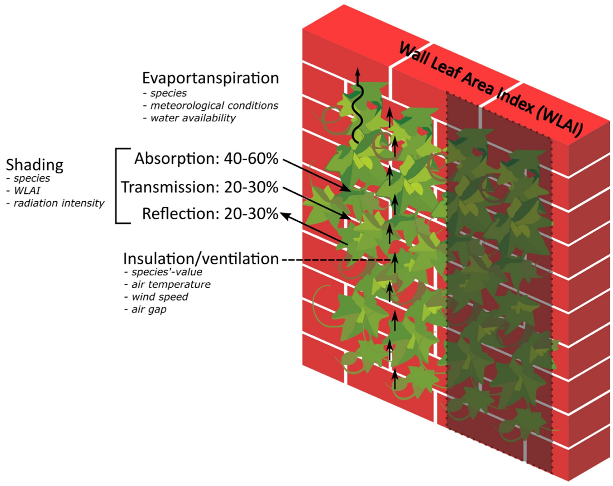


Figure 5.3: Schematic overview of VGS cooling mechanisms and their determining parameters [26]

5.3.3 Performance

The thermal performance of VGS is defined as the impact of VGS on building heat transfer [10]. VGS can be a passive solution to reduce wall surface temperatures on hot summer days, therefore mitigating indoor heat stress [88]. VGS can also prevent heat losses during winter or cold nights. The two ways of damping temperature extremes can indirectly reduce the energy required to maintain a comfortable indoor temperature [88]. In other words, VGS can be passive systems for energy savings in buildings [80].

To characterise the effect of VGS on indoor thermal comfort, different indicators have been studied. The thermal benefits are demonstrated in research by either temperature differences for different locations compared to a bare wall, or by calculating the heat transfer through the facade [48].

Bakhshoodeh, Ocampo, and Oldham [10] identified $\Delta T_{externalwall}$, i.e. the difference in the temperature of an external wall surface behind a VGS and a similar nearby external wall without a VGS, as an indicator of improved thermal performance provided by the VGS. These external wall surface temperature reductions are the most reported parameter and are discussed hereafter as an indicator of mitigating indoor heat stress. The parameter is referred to as ΔT_{ow}. Other indicators and indirect energy savings are discussed subsequently. Figure 5.4 visualizes the external wall surface, air gap and ambient air for (in)direct green facades.

External wall surface temperature reductions

The building external wall surface temperature reduction (°C) due to the effect of the VGS is the most usable parameter to compare the effectiveness in thermal performance of different VGS [61].

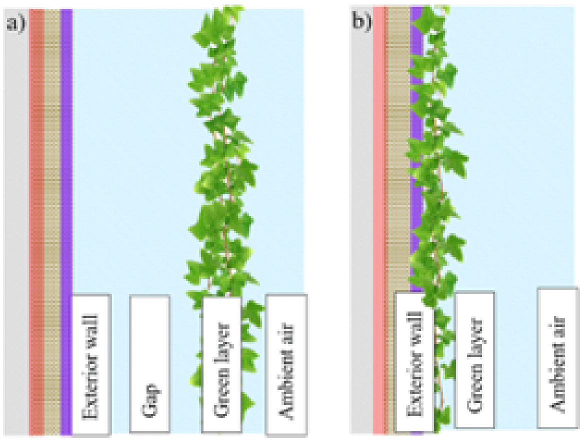


Figure 5.4: The regions defined for indirect (left) and direct GF (right) [10]

Pérez et al. [61] reasons that it is the first and most direct effect of a "sunscreen" mechanism, and that "neither the heat fluxes through the wall nor the interior surface wall temperature are comparable due to the differences between constructive systems of the facade building wall". This temperature difference on the outer surface of the building wall (ΔT_{ow}) is therefore considered an appropriate empirical indicator of VGS thermal performance.

The results of previous research show a pronounced insulating effect and a significant reduction in temperature fluctuations during both cooling and heating periods, corresponding to summer and winter in the northern hemisphere, respectively. Overall, review studies found that greened walls are cooler in summer and slightly warmer in winter, proving that VGS can mitigate temperature extremes [26].

The majority of studies consist of experiments with a bare control wall without VGS under similar conditions [43]. The surface temperature regulation potential can be clearly differentiated by VGS type [80]. Appendix 11.7.1 includes a literature study, analysis and table with the maximum surface wall reductions found in different conditions, for all VGS types.

Synthesis ΔT_{ow} Table 5.1 shows the mean ΔT_{ow} from the previous literature study and from review studies [10, 26, 89], as well as type-specific assumed performances for this MCDM study. Since ΔT_{ow} is a well-studied parameter, it is considered a suitable indicator of achieving indoor thermal comfort through VGS. A distinction between indoor thermal comfort and the following energy savings is made for adopting criteria. Therefore, ΔT_{ow} is adopted as an indicator for reducing indoor heat stress in cooling periods in the MCDM framework.

For cooling periods, performances per VGS type are assumed based on the literature study average. Although the cooling performance of LWSL is based on merely one study, its value (-8 °C) is considered reasonable, because LWSL consist of roughly the same volume of materials (that enhance insulation) as LWSMT. Mean temperature reductions from Koch et al. [26] confirm the relative performance differences for (in)direct GF and LWS. A review study of (in)direct GF shows that especially under warm conditions, IDGF perform better than DGF [10]. Since Susca et al. [89] found a median of -17.5 °C for summer daytime in Cfb climates, this might suggest that actual reductions in Cfb climate are higher than assumed. However, not enough comparable data is available to apply this suggestion in the considered performances already.

For heating periods, energy savings (%) instead of ΔT_{ow} are used as indicator for indoor thermal regulation. However, ΔT_{ow} in heating periods does create an understanding of the heating effect of VGS. For heating periods, the mean ΔT_{ow} for DGF from the literature review is considered. For IDGF, the mean from [10] is considered, since no study for IDGF was found in the literature review. Bakhshoodeh, Ocampo, and Oldham [10] also confirms the larger increment for IDGF, compared to

Table 5.1: Synthesis for assumed performances of ΔT_{ow} (°C) for cooling and heating periods (est. = estimation from graph; value in brackets = single study)

			Cooling				
	DGF	**IDGF**	**LWSC**	**LWSMB**	**LWSMT**	**LWSL**	**Source**
Mean of maximum ΔT_{ow}	-9.4	-12.7	-19.5	-13.3	-8.5	(-8.4)	Literature study
Mean ΔT_{ow}	-8 (est.)	-9 (est.)		-11 (est.)			[26]
Mean ΔT_{ow} in hot conditions (ΔT_o>30 °C)	-3.2	-3.1	-	-	-	-	[10]
Mean ΔT_{ow} in warm conditions (ΔT_o = 20-30 °C)	-0.5	-1.3	-	-	-	-	[10]
Median ΔT_{ow}, daytime, Cfb			-17.5				[89]
Assumed performance	**-9.4**	**-12.7**	**-19.5**	**-13.3**	**-8.5**	**-8.4**	
			Heating				
	DGF	**IDGF**	**LWSC**	**LWSMB**	**LWSMT**	**LWSL**	**Source**
Mean of maximum ΔT_{ow}	+2.4	-	-	(+0.5)	(+3.5)	(+10.6)	Literature study
Mean ΔT_{ow}	+1.7 (est.)	(+3.5) (est.)		+4.0 (est.)			[26]
Mean ΔT_{ow} in cold conditions (ΔT_o <10 °C)	+0.1	+2.8	-	-	-	-	[10]
Median ΔT_{ow}, daytime, Cfb			-3.6				[89]
Assumed performance	**+2.4**	**+2.8**	**+4.0**	**+4.0**	**+4.0**	**+4.0**	

DGF. For LWS, only single studies per LWS type were found, so the average ΔT_{ow} found by [26] is assumed.

As VGS in Cfb climate showcase a median ΔT_{ow} decrease on winter days, rather than the common increase, more research about the exact effect during heating periods in Cfb climate might be helpful. Koch et al. [26] suggests to apply deciduous plants in winter or cooler climates, to allow for solar heat transmission into the building in cooler conditions. From that perspective, an increase in ΔT_{ow} is beneficial and can help in energy savings for heating. Oppositely, other studies state that VGS can isolate and protect against freezing of the building facade in the same time frame [70]. One way or the other, this study considers the heating effects of VGS in winter periods for energy savings (next section), although the actual effects and their desirability in Cfb climate should be further investigated.

Other indicators

Although other parameters, such as heat flux or indoor temperature, are difficult to compare due to construction differences and limited data [61], they show the moderating effect of VGS on indoor temperatures, improving thermal comfort, especially during cooling periods (appendix 11.7.2).

Energy savings

Accordingly, the thermal effect of VGS has the potential to reduce the building energy demand in summer and winter. Tables 5.2 and 5.4 provides an overview of energy saving performances for cooling and heating periods, respectively.

Table 5.2: ΔE_c for different VGS types (adapted from [26] and [7])

Cooling energy savings ΔE_c (%)	Energy savings (kWh)	Maximum external wall surface temperature difference (C)	Period	Climate	Orien-tation	VGS type	Plant species	Type of study	Source
33.8		-13.9	s	Csa	E-S-W	IDGF	P. triscuspidata	Exp.	[90]
34		-16.4	s	Cfa	E,S,W	IGFT	P. triscuspidata	Exp.	[91]
26	62.03 kWh/p	-	s	Csa	S	LWSC	Cistus Jessami beauty and Cistus crispus	Exp.	[92]
-	1.45 ± 1.85 kWh	-16.0	w,s	Cwa	W, W-SW	LWSMB	Perennial grass	Exp.	[93]
58.9		-20.1	s	Csa	E-S-W	LWSMB	Rosemarinus officinalis, Helichrysum thianschanicum	Exp.	[90]
97		-15	s	Cfb	E, W	LWSMB	Sedum, Mentha, Thymus, Vinca, Campanula, Delosperma	Exp.	[94]
20		-19.3	s	Cfb	Several	-	P. triscuspidata	Mod.	[95]
50.6		-	s	Cfb	N,E,S,W	-	-	Mod.	[96]
37.7		-	s	Csa	N,E,S,W	-	-	Mod.	[96]

Cooling For cooling periods, various articles show reductions of peak air conditioning (AC) energy demand (ΔE_c) as an indirect benefit of VGS. In temperate climates (C), two studies found that IDGF can reduce cooling demand by 34% [90, 91]; (table **??**). The latter study estimated 58.9% savings in similar conditions for a LWSMB [90]. Cooler AC air intake (on average 5 °C) results in an average 26% summer energy saving for an LWSC, corresponding to 62.03 kWh/person, according to Perini et al. [92]. Absolute quantitative reductions in power consumption vary, as another study estimated a 1.45 ± 1.85 kWh reduction for an LWSMB [93]. Therefore, relative reductions (%) are more suitable for comparisons. Nevertheless, Cheng, Cheung, and Chu [93] shows that a ΔT_{ow} of -16.0 °C is associated with cooling energy savings. Another study confirms a strong relation between lowering surface temperatures and energy saving potential, and attributes this to a reduced heat flow into the building, which helps to reduce cooling loads [97].

Modelling studies simulate cooling energy savings from VGS and show reductions between 3% [98] and 50% [96] in different climates. Most frequently, reductions are between 20% and 30% [99], such as reductions of 19% [100] and 20% [95] found in Cfb climate. Larger reductions were found by Djedjig, Bozonnet, and Belarbi [96], with 50.6% in Cfb climate and 37.7% in Csa climate as cooling savings. This shows that VGS are an effective tool for cooling energy savings in temperate (C) climates, and suggests a larger potential in Cfb climate than Csa climate.

Still though, the modelling studies have difficulty to distinguish VGS types, characterize plant species, and lack extensive experimental tests to validate their results [99]. This might explain the underestimation of cooling and heating energy saving potential by modelling studies compared to experimental studies, as shown by Koch et al. [26] in figure 5.5.

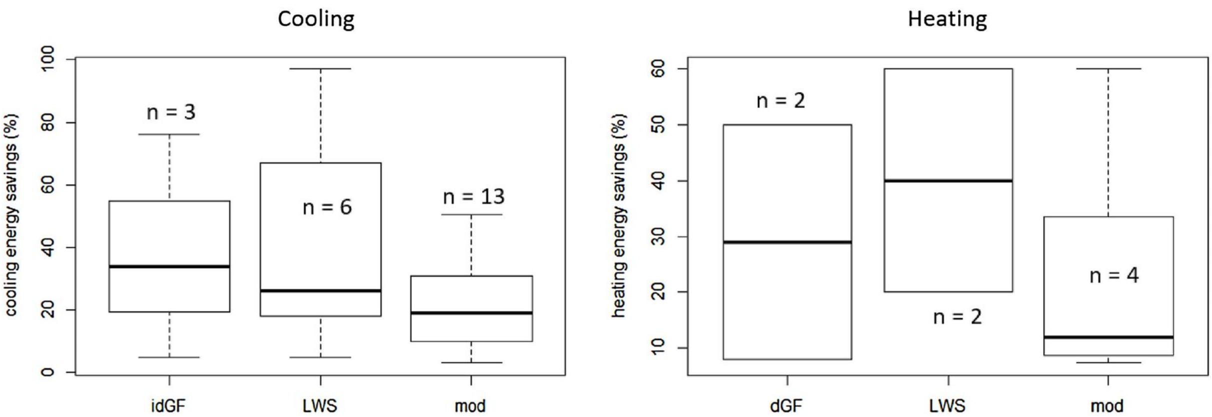


Figure 5.5: Cooling energy savings (ΔE_c ; left) and heating energy savings (ΔE_h ; right) (adopted from [26])

Overall, VGS can be a passive tool for cooling energy savings in buildings, and their performance is variable depending on VGS type [99].

Review studies show a somewhat larger mean ΔE_c for GF (34-37%) than LWS (26-34%) [26, 89], as shown in table 5.3. As Susca et al. [89] shows only LWS data for Cfb climate, also values for Csa climate were included in the table. Individual studies show widely varying values, but confirm the order of magnitude. Also, they indicate that LWSC savings might be somewhat lower [92], while energy demand savings for LWSMB can go up to 59% [90].

Therefore, assumed ΔE_c performances are mainly based on mean values found by Susca et al. [89] for Csa climate, with more specific type-specific performances based on individual studies (see table 5.3). For DGF, the lower bound of 20% found by generic modelling studies is considered.

Table 5.3: Synthesis of assumed performances for cooling energy savings ΔE_c (%) and heating energy savings ΔE_h (%) (est. = estimation from graph, value in brackets = single study)

			Cooling				
	DGF	**IDGF**	**LWSC**	**LWSMT**	**LWSMB**	**LWSL**	**Source**
Mean	-	34 (est.)	26 (est.)				[26]
Mean in Cfb climate	-	-	50.6				[89]
Mean in Csa climate	37.1		33.8				[89]
Individual studies	-	(33.8) (Csa)	(26) (Csa)	-	(58.9) (Csa)	-	Literature study
Assumed performance	**20**	**37**	**26**	**34**	**59**	**34**	
			Heating				
	DGF	**IDGF**	**LWSC**	**LWSMT**	**LWSMB**	**LWSL**	**Source**
Mean	29 (est.)	-	40 (est.)				[26]
Mean in Cfb climate	29.0		8.0				[89]
Mean in Csa climate	0.8		3.0				[89]
Individual studies	(8-50) (Cfb)	(1.9) (Csa)	-	-	(4.2) (Csa); (20) (Cfb)	-	Literature study
Assumed performance	**8**	**8**	**20**	**20**	**20**	**15**	

Heating For heating periods (table 5.4), energy savings (ΔE_h) for direct green facades in Cfb climate can be 8% on yearly average, and increase up to a maximum of 50% at a certain moment in time [101, 102]. For LWSMB in Cfb climate, a 20% decrease was observed [94]. Alternatively, Coma et al. [90] estimates an average reduction of 4.2%, owing to cooling effects because of reduced heat losses supplied by the LWSMB materials. The same study found that IDGF show an average energy saving of 1.9%, attributed mainly to nighttime insulation which reduces overnight heat losses [90].

A simulation model shows a 11.9% decrease for Cfb climate, as well as a 8.7% decrease for Csa climate [96]. This suggests that ΔE_h performance in Cfb climate is often larger than in Csa climate, which could partly explain the relatively low reductions found by Coma et al. [90] in Csa climate.

As such, it goes to show that for heating energy savings are often smaller than for cooling.

At first glance, review studies seem to show that GF reduce ΔE_h to a greater extent than LWS [89] (table 5.3). However, the mean 29% and 8% reductions for GF and LWS are likely determined by heterogeneous case studies, e.g. a LWS simulation [94] with smaller reductions than an IDGF experiment [89, 102]. Therefore, the tendency of higher LWS mean ΔE_h than for GF in Csa climate is adopted in this study, as these findings are based on more homogeneous data [89].

Due to the scattered results for ΔE_h in terms of values, typologies and climates, an estimate for performance is assumed based on the two studies in Cfb climate [94, 101], which reflects the higher heating energy savings for LWS than GF (see table 5.3).

Table 5.4: ΔE_h for different VGS types (adapted from [26] and [7])

Heating energy savings ΔE_h (%)	Energy savings (kWh)	Maximum external wall surface temperature difference (C)	Period	Climate	Orien-tation	VGS type	Plant species	Type of study	Source
8		+0.5 (mean)	w	Cfb	N	DGF	H. Helix	Exp.	[101]
50 (max.)		+3.0	w	Cfb	Several	DGF	H. helix	Exp.	[102]
1.9		-	s	Csa	E-S-W	IDGF	P. triscuspidata	Exp.	[90]
20		-	s	Cfb	E, W	LWSMB	Sedum, Mentha, Thymus, Vinca, Campanula, Delosperma	Exp.	[94]
4.2		-	s	Csa	E-S-W	LWSMB	Rosemarinus officinalis, Helichrysum thianschanicum	Exp.	[90]
11.9		-	s	Cfb	N,E,S,W	-	-	Mod.	[96]
8.7		-	s	Csa	N,E,S,W	-	-	Mod.	[96]
50.6		-	s	Cfb	N,E,S,W	-	-	Mod.	[96]
37.7		-	s	Csa	N,E,S,W	-	-	Mod.	[96]

5.3.4 Parameters

The magnitude of cooling or heating effects is highly dependent on different factors. As such, quantitative thermal performances cannot be directly attributed to certain types of VGS. While the temperature dynamics of VGS are well reported, only recently has literature explored how thermal performance changes with climate conditions, orientation and systems design. These parameters are discussed successively. Bakhshoodeh, Ocampo, and Oldham [10] points out how knowledge about parameters that can enhance effectiveness can help engineers and architects optimize design parameters to maximize the thermal benefits of VGS.

Climate conditions

Climatic parameters, such as temperatures, solar radiation, rainfall, humidity and wind, affect thermal performance of the building, VGS operation (e.g. water demand and plant growth), and thus passive energy saving potential [99]. The Köppen-Geiger climate classification is based on the annual and monthly temperature and precipitation averages, and its use is suggested by multiple authors [43, 61]. Even though studies claim that the largest number of studies conclude that VGS achieve better energy performance in warm-dry climates [15], there is no full understanding of the effect of climatic zone on passive energy savings yet.

For tropical (A), temperate (C) and continental (D) climate zones, some studies have determined outer surface wall temperature differences. Figure 5.6 shows ΔT_{ow} for temperature and continental climates. It displays considerable differences in extent of cooling and heating effects, but strengthens the observation that summer cooling effects are generally larger, in absolute terms, than winter heating effects. A review of 18 VGS studies in tropical climates complements these findings with an average tropical ΔT_{ow} of 8.8 °C [103]. It should be noted that these values are averages of a mix of VGS types.

Larger energy savings are associated with more extreme weather conditions, characterised by meteorological driving forces such as the coldest and hottest temperatures, strong wind or rain [48, 102, 104].

Evapotranspiration (ET) entails evaporation from the soil and vegetation, and transpiration from the leaf stomata, converted into water vapor. Solar radiation, determined by climate type, has the strongest influence on ET cooling [10], while sky factors (sunny, cloudy and rainy) have an influence too. Therefore, ET rates are higher on sunny days, than cloudy and rainy ones. Likewise, Koch et al. [26] states that VGS often show larger ΔT_{ow} reductions during clear-sky days, compared to cloudy or rainy ones, because of the high exposure to solar radiation, creating opportunity for the ET cooling effect, as well as for the shading effect. More radiation exposure has an amplifying effect on temperature reductions, because even under low radiation reductions, a median decrease in daytime ΔT_{ow} for all climate zones and heating and cooling seasons was found [89].

Stronger winds can enhance the ET cooling (as it replaces saturated air with drier air) as well as the wind barrier effect [99], but this influence is not quantified.

Similarly, Bakhshoodeh, Ocampo, and Oldham [10] concludes that the greatest thermal impact of (in)direct GF on an external wall takes place under the more extreme ambient air temperatures. For GF, the greatest cooling effect (3.2 °C) is observed under hot conditions and the greatest heating effect (2.8 °C) is found under cold conditions [10] (table 5.7). For more moderate cool and warm conditions, the thermal effects were smaller. This shows that GF are specifically effective in reducing wall temperatures, and presumably energy consumption, during hot and cold periods in any climate, or in climates characterised by long-lasting hot and cold periods.

Orientation

An influence of the building facade orientation on thermal behaviour is observed in past studies, highlighting increased temperature reductions for west and south oriented facades, in the northern hemisphere [90, 96]. The orientation determines sun exposure and shading over the diurnal cycle,

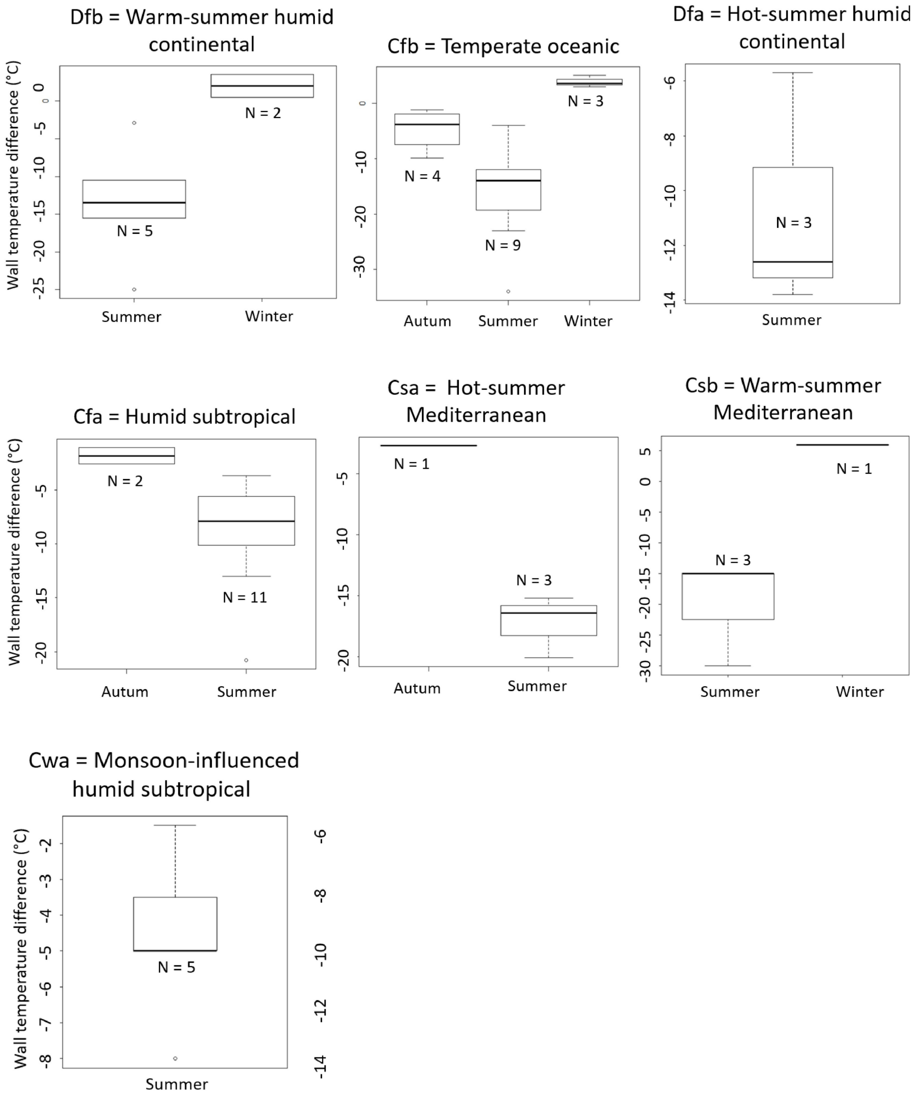


Figure 5.6: ΔT_{ow} for different Köppen-Geiger climate zones and seasons (adopted from [26])

Ambient air temperature (C)	DGF (gap width ≤ 5 cm)	IDGF (gap width 5-20 cm)
Hot (≥30 C)	-3.2 ± 3	-3.1 ± 2
Warm (20-30 C)	-0.5 ± 3	-1.3 ± 3
Cool (10-20 C)	-2.1 ± 5	No data
Cold (≤10 C)	+0.1 ± 3	+2.8 ± 12

Figure 5.7: Mean ΔT_{ow} for (in)direct green facades and different temperature conditions (adapted from [10])

which affects plant growth and thermal performance [10]. South walls in summer receive a longer period of solar radiation compared to winter, significantly increasing the external wall temperature. Thus, Jim [105] reasons that VGS could be considered a solution most appropriate for south-facing walls to provide external wall cooling during summer. Results from a recent study in Spain showed that south-facing facades reduced the annual heating, ventilation and air conditioning (HVAC) usage by about 20%, while this reduction for north-facing facades was less than 2% [106].

Figure 5.8 shows ΔT_{ow} for GF in the northern hemisphere, under different facade orientations [10]. The maximum external wall cooling was achieved for south-facing facades, followed by west, east and north-facing ones. This is confirmed for LWS in Am, BWh, Csb and Dfa climate by another review study [89]. One of the included VGS was able to reduce a southwards oriented facade

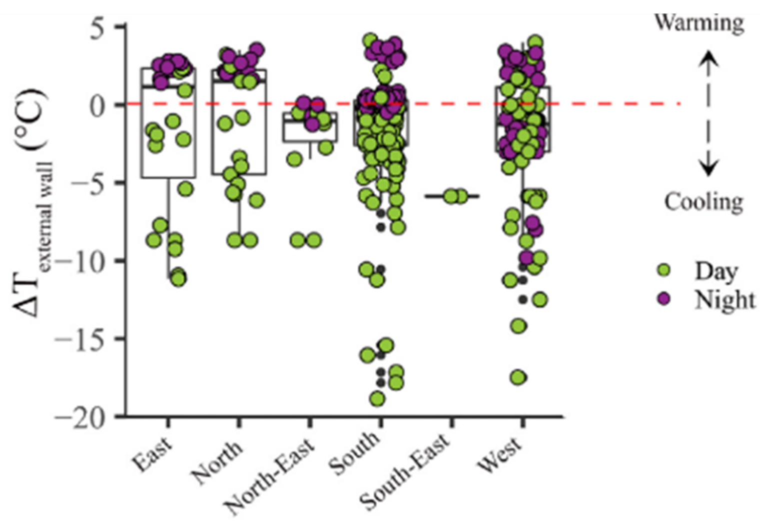


Figure 5.8: GF ΔT_{ow} for different facade orientations and day- and nighttime, in the northern hemisphere, (Boxes represent interquartile ranges, thick horizontal line indicates median) [10]

temperature by 21.5 °C, while west and east ΔT_{ow} were reduced by 6.5 °C and 4.5 °C, respectively [90]. Hence, this study identifies orientation as one of the most influential parameters to temperature reductions.

Cold-season warming ΔT_{ow} effects for GF are consistently around 3-4 °C for all orientations [10] (table 5.8). Yet some studies imply the north orientation provides the most significant surface temperature reduction during heating periods, in Cwa climate [107].

Although limited data is available on orientation as a design factor for thermal performance [10, 99], based on the results found, south-facing installation should be prioritized to maximize the daytime cooling energy saving effect of a single VGS during summer [89, 105].

Systems design

Both plant material and substrate are responsible for thermal effects [26], and their diversity makes predicting thermal performance of VGS difficult. Also other system components, such as the supporting system or air gap, play a role, specifically in adding insulation value to the thermal resistance of the building facade (Interview A).

Vegetation coverage

A review by Radić, Dodig, and Auer [15] states that the degree of vegetation coverage of the building facade is the most important parameter for cooling capacity. Jim [65] reasons that a building facade with more VGS vegetation canopy will absorb more heat flux, contributing to indoor and outdoor cooling. For DGF, Yin et al. [108] found a linear relationship between plant coverage and cooling. The coverage percentage is also regarded a key parameter for IDGF [109]. Interpretation of this parameter is elaborated under section 5.4 about UHI mitigation.

Vegetation

On average, the vegetation layer's shading effect is important for GF, whereas insulation effects of substrate and vegetation are paramount for LWS [89]. Still though, during hot summer days, evapotranspirative cooling typically dominates heat transfer [89]. As such, the predominant thermal mechanism differs per VGS type and period, which affects both building energy use and UHI mitigation efficacy [89].

Plant species According to Koch et al. [26], the shading potential partly depends on plant species. Relevant species characteristics include transpiration rate, dominant cooling mechanism, and being deciduous or evergreen.

Plant species choice can affect both ET and shade cooling. For ET cooling, a high transpiration rate is preferred [86]. For example, grass plants have a 3-4 times higher ET rate than succulent plants [10]. Still though, a plant catalogue with transpiration rates for VGS use does not exist [80], which makes it difficult to select plant species that have good ET cooling capacity. For shade cooling, the plant species albedo plays a role in the reflectivity of the VGS.

All plant species for a DGF can significantly reduce the T_{ow}, which emphasizes the importance of the shading effect for GF [102]. *Hedera* and *Stachys* were found to be the best candidates for building wall cooling, as shown in table 5.7) [110]. Yet there are differences in cooling capacity per species (table 5.9), which can be explained by different cooling mechanisms being most important [110]. For example, *Fuchsia* is more effective in ET cooling, whereas *Lonicera* and *Jasminum* provide a greater shading effect [110].

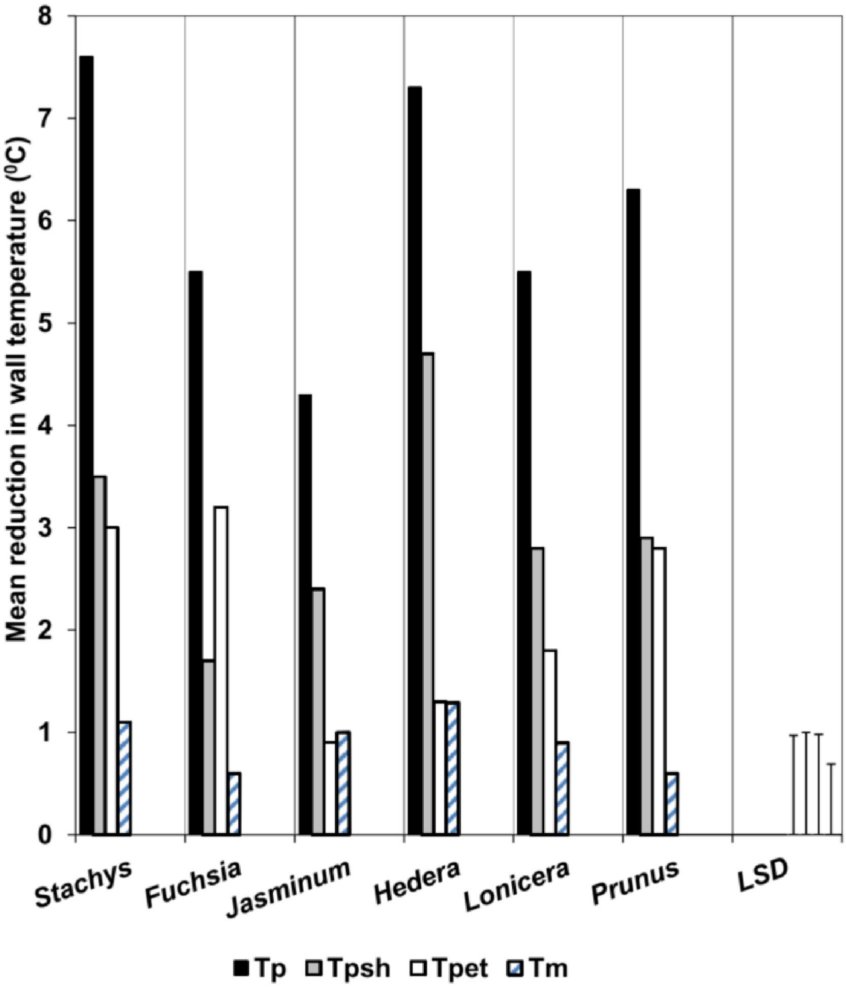


Figure 5.9: Mean ΔT_{ow} for different plant species [102]

What do these species differences imply for the thermal performance of different VGS? Typically, green facades use climbing plants, which can be deciduous or perennial (i.e., evergreen) species. Most used deciduous species are Boston Ivy (*Parthenocissus tricuspidata*) and Wisteria, and most used evergreen species is Ivy *(Hedera helix*) [99]. Oppositely, LWS most commonly use herbaceous, grass and shrub species, usually evergreen [43]. This adds to the insulation value and shading potential of VGS in wintertime (Interview A).

These typical, common species are omnipresent in the results found for temperature reductions and energy savings. Therefore, the somewhat better or worse performance of certain species is - to a certain extent - already reflected in the different performances (in energy savings and UHI mitigation) assumed for different VGS types.

Plant species characteristics are not well reported, and different plant species create different wind flow patterns alongside VGS, further complicating the insulation, wind barrier and ET cooling effect [26]. Therefore, it is not possible to predict exact species performance and to make specific plant recommendations in the framework.

For GF, the choice between evergreen and deciduous species has a strong influence on the thermal performance for energy savings. When using deciduous species, solar radiation will reach the building facade during the heating (leafless) period [99]. On the other hand, using evergreen species can enable heating energy savings. For example, an experimental study found higher heating and cooling performance for evergreen species on a LWS than for deciduous vegetation on GF [90]. Depending on the thermal requirements of a project, the choice of evergreen or deciduous species can be made.

Plant density All four cooling mechanisms are expected to depend on the leaf area index (LAI). LAI characterizes the vegetation density and is defined as the leaf area per unit wall surface area (m2/m2), i.e. the wall-projected leaf area [10].

The shading coefficient (ratio of solar radiation reaching the building wall through transmission) decreases linearly with LAI [111]. To be specific, the shading coefficient decreases by 30% when the LAI doubles [26]. So, a larger LAI enables a larger shading effect. A higher LAI results in a higher volume of plants that can transpire, and thus can also enable higher ET [10].

For an IGFT, a 34% ΔE_c was obtained for a LAI of 3.5-4.0 [91]. Moreover, a direct relationship between higher LAI and improved building energy performance for heating and cooling has been established, mainly due to shading and evapotranspiration [112].

For GF, a strong inverse relationship (Pearson coefficient of 0.78) between LAI and T_{ow} in cooling periods is found [10]. Figure 5.10 shows this relation, with high cooling (26 °C) performance for LAI of 6 and low cooling (7 °C) for LAI of 0.69. As both cases were measured on hot sunny days, this shows the large influence of LAI on thermal performance and suggests it is even more determining than radiation conditions.

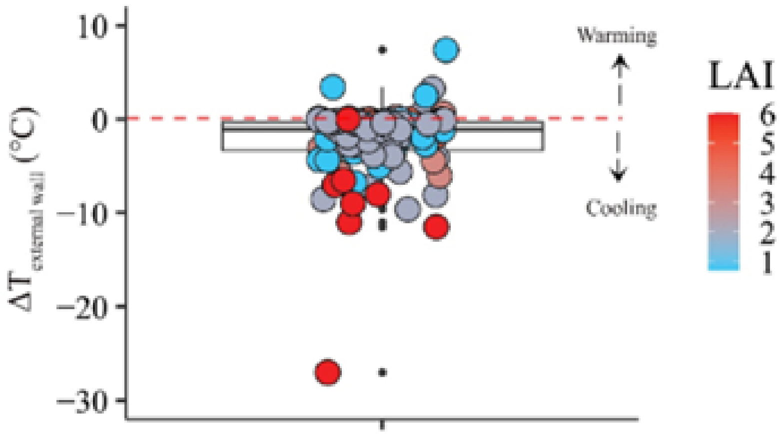


Figure 5.10: Daytime ΔT_{ow} for different LAI [10]

Foliage thickness, leaf shape and size are mentioned as plant characteristics that could affect thermal performance, but as data about these parameters is rarely reported, no definitive conclusions can be made [43].

Substrate

The presence of a substrate in LWS enables evapotranspiration from substrate and plants, which enlarges their cooling potential [70]. Within LWS, substrate moisture, typology and depth play a role [7].

Evapotranspirative cooling is affected by the volumetric water content of the substrate, i.e. the substrate moisture content [10]. Therefore, adequate irrigation is necessary to obtain optimal cooling by transpiration [26].

The substrate typology is also considered to have an effect on thermal performance [80]. However, many studies do not report about chemical (e.g. plant nutrients availability, thermal conductivity) and physical (e.g. soil structure, porosity) substrate properties [43, 68], which hinders establishing and quantifying a relation between substrate and thermal effectiveness of VGS.

Studies find that LWSMB score highest on cooling energy savings [97], and LWSC score less compared to modular systems [113, 114]. This can be related to the depth or thickness of the substrates involved. As LWSMB often consist of a thick substrate layer, this can act both as an insulator and a cooler through evaporation [26], whereas felt systems (LWSC) often have a smaller volume of substrate. These differences in thermal performance are also reflected in the assumed performances for cooling energy savings.

Air gap width

An air gap between VGS and building facade can act as a stagnant air layer and insulation barrier, which can be an explanation for the higher energy saving performances of IDGF compared to DGF [99].

A strong direct relationship (Pearson coefficient of 0.86) is found between gap width and the gap cooling effect (ΔT_g) [10]. As gap width increases, the cooling effect also increases, in terms of both the gap and exterior surface wall temperature. For example, gaps larger than 100 cm reduce T_{ow} by 3.8$\pm$4.3 °C during hot daytime conditions, whereas gaps of 25-50 cm reduce this value by 3.3$\pm$1.9 °C [10].

5.3.5 Key findings

In providing indoor thermal comfort, the key take-aways for VGS are:

- VGS are a passive tool for energy savings at building scale, because they can lower heating and cooling loads.
- Exterior wall surface temperature reductions in cooling periods (ΔT_{ow}) is regarded a suitable indicator for reducing indoor heat stress, and thereby contribute to healthy indoor climate. Indoor (ΔT_i) temperature differences support the thermal behaviour found for different VGS types.
- Energy savings for heating and cooling periods (%), respectively, explicitly express the economic benefit obtained from this ecosystem service.
- Table 5.5 shows the assumed performances in terms of ΔT_{ow} and energy savings, based on extensive literature research. Since the climatic differences are ambiguous, performances for Cfb (temperate oceanic) climate, or temperate (C) climates in general, were considered, given that sufficient data is available.
- Table 5.6 shows the parameters that determine to what extent energy savings can be achieved. Solar radiation exposure is the key factor for temperature moderation of VGS facades. It is related to the Köppen-Geiger climate class differences as well as amplified temperature reductions during sunny (hot) days and for southern facades. Thus, the extent of cooling largely depends on solar radiation.

Table 5.5: Criteria, indicators and performances for indoor thermal benefits

Criterion	Indicator	DGF	IGFC	IGFT	LWSC	LWSMT	LWSMB	LWSL
Maximize indoor heat stress reduction	External wall surface temperature reduction ΔT_{ow} (°C) in cooling period	9.4	12.7	12.7	19.5	13.3	8.5	8.4
Maximize cooling energy savings	Energy savings for cooling ΔE_c (%)	20	37	37	26	34	59	34
Maximize heating energy savings	Energy savings for heating ΔE_h (%)	8	8	8	20	20	20	15

Table 5.6: Influence of parameters on VGS efficacy in ΔE_c and heat stress reduction (cooling) and ΔE_h (heating) (+++ = strong, ++ = intermediate, + = small effect, brackets = assumed)

Level	Parameters	Effect on cooling	Effect on heating
Environment	Climate type	+++	+++
	Temperatures	++	++
	Radiation intensity	++	(+)
	Wind	+	(+)
Systems design	Orientation	+++	+
	Building vegetation coverage	++	(++)
	Vegetation density (LAI)	+++	(+++)
	Plant species	+	++
	Substrate		
	Moisture content	+	
	Depth	+	(+)
	Air gap width	+	(+)

5.3.6 Further research: indoor thermal effects

Thermal effects of VGS are the most-studied benefit, and therefore relatively well-substantiated. However, future research could shed a light on topics such as:

- Improve unclear time-frame of measurements, so that it is clear whether results show peak reductions, or yearly averages.
- Role of climate type on energy savings.
- The effect of vegetation density (LAI) on thermal benefits, and the development of vegetation density over time for different systems [26].
- Understanding of plant and substrate characteristics in optimizing thermal benefits.
- Role of physical building characteristics in thermal transfer, such as the glazing area or shading of the facade [7].

5.4 Urban heat island reduction

The urban heat island (UHI) effect describes an urban area whose temperature is considerably warmer than the surrounding suburbs and rural regions, due to extensive heat-absorbing sealed surfaces, such as asphalt and concrete, concentrated heat production, impeded airflow and street configurations with a reduced sky view factor [115]. Metropolitan hardscapes such as asphalt and concrete have low albedo (reflectivity), resulting in the absorption of radiant heat from the sun and re-radiation at night [99]. In general, the difference in temperature can be 2-5 °C and is more pronounced at night [67]. Urban areas with more than 1 million inhabitants may be 1-3 °C hotter than surrounding areas during daytime and 8-9°C, up to 12 °C, warmer in the evening [5, 8]. In the Netherlands, the temperature difference between city and surrounding area remains below 3 °C degrees over the year. On summer days, the difference can be as much as 7 °C or 8 °C [116].

5.4.1 Issue

Hotter urban conditions increase heat-related illnesses, including heat strokes, asthma, heat stress and insomnia, as well as mortality rates during heat waves [8]. Also, increased heat can result in increased regional peak energy demands, higher cooling costs, amplified air pollution levels, poor water quality, and modified wind and precipitation patterns [5, 117]. With urbanisation and climate change, the UHI is likely to worsen because cities are facing higher mean temperatures and more frequent heat waves. For example, New York can expect a tripling of heat waves by 2050 [5]. The UHI has a negative impact on urban livability, in particular during summer, when ambient air temperatures are already relatively high [30]. Especially cities in hot humid tropical climate are negatively affected, as thermal comfort relates to temperature and humidity [16].

5.4.2 Mechanism

Vegetation can contribute to urban cooling and therefore combat the rising number of heat-related deaths [118]. The mechanism that reduces the UHI is twofold. On the one hand, greened surfaces shade sun-exposed surfaces. As an effect, plants intercept and largely absorb light and heat radiation for biological processes, reducing heat uptake and re-radiation of heat by wall surfaces into the atmosphere [61, 67] (Interview A). Vegetation on the VGS increases the surface albedo (reflectivity) of the building facade from 0.1-0.2 to 0.7-0.85 [7]. On the other hand, the transpiration of water by plants actively uses heat energy, combined with the evaporation of water from the stomata into the atmosphere increases air humidity (evapotranspiration), which supports the down-regulation of air temperature [13, 16, 115]. Several studies confirm the shading and evapotranspiration cooling effects of VGS [119]. While shading only has a direct impact on the underlying building wall, evapotranspiration influences the micro-climate around buildings, and might thus be more relevant to UHI mitigation [26].

Compared to other forms of urban green infrastructure, VGS are especially effective at shading the building facade, at mitigating heat stress at pedestrian level [71], and at not inhibiting natural ventilation in street canyons, unlike trees [26] (Interview C).

5.4.3 Performance

Many authors indicate an important potential of VGS to lower urban temperatures, but a significant ambient air temperature reduction due to the influence of VGS on the surrounding built environment is not always demonstrated [13]. Different indicators can characterise potential urban micro-climate temperature reductions caused by VGS.

The few authors that have studied the global effect of VGS on the larger-scale urban environment describe how greenery (including planter boxes on street) has a powerful impact on the passive cooling of a building surrounding in Vienna [120], as it can reduce ambient air temperatures up to 1.66 °C. They also describe an important potential of greened building envelopes to lower urban temperatures [121].

Surface temperature

External wall surface temperature variations are considered in several studies for UHI mitigation, similarly as for indoor thermal improvements. This is related to the heat-skin effect, as less heated surfaces also emit less heat to their surroundings. Therefore, it is considered an indirect indicator, or a proxy, of the effect on outdoor thermal comfort. ΔT_{ow} values found in the literature study can be found in section 5.3. VGS can decrease T_{ow} up to 18 °C and 8 °C in cooling and heating season during daytime, respectively [89]. This indirectly shows a tendency to mitigate UHI.

Fluctuations over time

The degree of external wall temperature moderation fluctuates over time. Several studies report a delay of about 4 hours in the daily outer wall surface temperature fluctuation, since the VGS acts as a thermal buffer [93]. As a result, the building facade gains and loses heat at a later time in the day [94]. Figure 5.11 from an experiment by Salonen et al. [25] shows this delay, as well as the inhibiting effect of VGS for the heating from solar radiation on summer days. At night in hot

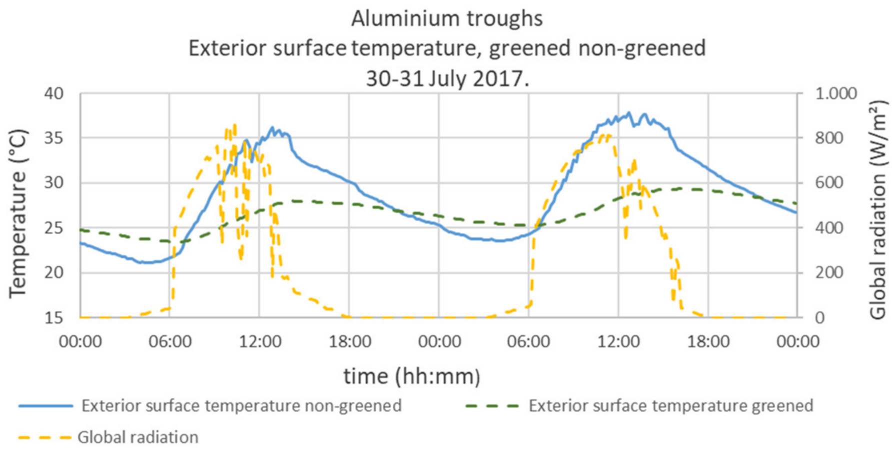


Figure 5.11: T_{ow} for a LWSMT and non-greened facade over a 2-day summer period, 30–31 July 2017 (adopted from [25])

periods, the insulation by the VGS prevents the facade from cooling down by convective heat transfer (heat dissipation) as much as a bare facade would (figure 5.11) [122]. Yet, these nighttime effects are mostly smaller than the temperature reductions during daytime, and therefore do not negate the summer heat moderation during daytime [26]. Also, UHI mitigation during daytime affects more people populating the streets.

This is illustrated by table 5.7, which shows median ΔT_{ow} for a Cfb climate found in a review study by Susca et al. [89]. At daytime, the values show considerable reductions during cooling periods (summer), and smaller reductions during heating periods (winter). These smaller reductions are related to reduced biological activity of plants [89].

At nighttime, slight increases in the wall surface temperature are found in both cooling and heating season, due to the vegetation that reduces heat dissipation, making the buildings able to cool down less. The increase in cold-season nighttime T_{ow} can also prevent freezing of the facade [70].

Since both GF and LWS show limited and inconsistent effects during nighttime on surface temperatures for both heating and cooling season, the small temperature increments or reductions at nighttime are neglected in the indicators and parameters for indoor comfort and UHI.

Gap temperature

The difference between ambient air temperature and the temperature inside the air gap between VGS and building facade (ΔT_g) is interpreted as one of the indicators of outdoor thermal comfort, and therefore of UHI mitigation by Bakhshoodeh, Ocampo, and Oldham [10]. During hot periods ($T_o > 30$ °C), the average gap temperature for indirect GF was 1.3 ± 1.1 °C cooler than ambient air [10]. Ottelé and Perini [123] complements this with ΔT_g reductions of 0.7 °C, 8.6 °C and 5.9 °C for a DGF, LWSL and LWSMB, respectively (table 5.8). Chen, Li, and Liu [122] found an average

Table 5.7: Median ΔT_{ow} in Cfb climate for cooling and heating period, and during day- and nighttime (median value (min value; max value), adapted from [89])

Median external wall surface temperature variation (°C)	**Cooling / heating period**	**Daytime / Nighttime**	**Climate**	**Type of study**	**Source**
-17.5 (-34.0; -3.0)	Cooling	Daytime	Cfb	Review	[89]
+1.3 (0.0; 2.0)	Cooling	Nighttime	Cfb	Review	[89]
-3.6 (-23.0; 2.4)	Heating	Daytime	Cfb	Review	[89]
+1.1 (0.4; 1.5)	Heating	Nighttime	Cfb	Review	[89]

3.1 °C ΔT_g reduction, up to a maximum of 9.7 °C, for an LWSMB. These findings show that an air cavity (for IDGF and LWS) creates an additional thermal insulation layer [92]. Gap temperatures are hardly considered in VGS studies, which makes that this indicator is not comparable across different typologies and conditions. Hence, these findings are regarded as an indirect indication of outdoor air temperature reductions by IDGF, and even more by LWS.

Table 5.8: Average ΔT_g for different VGS

Average gap temperature difference ΔT_g (C)	**Period**	**Climate**	**Orien-tation**	**VGS type**	**Plant species**	**Foliage thickness (cm)**	**Type of study**	**Source**
-0.7	s	Cfb	-	DGF	H. helix	20	Exp.	[123]
-1.3	s	Several	Several	IDGF	-	-	Rev.	[10]
-4.7	s	Csa	S	LWSC	Cistus Jessami beauty and Cistus crispus	-	Exp.	[92]
-5.9	s	Cfb	-	LWSM	Ferns, Geranium sp. Carex sp.	10	Exp.	[123]
-3.1	s	Cfa	W	LWSMB	-	-	Exp.	[122]
-8.6	s	Cfb	-	LWSL	Lamium galeobdolon, Carex, Alchemill, Host	10	Exp.	[123]

Air temperature

A more direct or explicit indicator of outdoor thermal comfort at street level, and thus UHI mitigation, is the ambient air temperature reduction ΔT_o. Table 5.9 shows maximum reductions found by modelling and experimental studies in different conditions. Following the reasoning of the heat-skin effect, a reduction in ΔT_{ow} should be accompanied by a reduction in ΔT_o as well. Several studies show that this is the case, albeit for a smaller amount of studies and to different extents than ΔT_{ow}.

Table 5.9: Maximum ΔT_o (ms = multi-seasonal, s = summer, w = winter, a = autumn, est. = estimation from graph; adapted from [26] and [124])

Maximum ambient air temperature difference ΔT_o (C)	Distance from wall (m)	Period	Climate	Orien-tation	VGS type	Plant species	Foliage thickness (cm)	Type of study	Source
-2.6 (av. -1.9)	-	s	Cfb	Several	-	-	-	Mod.	[121]
-4.7	-	-	Csb	-	GF	-	-	Mod.	[125]
-2.1	0.05	s	Dfa	E	DGF	P. triscuspidata	20	Exp.	[126]
-1.0 (est.)	0.12	s	Cfb	-	DGF	H. helix	20	Exp.	[123]
-0.5 (est.)	0.03	s	Cfb	-	LWSL	Lamium galeobdolon, Carex, Alchemilla, Host	10	Exp.	[123]
-3.0 (est.)	0.06	s	Cfb	-	LWSMB	Ferns, Geranium sp. Carex sp.	10	Exp.	[123]
-0.9 (mean)	0.20	ms	Dfc	S-E	LWSC	Grass	-	Exp.	[127]
-2.7	1.5-4.0	s	Csa	SE	LWSC	>250 species	-	Exp.	[128]
-2.3	1.5-4.0	a	Csa	SE	LWSC	>250 species	-	Exp.	[128]
-2.9	0.15	ms	Af	-	LWSMB	-	10	Exp.	[97]
+0.4	0.30								
-1.3	0.60								
-2.1	0.15	ms	Af	-	IGFT	-	1	Exp.	[97]
-0.8	0.30								
-0.8	0.60								
-3.3	0.15	ms	Af	-	LWSMB	-	12	Exp.	[97]
-1.7	0.30								
-0.8	0.60								

A simulation for VGS in London results in a ΔT_o summer reduction of 1.9 °C on average, up to 2.6 °C [121]. Modelling of a courtyard with GF in Portland shows a larger maximum reduction of 4.7 °C [125]. Experimental set-ups complement these findings with reductions between 0.8 °C and 3.3 °C. Susca et al. [89] found only one study in Cfb climate regarding a GF, with median variations of -1.5 °C and 0.5 °C, for daytime and night-time, respectively.

In an experiment with three VGS, Wong et al. [97] found reductions in ambient temperature up to 3.3 °C at a distance of 0.15 m away. Effects on the ambient temperature could be felt from up to 0.60 m away from the VGS. Thus, the influence of one VGS on the surrounding built environment was only measured very close to the VGS. Another study found no temperature differences further than 10 cm from the VGS [86]. Opposed to this, Jesus et al. [128] found maximum air temperature reductions in a range of 2.5 – 2.9 °C in summer at 1.5-4.0 m from the facade. The study concluded that there is a significant temperature reduction in the intermediate micro-climate environment. Likewise, [129] states that the influence of VGS on outdoor micro-climate is limited to 3 m in front of the VGS. Moreover, [130] found that the mean radiant temperature difference became insignificant at a distance further than 2.5 m from the VGS.

Since air temperature is regarded the most influential parameter that defines the outdoor thermal performance [103], it is regarded the most suitable indicator for UHI mitigation. Table 5.10 shows the type-specific averages of the ΔT_o values found in the literature study, which serves as the basis for the assumed performances per VGS typology. As data for LWSMT was not found, this system is assumed to show similar thermal behaviour as LWSMB, given their comparable thickness and components. LWSL are assumed to perform similar to IDGF, as both create an insulating air gap with climbers.

Table 5.10: Synthesis for ΔT_o performances

Maximum ambient air temperature difference ΔT_o (°C)	**DGF**	**IDGF**	**LWSC**	**LWSMB**	**LWSMT**	**LWSL**	**Source**
Mean of maximum summer ΔT_o close to VGS	-1.6	(-2.1)	-2.5	-3.1	-	(-0.5)	Literature study
Assumed performance	**-1.6**	**-2.1**	**-2.5**	**-3.1**	**-3.1**	**-2.1**	

Other indicators

Other studies employ different indicators for UHI mitigation. Calculation of the Universal Thermal Climate Index (UTCI), indicating human thermal sensation, by Medl et al. [127] for a substrate-filled LWS without vegetation resulted in a reduction of heat stress. Another study calculated the predicted mean vote (PMV), denoting human thermal sensation, and verified that VGS affect their immediate surroundings [131].

Figure 5.12 and 5.13 provide an overview of the thermal indicators for indoor heat stress reduction (ΔT_{ow}), heating and cooling energy savings (ΔE_h and ΔE_c), and for UHI mitigation (ΔT_o).

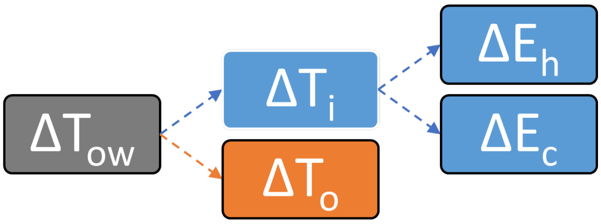


Figure 5.12: Overview of related thermal indicators, with used indicators delineated (Blue = Indoor; Orange = Outdoor; Grey = In- and outdoor)

Indicator	Unit	Description	Formula
ΔT_{ow}	˚C	Exterior surface wall temperature difference	$T_{ow, VGS} - T_{ow, bare wall}$
ΔT_i	˚C	Indoor air temperature difference	$T_{i, VGS} - T_{i, bare wall}$
ΔE_h	%	Heating energy savings	$E_{h, VGS} - E_{h, bare wall}$
ΔE_c	%	Cooling energy savings	$E_{c, VGS} - E_{c, bare wall}$
ΔT_o	˚C	Outdoor ambient air temperature difference	$T_{o, VGS} - T_{o, bare wall}$
ΔT_g	˚C	Gap temperature difference	$T_{g, VGS} - T_{o, bare wall}$

Figure 5.13: Overview of thermal indicators

5.4.4 Parameters

Urban heat islands themselves are dynamic and affected by seasonal and weather changes, which can, for example, move them downwind ([6]). The effectiveness of the VGS cooling effect is primarily related to the percentage of greened area and evapotranspiration effects of the vegetation ([132]; [89]). Others complement this with the leaf area index (LAI) and wind as important factors ([133]), or the grid (H/W ratio) and exposure to solar radiation ([5]).

Main parameters influencing UHI mitigation efficacy of VGS are discussed in this section.

Climate and orientation

Susca et al. [89] shows differences in ΔT_o performance among different climate zones. Similar to orientation, these differences are related to the amount of incoming solar radiation. VGS are more efficient in mitigating air temperature under high radiation weather conditions ([89]), such as sunny hot days, and for orientations with high sunlight exposure (generally south for northern hemisphere) ([134]; [135]). Interviewee A emphasises that VGS mitigate most facade-heating by applying them on parts of the building exposed to sun during the hours of the day with strongest radiation exposure.

Alexandri and Jones [121] modelled different climates and states that "the hotter and drier a climate is, the greater the effect of vegetation on urban temperatures". For example, maximum ΔT_o in hot and arid climate was 11.3 °C, while a maximum 8.4 °C decrease was found for a humid climate in Hong Kong (both values assume greened roofs and facades) ([121]). The study also determined that for a VGS-only scenario in hot and arid climate, daytime average and maximum ΔT_o reductions are 3.4 °C and 5.1 °C, respectively. A different study found maximum ΔT_o of 8 °C (Susca et al. [89]). Essentially, this suggests the maximum attainable ΔT_o for VGS is ∼5-8 °C.

Studies show that wind can cause proper ventilation and avoid UHI amplification caused by increased humidity ([121]), and increase the ET rate ([10]). Still though, the wind direction does not have any significant effect on temperature decreases by VGS since air velocities inside canyons are low ([121]). In addition, the orientation of streets in relation to the regular wind direction in hot periods should be considered locally to determine whether there are risks of UHI formation (Interview A). This suggests that wind velocity affects the intensity of UHI, whereas the exact effect of wind on temperature reductions is still undetermined.

Aspect ratio

The urban building grid affects UHI mitigation. Effects of VGS are greater in narrow streets surrounded by high-rise buildings (street canyons), shows one case study ([89]).

A modelling study shows the effects of VGS in reducing UHI, including peak temperature reductions of up to 10 °C for areas with a H/W ratio larger than 2 ([5]). Graph 5.14 shows the correlation between aspect ratio and maximum ΔT_o found by two studies. Multiple studies conclude that the air-cooling capacity of VGS declines with wider street canyons and lower facade heights ([121]; [89]). Aspect ratios above 2 are often (very) dense city centres, like in Hong Kong or Melbourne ([25]).

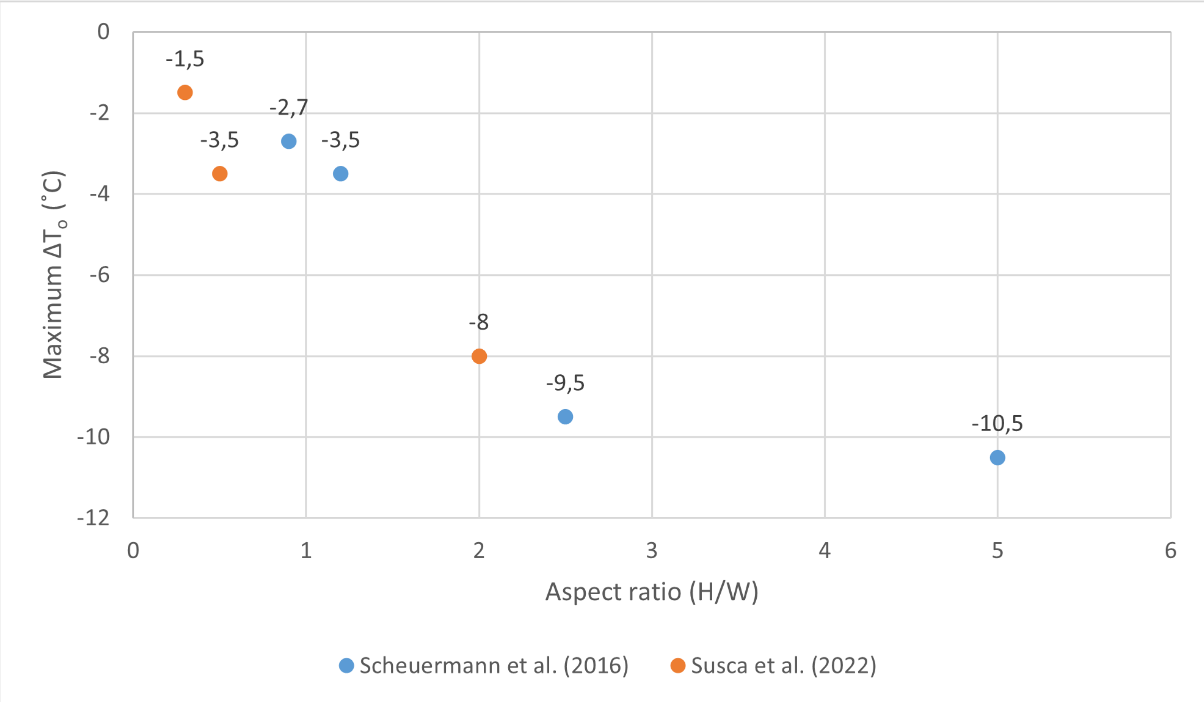


Figure 5.14: Maximum ΔT_o for different aspect ratios, based on Scheuermann et al. [5] and Susca et al. [89]

Building and district vegetation cover

A key element defining UHI mitigation potential is the degree of vegetation.

For temperature climate zones (C), a review study by Antoszewski, Świerk, and Krzyżaniak [134] identified critical design parameters for UHI effectiveness of VGS. It found eight studies that confirmed the extent of facade greenery is the main geometrical parameter. Morakinyo et al. [135] made similar claims, stating that the cooling effect of the coverage ratio was more substantial than the effect of orientation.

On a building scale, the facade coverage with VGS affects the surface temperature reductions. Susca et al. [89] found an inverse correlation between vegetation coverage (%) and variations in surface temperature (ΔT_{ow}) in almost all climates. Figure 5.15 shows this correlation for Cfb climate. It displays that for an increase of vegetation coverage from 50% to 100% of the building facade, an ΔT_{ow} increment of -13 °C to -15 °C (+15,4%) can be expected. Also Iaria and Susca [136] shows that UHI mitigation potential increases linearly increases with coverage percentage.

On district level, one study shows greening 30-50% results in a 1 °C local air temperature reduction during day and night in Hong Kong ([135]). Figure 5.16 shows that median air temperature

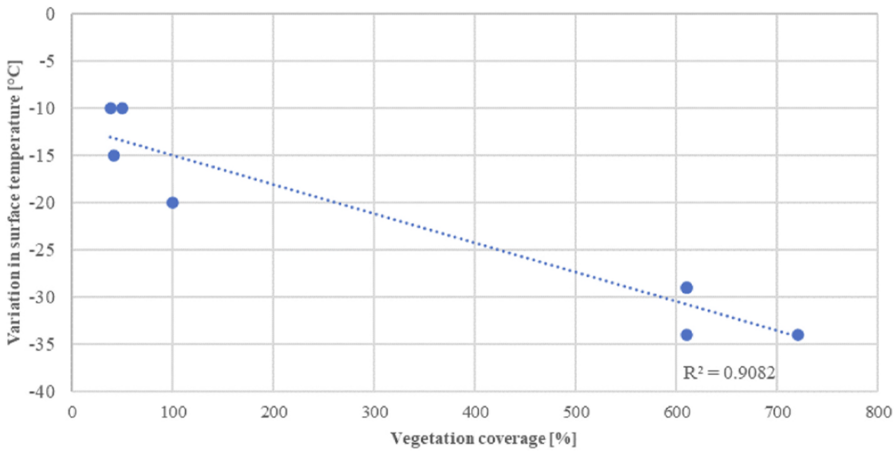


Figure 5.15: Correlation between ΔT_{ow} in Cfb climate summer daytime and vegetation coverage (0-100% on building level; > 100% on district level) (adopted from [89])

differences (ΔT_o) during summer increase when VGS are applied on street or city (block) scale. Interviewee A states: 'the more green facades, the less those walls reflect the heat in that particular street'. Other reviews confirm this ([121]; [30]). A study shows that if Manchester increased its green infrastructure by 10% in areas with limited or no green cover, it would reduce average air temperatures by up to 2.5 °C ([137]). Still though, the median decrease by VGS for application at building scale is 1.0 °C, contributing to a mitigation of UHI effects ([89]).

Interviewee A points out that the reflectivity (albedo) of the surrounding non-greened facades plays a role in the exact temperature reductions, although this effect is regarded minimal.

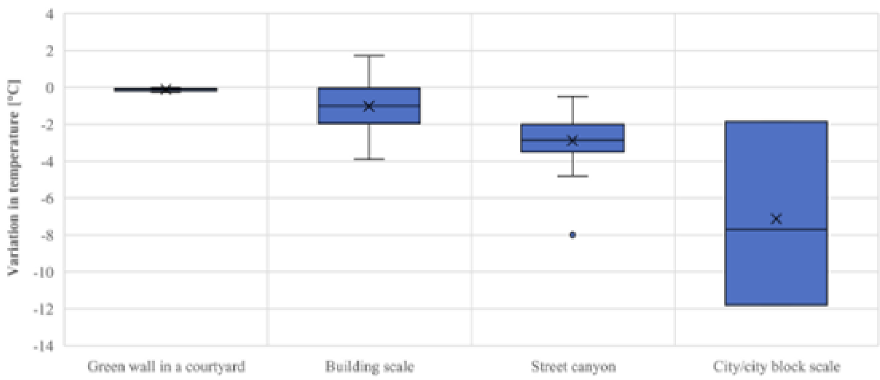


Figure 5.16: Variation in warm season ΔT_o, depending on VGS scale of application (adopted from [89])

Vegetation density

For systems design, some characteristics play a role in UHI mitigation efficacy.

Foliage density, expressed in terms of the leaf area index (LAI, m2/m2), is another critical parameter according to seven studies ([134]; [133]; Interview B). Increasing the LAI from 1 to 5 reduces the surface temperature (ΔT_{ow}) by 12 °C on a hot summer day, and reduces the annual cost of indoor air conditioning (ΔE_c) by 1.4% ([91]). An increase for the LAI from 3 to 5 increases the UHI mitigation potential (air temperature) by 20% for GF and by 30% for LWS ([136]). Moreover, for GF, the UHI cooling capacity is negligible when LAI is 1.5. Interviewee B confirms that the cooling potential of GF is limited when not fully grown yet. When LAI increases from 1.5 to 3 for

LWS, the cooling capacity increases by 90% ([136]).

This dependency of cooling capacity on LAI is related to the predominant shading effect during warm season daytime ([89]), because vegetation density affects the surface albedo (reflectivity) and emissivity ([7]). Temperature decreases due to VGS are primarily affected by the vegetation itself (coverage and density), more than the canyon geometry (aspect ratio) ([121]). Still though, typical LAI cannot be attributed to a certain VGS type, neither can it be predicted before installing a VGS.

Height

Some studies found no significant advantage to pedestrian comfort by increasing VGS height above a certain threshold ([129]; [136]), because the upper airflow may weaken cooling by dispersing and diluting the cooled air ([138]). Although Acero et al. [129] thus a critical height of 6 m, Iaria and Susca [136] found a proportional increase of UHI mitigation with building height until 20 m.

Other parameters

Other parameters, such as substrate thickness or evapotranspiration rate, are mentioned to partly determine UHI mitigation efficacy. Interviewee B points out that the moisture content of the substrate, enabled by proper irrigation, enhances evapotranspirative cooling of the air, alike found for indoor thermal comfort. Thus, this is also assumed to affect UHI mitigation to a small extent. Perini et al. [139] show that plant species differ in their evaporative capacity, and this affects their cooling potential. Yet, they also state that a more major role is played by system characteristics, such as vegetation density.

5.4.5 Key findings

- Urban heat islands compromise outdoor thermal comfort. VGS can contribute to local dampening of hot urban conditions and therefore make cities more resilient to rising temperatures. As such, VGS allow to regulate the urban climate and contribute to climate adaptation ([3]).
- Exterior wall surface temperature differences ΔT_{ow} are regarded a proxy for UHI mitigation, and show large reductions (17.5 °C) during summer days and smaller reductions (3.6 °C) during winter days (in Cfb climate). Small reductions or increments during the night do not alter the total UHI mitigation potential.
- Gap temperature reductions (ΔT_g) show that IDGF and LWS contain an air gap that acts as an insulation barrier.
- Maximum ambient air temperature reductions (ΔT_o) are regarded the most suitable indicator for UHI mitigation. Table 5.11 shows the assumed performances in this regard.
- Effects on the ambient temperature from VGS can be felt up to 3-4 m from the facade.
- Table 5.12 shows which parameters (presumably) affect UHI mitigation most. Air temperature is most mitigated under high radiation weather conditions, such as sunny hot days. Therefore, the assumed ΔT_o performances take place in summer during day-time.
- Crucial to the degree of street cooling by VGS is the scale of application. Thus, building and district vegetation coverage have a large effect on UHI mitigation. In addition, a high aspect ratio (i.e. in street canyons) is associated with significantly higher air temperature reductions.

Table 5.11: Criterion, indicator and performances for UHI mitigation

Criterion	Indicator	DGF	IGFC	IGFT	LWSC	LWSMT	LWSMB	LWSL
Maximize urban heat island mitigation	Maximum ambient air temperature reduction ΔT_o (°C)	1.6	2.1	2.1	2.5	3.1	3.1	2.1

Table 5.12: Influence of parameters on VGS efficacy in UHI mitigation (+++ = strong, ++ = intermediate, + = small effect, brackets = assumed)

Level	Parameters	Effect on UHI mitigation
Environment	Climate type	++
	Temperatures	++
	Solar radiation	++
	Wind	+
	Street aspect ratio (H/W)	+++
	District vegetation coverage	+++
Systems design	Orientation	(+)
	Building vegetation coverage	+++
	Height threshold	+
	Vegetation density (LAI)	+++
	Plant species	(+)
	Substrate	
	Moisture content	+

5.4.6 Future research

Recommendations for further research about UHI mitigation are:

- Develop more understanding of combining VGS with trees or other NBS, since shadowing can counteract dry soil and reduce water demand (Interview A).
- For thermal benefits, a covered facade is assumed for GF, yet with low vegetation density. Research into trategies to increase the coverage speed of GF, e.g. using pre-planted types, are recommended.
- Since the relative differences of UHI mitigation found in this study are not extremely different, it would be interesting to further research the decisiveness of UHI mitigation in selecting a certain system.

5.5 Air purification

VGS are increasingly advocated as a solution to reduce air pollution [140]. After the definition of air pollution components and health implications, this section discusses the effectiveness of VGS to mitigate particulate matter, gaseous pollutants and carbon dioxide, successively.

5.5.1 Issue

Air pollution consists of airborne contaminants including dust, pollen, factory emissions, soot, smoke and motor vehicle exhaust, raising nitrogen dioxide (NO2) and particulate matter (PM) (Scheuermann et al., 2016). Particulate matter is one the main air pollutants in urban environments globally. The sources of fine and ultrafine PM are mainly residential heating and traffic [141]. Also ground-level ozone (O3), sulfur dioxide (SO2) and carbon monoxide (CO) are air pollution components, which usually have higher concentrations in urban areas due to intense road and air traffic, and concentration of industries [7, 142].

Air quality is a key driver for public health. Air pollution exacerbates respiratory and cardiovascular health issues such as asthma and lung disease. Long term exposure can lead to lung cancer and premature death [141]. Particulate matter is of particular interest because it has a greater impact on health than any other air pollutant [143]. The risk of harmful effects of PM on human health is greater for smaller particles, since they can penetrate deeper into the lungs and even end up in the blood stream [144]. The Agency [145] considers adverse health effects from especially particulate matter (PM_x) and gaseous pollutants, i.e., nitrogen oxides (NO_x), and ozone (O_3).

In the United Kingdom, mortality due to air pollution was estimated at 40,000 deaths per year [146]. Worldwide, it is estimated to be responsible for 6.4 million deaths annually, associated with a global economic loss of nearly 21 billion USD in 2015 [147]. Large metropolitan cities such as London and New York regularly exceed WHO limits for particulate matter. Even more so, 84% of the global population is exposed to PM levels that exceed the WHO guidelines [141].

Urban street canyons are formed by tall buildings on either side of the road, and represent a major air pollution hotspot [148], due to high traffic emissions and a lack of natural ventilation [149]. Street canyon dimensions are usually expressed in an aspect ratio (H/W), defined as the height of the buildings (H) divided by the width of the road (W). They can be characterised as shallow (H/W $\leq$ 0.5), medium (0.5 $<$ H/W $<$ 2) and deep (H/W $\geq$ 2) [149].

The direct effects of VGS on air quality are mainly related to the absorption of fine dust particles and the uptake of gaseous pollutants, and can play a role in carbon sequestration. These three ways of air purification are discussed hereafter.

Some modelling studies show a potential for VGS to mitigate NO2, O3 and SO2 that are main gaseous pollutants of concern for their health effects (appendix 11.7.4). However, due to the lack of studies that validate these data with experimental studies, compare different species or VGS typologies, or determine the contribution of system components (e.g. vegetation), a system-specific (range of) performance for gaseous pollutants removal cannot be reasonably assumed.

5.5.2 Particulate matter

Particulate matter (PM) is a complex mixture of various components of both small particles, liquid droplets including organic chemicals, acids, metals and soil or dust particles [144]. The WHO classifies PM according to their size in coarse PM (PM10), fine PM (PM2.5) and ultrafine PM (PM0.1) with an aerodynamic diameter smaller than 10 µm, 2.5 µm and 0.1 µm, respectively [141]. PM pollution primarily comes from combustion sources, with (ultra)fine PM from mostly anthropogenic and coarse mainly from natural sources [8, 149].

Mechanism

Both dispersion and deposition of PM determine local air quality [144]. Dispersion refers to transport by wind and dilution of PM by mixing with ambient air [150]. Deposition considers the removal of particles from the atmosphere onto plant leaves, and can occur wet (by precipitation) or dry (by gravity, diffusion, impaction and interception) [150].

Vegetation can accumulate PM deposited on leaves and branches [142], because it alters the flow pattern and acts as a momentum sink encouraging deposition of particles on the leaf surface [150]. Weerakkody et al. [151] demonstrates that plants are more effective in capturing air pollutants than other land surfaces owing to the high air turbulence caused by their complex morphology and large surface area per unit volume.

Performance

Plants can improve air quality by collecting particles on their leaves and stems through deposition [139, 152, 153].

Field studies and modelling studies have investigated the PM mitigation potential of VGS.

For direct green facades, field studies on the PM mitigation potential of the most common species Ivy was related to amounts of PM found on the surfaces of the leaves ([152]; [153]; [154]). Pollution level, the size fraction, amount of rainfall and season had a significant influence on PM accumulation ([154]). According to Ysebaert et al. [144], field measurements serve as an indication of which species can perform best and at which locations plants can have highest impact, rather than make quantitative statements on the PM mitigating potential of a VGS.

For living wall systems, field studies focused on PM accumulation on leaves of different species. Weerakkody et al. [155] and Ottelé, Bohemen, and Fraaij [153] measured that a DGF with *Hedera helix* (Ivy) located on a busy roadside captures roughly 10^{10} to 10^{11} particles per m2 leaf area. More specifically, Weerakkody et al. [155] evaluated the reduction of traffic-generated PM by 20 living wall species. Table 5.13 presents the average estimations of PM capture from three studies. The experiments demonstrate an inverse correlation between particle size and quantity of PM captured for locations near road traffic, as does an earlier study for PM generated by rail traffic [156]. The similarity of the elemental composition of PM found on the leaves of LWS and traffic-generated pollutants indicate the PM filtering potential of LWS in roadside settings [149]. Differences between estimations for the same PM fraction could possibly be attributed to differences in measuring method, e.g. magnification factor and using exposed or covered foliage.

As elevated PM levels are found approximately within 100-300 m from roads [157], VGS which are close to the traffic can play a large mitigating role [144]. Moreover, VGS do not obstruct air flows in street canyons, unlike trees and hedges [139, 140].

Table 5.13: Field study estimations of PM capture for different PM fractions (est. = derived/estimated from total capture for specimen area)

PM capture (x $10^7 m^{-1}$)	PM fraction	VGS type	Species	Location	Surface area (m^2)	Type of study	Source
842 (est.)	PM0.1	DGF	Hedera helix	Bergen op Zoom, NL	Height=2.5 m	Field study	[153]
2090 (est.)	PM1-10	DGF	Hedera helix	Oxford, UK	-	Field study	[152]
22.08 ± 6.9 8.24 ± 0.72 4.45 ± 0.33	PM1 PM2.5 PM10	Modular LWS	Average of 20 species	Stoke-on-Trent, UK	16.6	Field study	[155]

Numerical modelling studies provide more elaborate quantified performances (appendix 11.7.3). Pugh et al. [148] found reductions of up to 60% in PM10 street-level concentrations in street canyon environments (H/W = 2) for full coverage of the canyon. Modelling studies on city scale found PM10 removal rates of 1.37 mg/year in Toronto [158] and 314 mg/year in Melbourne [159]. Appendix 11.7.3 includes their respective PM removal efficiencies (%), and those of other studies, as calculated by Ysebaert et al. [144]. Removal efficiencies range between 4.9% and 100%, influenced by different parameters.

The modelling studies have several drawbacks. Some studies were not validated with real-time measurements, not guaranteeing the reliability of the results [158, 159]. The same studies assumed a hedge of trees as VGS, which makes their performance less directly applicable to real VGS. Similarly, Morakinyo and Lam [160] considered conifers for provision of validation data for a VGS.

Parameters

The PM collecting capacity depends on site conditions and vegetation characteristics. The main influencing factors are discussed in this section.

Canyon geometry The most influencing feature is street canyon morphology. PM10 removal efficiencies at pedestrian level from two modelling studies for increasing aspect (H/W) ratios are visualised in figure 5.17 [148, 161]. An increasing aspect ratio, i.e. a more narrow street, allows PM pollution to come in closer contact with the VGS, increasing the residence time and opportunity for deposition [144]. Figure 5.17 shows how a doubling in H/W ratio can approximately lead to a doubling in PM reduction efficiency as well. Therefore, greater PM reductions can be seen in deeper street canyons [148].

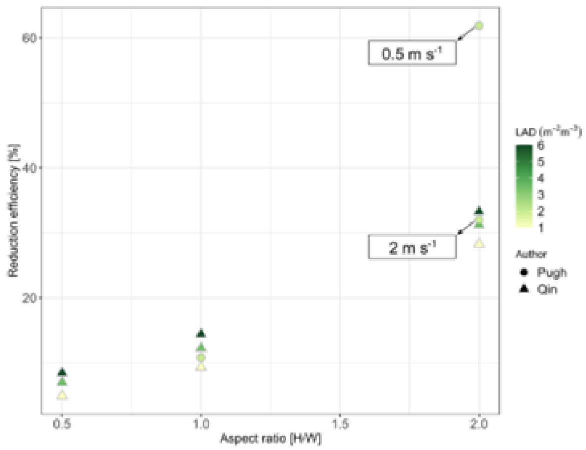


Figure 5.17: PM10 reduction efficiencies for different values of LAD and wind speed, as a function of the street canyon aspect ratio (adopted from [144], based on [148] and [161])

Wind speed and rainfall Weather conditions in terms of wind and rainfall affect the PM collecting capacity as well. Modelling lower above-roof wind speed in street canyons resulted in higher deposition rates by enhancing the residence time [148] (figure 11.6). The influence of rainfall on re-suspension of deposited PM from paved surfaces has been studied and found to affect PM fluxes [162], but future research needs to give conclusive answers.

Vegetation cover Pugh et al. [148] showed the influence of the relative vegetation cover of street canyon(s). Figure 5.18 displays the positive correlation between vegetation cover (%) and in-canyon PM10 concentration reduction, with full coverage resulting in the highest PM10 reductions. Interviewee C confirms that the area of the vegetation cover is key to the amount of PM reduced.

Pollution level Different studies show that a higher atmospheric particle concentration results in higher PM deposition on the plant leaves [152–154]. However, review studies indicate that this relationship is not significant for particles smaller than 5 m. While fine and ultrafine PM are typically associated with traffic emissions, the influence of ambient PM concentrations on those PM fractions has yet to be determined [144]. Still though, figure 5.20 shows that the largest PM collection capacities are most often taking place at traffic locations (with average traffic density of 20,000 cars/day), rather than rural or railroad environments. This makes VGS somewhat more effective in PM collection near road traffic.

Seasonality Research does not agree on seasonal variety of PM deposition on VGS. Whereas one study found an increasing PM content over time from February to June [154], others found no significant differences during a period of around 3 months [139, 153] or a near-constant monthly removal for a full year (see figure 5.19) [159]. Therefore, seasonality is considered to have a very small impact on the PM deposition.

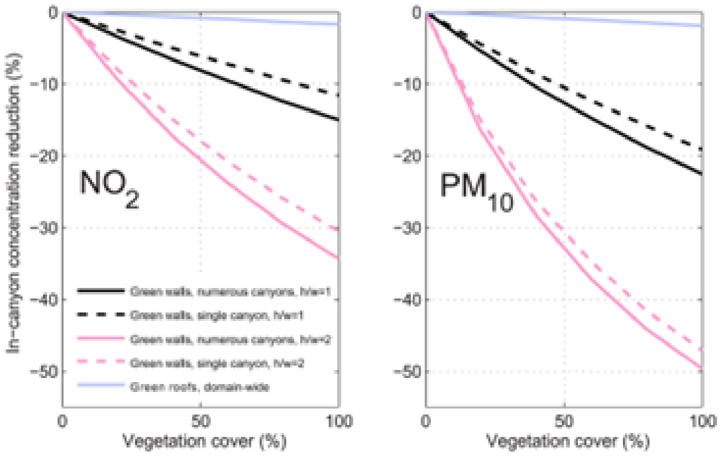


Figure 5.18: In-canyon NO2 and PM10 reduction as a function of wall or roof coverage, from modelled daytime average (06:00-18:00), with above-roof wind speed of 1 m/s (adopted from [148])

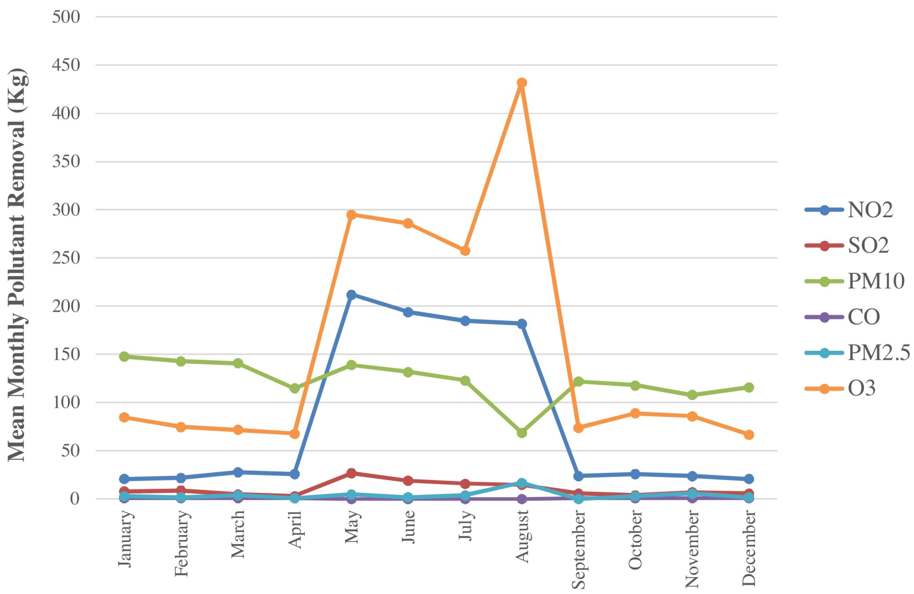


Figure 5.19: Mean monthly pollutant removal during one year, from modelling (adopted from [159])

Vegetation Figure 5.20 shows the total number of particles per m2 leaf area collected by leaves of *Hedera helix* (GF) and LWS species [144]) The differences between species can be related to the macro-structure of the vegetation and micro-structure of the plant leaves [163]. Rowe [164] adds to this that evergreen plant species may provide a greater benefit than deciduous species, because they keep leaves year-round.

Macro-structure The macro-structure is often quantified by the vegetation density in terms of leaf area index (LAI/WLAI), i.e. the amount of vegetation surface area per vertical wall surface area (m2/m2), or in terms of the leaf area density (LAD), i.e. the total one-sided leaf area per unit volume (m2/m3) [144]. The density affects the mean wind speed and turbulence inside the vegetation, and therefore the PM deposition. Also, a higher WLAI results in more PM accumulation, as the potential leaf area for deposition is larger [156, 165] (Interview C).

When the leaf area density is increased from 1 to 6, while keeping the H/W constant, an increase in PM reduction efficiency is observed, although the increase is less pronounced than for aspect ratio or wind speed [161] (Figure 5.20).

In addition, the leaf size affects the PM accumulation potential of species. Smaller-leaved species (area ¡ 200 mm2) are shown to accumulate more PM than wider or larger leaves (area 1280 – 6990 mm2) due to a relatively large edge effect [155, 163, 165]. Still though, it needs to be noted that small linear-leaved or grass-like species tend to bend easily with wind flow, creating less turbulence and depositing less particles [156]. One study found that more complex shaped leaves increase turbulence, enhancing PM deposition [165], but this is not considered enough evidence to make solid claims [142].

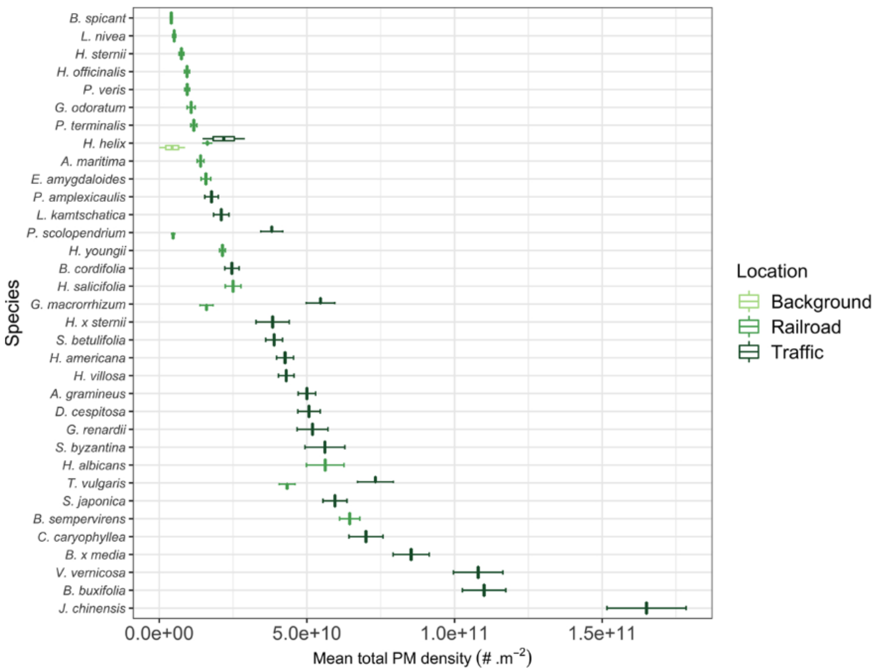


Figure 5.20: Mean total PM density of different GF (Hedera helix) and LWS species (adopted from [144]; 'background' = rural area, 'traffic' = average traffic density of 20,000 cars/day)

Heterogeneous (random) arrangement of tall and short plants was found to increase PM densities on plant leaves, compared to a homogeneous (clustered) design [151]. Thus, placing plants in alternating order of different heights in LWS can enhance PM uptake.

Micro-structure Micro-morphological surface characteristics of leaves, such as cuticle, wax and hairs, play a role in deposition capacity [166].

Hellebaut, Boisson, and Mahy [142] reviewed literature that studies specific plant traits that enhance PM capture capacity for trees and VGS. Figure 5.21 shows that the presence of hairs as well as the roughness of the leaf surface were traits identified in numerous studies.

Results of six studies converged to a positive correlation between the presence of hairs or trichomes and the capacity to capture PM for VGS vegetation [142]. This effect is related to leaf hairs that increase the surface area for PM interception and decrease the chances that PM will be re-suspended with leaf movements [167]. Despite [139] found that waxy leaves collect a higher number of particles than hairy leaves, these contradicting results might be attributable to the washing of leaves as method of counting particles. Only two studies quantify the exact magnitude of the leaf hair effect, but the presence of leaf hairs is considered the most influential leaf surface trait for PM capture [155].

Leaf roughness, in terms of ridges and grooves densities, was found to contribute to PM capture. Two VGS studies confirmed this [163, 165]. A rough leaf surface, with ridges, grooves or striations, was shown to be more efficient than smooth leaves [142], but the correlation was not significant [155]. Therefore, the impact of leaf roughness is considered small.

Studies on the impact of leaf wax and stomatal density of VGS plants showed contrasting or were little studied, thus the effect of these traits is not conclusive.

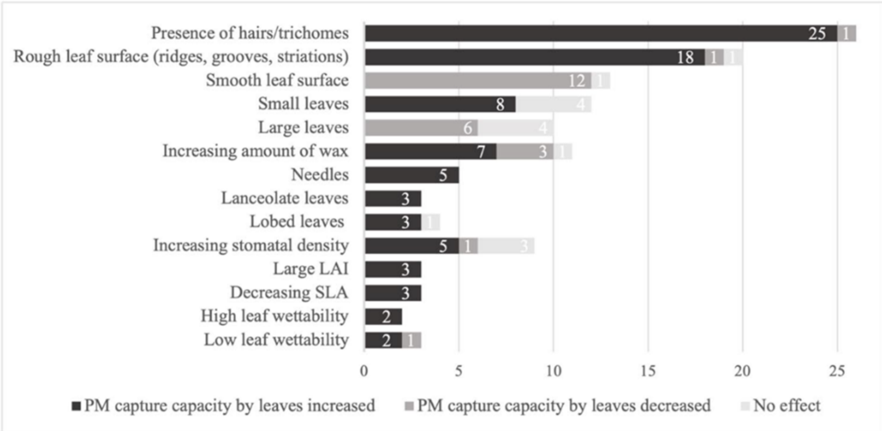


Figure 5.21: Number of studies reporting effects of plant traits on PM capture capacity (adopted from [142])

Key findings

For particulate matter reduction, key findings are:

- VGS can play a major mitigating role in PM mitigation, especially in shallow urban canyons, without restricting air flows. Performances differ greatly, but go up to 60% PM reduction efficiency in specific conditions [148].
- The limited number of VGS experimental studies on DGF and modular LWS do not allow to derive system-specific performances. However, in systems design mostly vegetation characteristics determine the efficacy in PM capturing capacity.
- Green facades are considered to have the highest potential vegetation density, compared to LWS [45]. However, the most often used species for GF, *Hedera helix*, showed relatively poor PM capturing capacity (figure 5.20) and LWS allow for a choice among a much wider range of suitable species that could be optimized on PM-capturing characteristics.
- Therefore, the performances shown in the table below are considered for the potential PM reduction. Because of the strong influence of environmental parameters, such as canyon aspect ratio and vegetation cover (table 5.16), ranges for potential PM reduction are used.
- A specific performance (assumption), based on canyon aspect ratio and district vegetation cover, is derived under parametric scoring in section 6.1.

Table 5.14: Criterion, indicator and performances for PM reduction

Criterion	**Indicator**	**DGF**	**IGFC**	**IGFT**	**LWSC**	**LWSMT**	**LWSMB**	**LWSL**
Maximize potential PM reduction	Potential (7-point scale)	2-4	2-5	2-5	4-6	4-7	4-7	2-5

Table 5.15: Definition of scores on 7-point scale for qualitative assessment

Qualitative assessment	Very poor	Poor	Modest	Fair	Good	Very good	Excellent
Score	1	2	3	4	5	6	7

Table 5.16: Influence of parameters on VGS efficacy in PM reduction (+++ = strong, ++ = intermediate, + = small effect, - - = intermediate negative effect)

Level	Parameters	Effect on PM reduction
Environment	Wind speed	- -
	Street aspect ratio (H/W)	+++
	Pollution level	+
	District vegetation coverage	+++
Systems design	Building vegetation coverage	+++
	Vegetation density (LAI)	++
	Random arrangement of in tall/short plants	+
	Plant species	++
	Leaf size	
	Presence of hairs	
	Leaf roughness	

5.5.3 Carbon sequestration

Vegetation has the potential to contribute to climate change mitigation through carbon sequestration [8].

Mechanism

VGS can play a part in reducing carbon dioxide, by processing it in the plant tissues and the soil substrate, and replacing it with oxygen, acting as natural filters [15, 164] (Interview B).

Performance

The vast majority of urban vegetation as carbon dioxide sinks can be attributed to trees [6]. For example, sequestration by four parks in Rome was equivalent to 3.6% of the total emissions for the city in 2010 [8].

One modelling study of LWS carbon sequestration estimated that an area of 98 m2 of VGS captures an average flux of CO2 between 13.41 and 97.03 kg CO2 eq per year, equivalent to 0.44–3.18 kg CO2 eq/m2 [168] (table 5.17). A 6-month experimental study on LWS carbon sequestration in a tropical climate [113] resulted in only a fraction of the amount of the annual carbon sequestration suggested by Marchi et al. [168] (table 5.17). The authors attribute this low sequestration value to the unhealthy plant conditions during summer. Despite this sequestration potential, the limited substrate volume of VGS limits the amount of CO2 stored (Interview C).

Table 5.17: Carbon sequestration estimations in literature

CO2 sequestration (kg/CO2-eq/m2/y)	Plant species	Climate	Type of study	Source
0.44 – 3.18	*Sedum spurium, Salvia nemorosa, Rosmarinus officinalis, Geranium sanguineum, Carex brunnea, and Fatsia japonica*	Cs	Modelling study	[168]
0.004 – 0.030	*C. hyssopifola H.B.K. or E. conchinchinensis or T. urvilleana*	Af	Experimental study	[113]

Parameters

Charoenkit and Yiemwattana [113] points out that the vegetation is important for the process of carbon sequestration, whereas the storage of carbon is mostly concentrated in the substrate (85-90%). The differences between different plant species indicate that this is a parameter to take into account as well ([113]). Perini and Roccotiello [166] argues that choosing evergreen plant species for VGS might be beneficial, since during winter CO2 and air pollutants emissions from road transport reach their maximum. Thus, plant species and substrate depth are assumed to affect carbon sequestration potential. Since the amount of vegetation is considered to be important as well, the building vegetation and coverage and vegetation density are also assumed to be influencing parameters.

Key findings

Regarding carbon sequestration, two studies confirmed the potential of VGS. As these studies concern LWS, and LWS include a substrate volume to store carbon, these systems are considered having the highest carbon sequestration potential. Figure 5.19 shows the (assumed) systems design parameters that affect carbon sequestration.

Table 5.18: Criterion, indicator and performances for carbon sequestration

Criterion	Indicator	DGF	IGFC	IGFT	LWSC	LWSMT	LWSMB	LWSL
Maximize potential carbon sequestration	Potential (7-point scale)	2	2	2	4	5	5	3

Table 5.19: Influence of parameters on VGS efficacy in carbon sequestration (+++ = strong, ++ = intermediate, + = small effect, brackets = assumed)

Level	Parameters	Effect on carbon sequestration
Systems design	Building vegetation coverage	(++)
	Vegetation density (LAI)	(++)
	Plant species	+++
	Substrate	(++)
	Depth	

5.6 Noise reduction

5.6.1 Issue

Noise is the second largest environmental cause of health problems, just after the impact of particulate matter, according to WHO [169]. It is a leading nuisance in cities that reduces work productivity, disturbs sleep (leading to premature deaths), can cause cardiovascular disease and contributes to mental illness ([5]; [169]).

Adverse health effects are especially prominent at night, when noise levels above 40 dB are harmful ([169]). According to Agency [170] regulations, current thresholds for excess exposure are 50 dB at night (Lnight), and 55 dB as Lden , a weighted average during day, evening and night. The fact that about 18.000 Dutch households live in areas with a noise level that is considered harmful to their health, especially due to road traffic ([171]) illustrates the prominence of this urban health issue. Approximately 125 million people are affected by noise levels greater than 55 dB Lden , of which road traffic is the most dominant source ([170]).

5.6.2 Mechanism

Perception of loudness is related to sound pressure level, with the unit decibels (dB). A 3dB decrease is just perceptible, while a 5 dB decrease is clearly noticeable, and 10 dB decrease corresponds to a halving of the perceived loudness [5].

Three main effects of vegetation, green belts and trees (green infrastructure) near roads reduce sound levels in urban environments ([172]; [19]). First, plants provide diffraction of sound, i.e. the sound can be reflected and scattered by plant elements. The second effect is absorption by plants through mechanical vibrations of plant elements, dissipating sound energy and converting it to heat. Also, plants contribute to sound attenuation by thermos-viscous boundary layer effects at vegetation surfaces ([19]). The third mechanism relates to the destructive interference of sound waves between the direct contribution from the source to the receiver and a ground-reflected contribution, also referred to as the 'acoustical ground effect', resulting in sound levels reduction.

5.6.3 Performance

While the effect of tree belts is clearly demonstrated by traffic noise control with reductions from 5 to 10 dB ([172]), the potential of VGS to reduce noise at city scale is researched in a handful of articles.

In-situ measurements of the noise insertion loss (difference VGS and control wall) in a study by Wong et al. [173] resulted in a large contribution (5 – 10 dB) related to the absorption effect of substrates, at low to middle frequencies (125 – 1250 Hz). Also, another, smaller contribution (2 – 3.9 dB) was observed for all systems at a high frequency spectrum (4 – 10 kHz), owing to the scattering effect of greenery. An exception was an LWSL, with a maximum reduction of 8.8 dB for these high frequencies. The specific values for insertion losses found for different systems and frequencies are displayed in table 5.22.

Other studies confirm that the vegetation can attenuate high-frequency sounds and substrates or growing media can attenuate low-frequency noises ([174]; [132]). The good sound absorption by LWSC (up to 8.4 dB for 125-1250 Hz) can be related to the absorption characteristics of the felt, as well as the sound insulation provided by the continuous material (Interview B). Modular LWS are more prone to sound leaks through the seams between panels, and therefore show lower attenuation values (Interview B).

Impenetrability of the VGS surface was also brought up by interviewee B. Continuous felt systems (LWSC) would provide good sound absorption

Table 5.20: Noise reduction performances (dB) for different frequency ranges from literature

Maximum insertion loss (dB)	Frequency range (Hz)	VGS type	Substrate thickness (m)	Plant thickness (m)	Type of study	Source
5.6	125 - 1250	LWSMB (wire cage)	0.250	0.100	In-situ exp.	[173]
3.1	4000 – 10,000	LWSMB (wire cage)	0.250	0.100	In-situ exp.	[173]
9.9	125 - 1250	IGFC	0.080 (only at ground)	0.010	In-situ exp.	[173]
3.8	4000 – 10,000	IGFC	0.080 (only at ground)	0.010	In-situ exp.	[173]
2.2	125 - 1250	LWSMB	0.230	0.120	In-situ exp.	[173]
3.2	4000 – 10,000	LWSMB	0.230	0.120	In-situ exp.	[173]
4.0	125 - 1250	LWSMB	0.080	0.120	In-situ exp.	[173]
2.0	4000 – 10,000	LWSMB	0.080	0.120	In-situ exp.	[173]
7.0	125 - 1250	LWSMB	0.070	0.110	In-situ exp.	[173]
2.8	4000 – 10,000	LWSMB	0.070	0.110	In-situ exp.	[173]
5.4	125 - 1250	LWSMT	0.065	0.055	In-situ exp.	[173]
3.2	4000 – 10,000	LWSMT	0.065	0.055	In-situ exp.	[173]
8.4	125 - 1250	LWSC (pockets)	0.060	0.120	In-situ exp.	[173]
3.9	4000 – 10,000	LWSC (pockets)	0.060	0.120	In-situ exp.	[173]
3.1	125 - 1250	LWSL (trough planters)	0.280	0.200	In-situ exp.	[173]
8.8	4000 – 10,000	LWSL (trough planters)	0.280	0.200	In-situ exp.	[173]
15 (Rw)	100 - 5000	LWSMB	0.080	0.400	Laboratory	[174]
1 (Rw)	Full spectrum	IGFM	-	0.250	In-situ exp.	[132]
1 (Rw)	Full spectrum	LWSMB	-	0.250	In-situ exp.	[132]
3	Pink noise (low freq.)	IGFM	-	0.250	In-situ exp.	[132]
2	Pink noise (low freq.)	LWSMB	-	0.250	In-situ exp.	[132]

Azkorra et al. [174] conducted a laboratory evaluation of a modular LWS and concluded that VGS can be an effective passive acoustic insulation system, with a weighted sound reduction index (Rw) of 15 dB. This large value, compared to other studies, might be attributable to the relatively thick plant layer of 40 cm. Still though, this sound reduction coefficient is lower than for other building materials, such as glazing, brick or plasterboard.

Another result from the study by Wong et al. [173] is the higher sound absorption coefficient than those of other building materials, especially at frequencies larger than 250 Hz. Figure **??** shows the sound absorption coefficients found in a reverberation chamber, as well as typical values for building cladding materials. Values range from 0.04 (for 100 Hz) to 0.61 (for 1000 Hz) and increase with increasing frequencies and with larger greenery coverage on the VGS itself. It should be noted that the plant used has a high LAI value of 6.76, so it reflects the maximum rather than the medium performance.

Azkorra et al. [174] found a weighted sound absorption coefficient of 0.40, in line with the results of Wong et al. [173], except that such values were also found for lower frequencies. This VGS absorption coefficient was similar or better than common building facade materials. The thick plant layer (40 cm) signals that this might be a maximum attainable value, rather than an average.

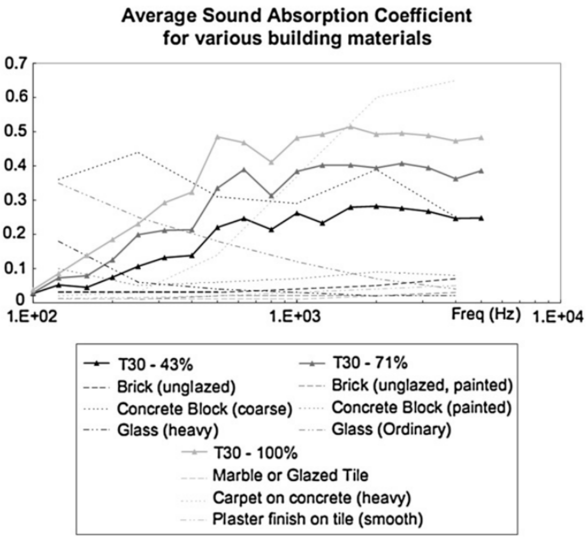


Figure 5.22: Absorption coefficients for typical building materials [173]

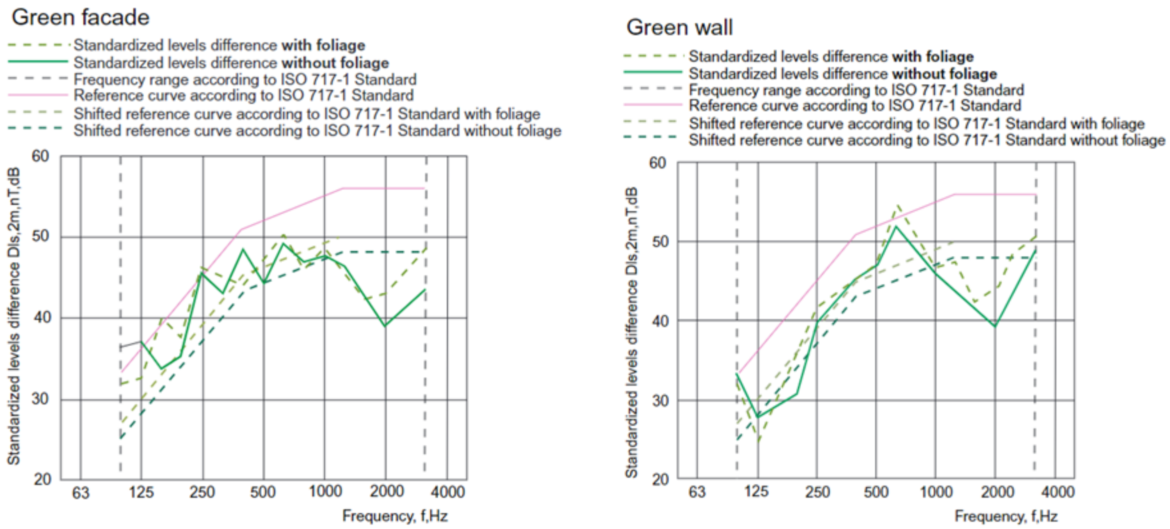
Another in-situ experiment assessed an indirect GF and a modular LWS ([132]). It concluded that a 20-30 cm layer of vegetation in both these systems can provide an increase of 1 dB to sound insulation for a normalized traffic noise spectrum (more weight to lower frequencies). This is a limited, not perceptible, effect. In the case of considering pink noise (e.g. high speed road and rail traffic), an increase in soundproofing of 2 dB for the LWSMB and 3 dB for the IDGF was found. This effect would be perceptible (Interview C). The authors suggest the difference of their in-situ measurements with earlier laboratory experiments could be caused by factors such as the mass of substrate and vegetation, impenetrability and structural insulation (support structure).

In addition, the contribution from vegetation (scattering effect in high frequencies) was verified for both the IDGF and LWSMB, as was the contribution from substrate (absorption effect in middle frequencies) for the LWSMB ([132]). Figures 5.23 show these effects.

5.6.4 Parameters

Both system components and environmental factors influence the efficacy of VGS in sound attenuation. Besides the importance of VGS materialization (Interview B), Pérez, Coma, and Cabeza [19] lists three system components with a strong influence on the final acoustical performance of VGS:

Figure 5.23: Noise attenuation curves with and without foliage ([132])



(a) Indirect green facade

(b) Modular living wall system

the presence of an air gap layer, the use of substrates and/or support for plants, and the plant species used.

Plants

Characteristics of the plant layer that predominantly affect the noise absorption coefficient of plants are the foliage density and the angle of leaf orientation ([175]). For larger foliage density and a larger dominant angle of leaf orientation, higher values of acoustic absorption can be attained. Increasing vegetation coverage (of the VGS itself) can increase the absorption coefficient by around 0.2 at low and middle frequencies ([176]). Another study found that increasing the vegetation coverage from 43% to 100% increase the absorption coefficient with approximately 0.25, indicating around a doubling ([173]).

As such, the mass of vegetation is a key point for acoustic insulation and makes a well-developed plant layer important for effectiveness ([19]; [174]). In that sense, selection of a plant species that is well-adapted to local conditions for good biomass development, and possibly deciduous for year-round sound insulation, is beneficial.

Substrate and building wall

The biggest system differences are related to the lack of substrate in GF compared to LWS, as reflected in found performances for low to middle frequencies.

The thickness or depth of substrates is often mentioned to affect noise attenuation behaviour as well. Yet, increasing the soil depths from 50 to 200 mm in an experiment only resulted in small changes in the absorption coefficient of around 0.1 ([176]).

More importantly, an experiment in a reverberation chamber shows a significant decrease by approximately 0.6 of the absorption coefficient with an increase in the soil moisture content ([176]). Similarly, absorption increases with decreasing moisture content in green roofs ([177]).

Light-density, porous soils (e.g. perlite or polymer gels) exhibit higher values of acoustic absorption in comparison to high-density, low-permeability clay based soils ([175]). Likewise, a highly porous substrate can maintain a relatively high absorption coefficient of approximately 0.6, even when nearly saturated ([176]). However, when a porous medium is fully water-saturated, similar effects as for a rigid material could be expected, according to Renterghem et al. [178]. Anyway, texture and composition of substrate can affect acoustic performance of VGS.

A numerical study on the potential of vegetated buildings to lower road traffic noise, carried out by [178], shows the effect of substrates on acoustical performance. Substrates that are usually used for LWS have a high porosity and low density, leading to complex acoustic behaviour, with high absorption already at lower frequencies and stronger variations above 500 Hz. Yet substrates based on mineral- or stone-wool are considered to provide better sound insulation than soil-based systems (Interview B). This shows that VGS substrate sound absorption is still under research and only provides a first indication of noise reduction behaviour.

Facade material

In urban environments with acoustically softer bricks (reflection coefficient of 0.82), VGS had modest effectiveness, with a maximum effect below 2 dB. Therefore, the study implies the application of VGS is most effective in street canyon environments with acoustically hard facade materials behind the VGS. Calculations using a high reflection coefficient of 0.95 yielded an insertion loss of 4.4 dB in the case of fully vegetated canyon facades ([178]).

Urban environment

The urban form surrounding a VGS will also influence sound propagation, as facades increase sound wave reflection and diffraction ([7]). Although not explicitly researched in past studies, the total dimensions of vegetated facades in a street are expected to affect noise attenuation efficiency ([19]).

Other parameters

Other factors that could be of importance are the improvement of impenetrability (sealing of joints between LWS modules) and of structural insulation (physical separation between building elements to prevent sound transmission, instead of connection to supporting structure) ([19]). However, there is no scientific proof-of-concept of these design aspects yet.

5.6.5 Key findings

The impact of green facades on urban noise is not largely established, but ongoing research has published evidence indicating that VGS can be effectively absorb sound. Key takeaways are:

- For 125 – 2500 Hz frequency ranges, a 5 – 10 dB reduction can be achieved.
- For 4000-10.000 Hz frequency ranges, a 2.0 – 3.9 dB reduction can be achieved.
- Considering that traffic noise is generally characterized by a low frequency band of noise, dominated by frequencies around 1000 Hz, and that traffic noise is the most disturbing noise source in urban environments, maximizing outdoor traffic noise reduction is considered a suitable criterion. Based on the results of Wong et al. [173], maximum performances for 125 - 1250 Hz frequencies are considered for the different VGS types.
- The vegetation (coverage and density) and substrate as system components largely influence the efficacy in noise attenuation. Therefore, the maximum insertion losses can be attained for optimal system design choices, for which design recommendations are formulated (section 5.16)

Table 5.21: Criterion, indicator and performances for traffic noise reduction

Criterion	Indicator	DGF	IGFC	IGFT	LWSC	LWSMT	LWSMB	LWSL
Maximize traffic noise reduction	Maximum insertion loss (dB) for 125 - 1250 Hz frequencies	0	6.5	6.5	8.4	5.4	4.7	3.1

Table 5.22: Influence of parameters on VGS efficacy in noise reduction (+++ = strong, ++ = intermediate, + = small effect, brackets = assumed)

Level	Parameters	Effect on noise reduction
Environment	District vegetation coverage	(++)
	Urban geometry	+
Systems design	Building vegetation coverage	+++
	Vegetation density	+++
	Plant species	+
	Dominant angle of leaf orientation	
	Substrate	
	Depth	+
	Density and porosity	++
	Moisture content	+++
	Reflective facade material behind VGS	++

5.7 Biodiversity

VGS are frequently suggested to foster urban biodiversity. This section analyses to what extent that is the case.

Biodiversity is the variability among living organisms and the ecological complex to which they belong. It can be considered in terms of genetic variability within a species or population, as well as variability of species within and between ecosystems [21].

5.7.1 Issue

Development of the built environment replaces natural habitats with impervious surfaces, which typically increases habitat fragmentation, alters nutrient deposition and cycling and redistributes water [179]. Meanwhile, denser, more compact cities are likely to lead to a deterioration in the provision of ecosystem services, with a consequent decline in urban biodiversity and quality of life [6]. As cities can become inhospitable for many species, increasing biodiversity is one of the main challenges of urban planning [180, 181].

5.7.2 Mechanism

Urban green infrastructure, including VGS, contributes to the ecological preservation of existing biodiversity values, the restoration of threatened habitats, and the creation of new habitats ([7]; [15]). Contribution of VGS to biodiversity has an emphasis on the latter mechanism. This way, vegetation can increase biodiversity.

Biodiversity supports the ecosystem condition and can improve ecosystem multi-functionality ([45]; [7]). Habitat services provided by green infrastructure are the most important supporting urban ecosystem service, because of the importance of biodiversity in underpinning the delivery of other ecosystem services ([6]).Dover [8] approaches biodiversity as a delivery mechanism of ecosystem services, such as removing pollutants, acting as insulation and shading and removal of rainwater.

Therefore, he states that "without biodiversity there is no green infrastructure". As such, biodiversity can be seen as the underlying principle for ES delivered by GI (figure 5.24). Opposed to this, in a circular argument, enhancing GI can be seen as delivering habitats, which in turn improves the ecosystem services provided by biodiversity ([8]).

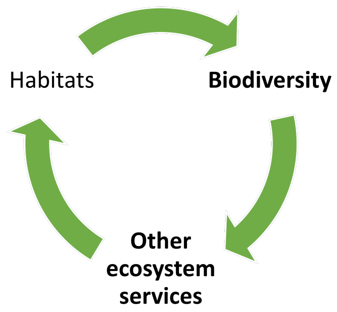


Figure 5.24: Circular argument for biodiversity as delivery mechanism for other ES, as well as an ES by itself (own work)

For VGS, this study interprets the provision of biodiversity as the degree (abundance) and variability (richness) of created habitats for both wildlife and plant species, rather than the indirect delivery of other ES.

5.7.3 Performance

While publications often refer to the general enhancement of biodiversity through vegetation in cities, studies that deal with the specific biodiversity potential of VGS and its quantification are rather scarce ([43]). Mayrand [180] stressed the value of each VGS as a habitat for plants and animals in urban environments, but to different extents.

Flora

The positive effect of VGS flora on biodiversity is mainly related to its plant species richness and 'nativeness' ([181]), because a more diverse and native set of plants attracts more animal species ([30]).

Regarding green facades, Jim [182] assessed the performance grade of 20 climbing plants in relation to establishment rate (height), growth rate, growth density and flowering. Climbers suitable for IDGF performed much better than those for DGF, demonstrating a faster establishment and growth rate and more ornamental flowers (figure 5.25; table 5.23). Under the presumption that a higher, more dense and more flowering foliage in a GF offers a better habitat for wildlife (including pollinators), a better biodiversity score for IDGF than DGF can be derived. The study took place in a tropical climate, which makes the scores not directly applicable on a temperature climate, but it does not change the overall better performance of indirect over direct green facades. The 'nativeness' of GF climbers if often good, as GF most often include native climber species (such as *Ivy, Vine, Honeysuckle*), which is valuable for flora biodiversity (Interview C).

Table 5.23: Average climber performance grades for (in)direct GF (based on [182])

	Direct green facade	**Indirect green facade**
Average climber performance grade, scale 1-5	1.9 (poor)	3.9 (good)

LWS are often highly diversified plant systems, as they allow for the integration of a wide variety of plants compared to green facades ([180]; [57]). For example, the Caixa Forum in Madrid was

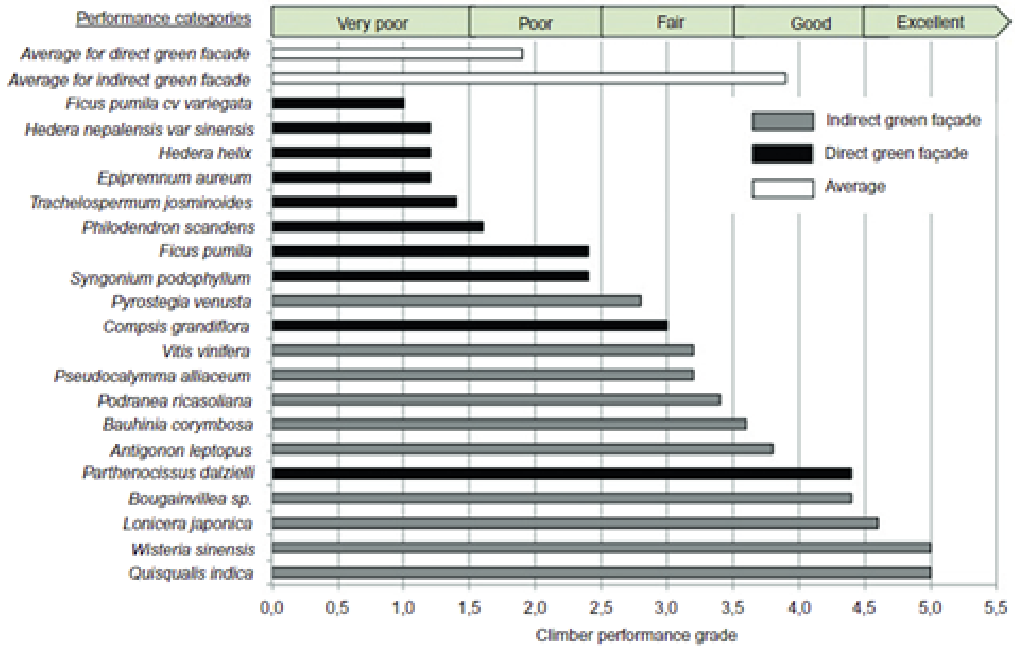


Figure 5.25: Average climber performance grades for direct GF, indirect GF and specific plant species ([182])

designed with 250 different species, whereas the catalogue of suitable species for GF is limited to around 10 species ([182]). Despite the advantage of LWS to choose a suitable species from a wide range, the frequent use of exotic (non-native) species and spontaneous growth being limited by maintenance could be disadvantageous for biodiversity ([180]).

The potential of VGS for supporting spontaneous flora ([180]; Interview C), including mosses, was considered out of scope for this study.

Fauna

VGS-specific studies have shown that VGS can improve biodiversity by offering shelter, foraging beds and food for insects and small flying animals, such as bees and birds ([183]; [184]; Interview C).

A relatively widespread observation is that invertebrates, especially beetles and spiders, were significantly more abundant in vegetated facades than on concrete facades, in particular in modular LWS (Figure 5.26 C and D; [48]; [185]; [30]). Among arthropods (including insects), good dispersers such as winged insects and wind-borne species such as spiders are particularly over-represented ([185]; [180]).

On the contrary, the function of VGS as a habitat for vertebrates, like birds and bats, has not been rigorously demonstrated ([30]; [180]). Chiquet [186] found that GF are associated with 4.5 times more birds on immediate vegetation surrounding the GF than on vegetation surrounding bare walls (figure 5.26 B). Attraction of birds could be attributed to the more “natural” environment, or the provision of food (e.g. invertebrates or berries), perching and breeding sites ([186]; Interview C). An empirical study on 27 green facades confirms the presence of birds on climbing vegetation, using the nesting, food and shelter opportunities ([119]). Yet, LWS as a place for nesting, food and shelter for birds remains a non-assessed matter ([180]). It is suggested to place nesting boxes near or in VGS, to facilitate nesting opportunities, even when a GF climber is not fully grown and bushy yet (Interview C).

A meta-analysis of VGS studies shows small mean effects for birds (1,29 in abundance) and invertebrates (1,30 in both abundance and richness) compared to building walls ([179]). Although the authors do not consider the results to be significant, this does confirm the proposed habitat provision for birds and invertebrates.

The number of studies regarding pollinators, e.g. bees, is limited, but GF are highly visited by specialist flower visitors for nectar and pollen([15]). This biodiversity could depend on the attractiveness of plant species for pollinators ([181]).

Figure 5.26 shows that IGFT and LWS generally support a much more diverse (A) and abundant (B) fauna than bare walls ([180]). Whereas species richness relates to the number of species, abundance relates to the number of individuals ([185]).

Figure 5.26 C and D display that LWS show highest occurrence of beetles and spiders, with modular LWS having the highest abundance. On the other hand, indirect green facades show a significantly higher abundance of insects (invertebrates) and snails. Direct green facades similarly serve as ideal habitats for generalist and common invertebrates ([15]).

Therefore, all forms of VGS can be a better habitat for fauna than bare walls. Depending on the type of animal species, either LWS or GF perform better.

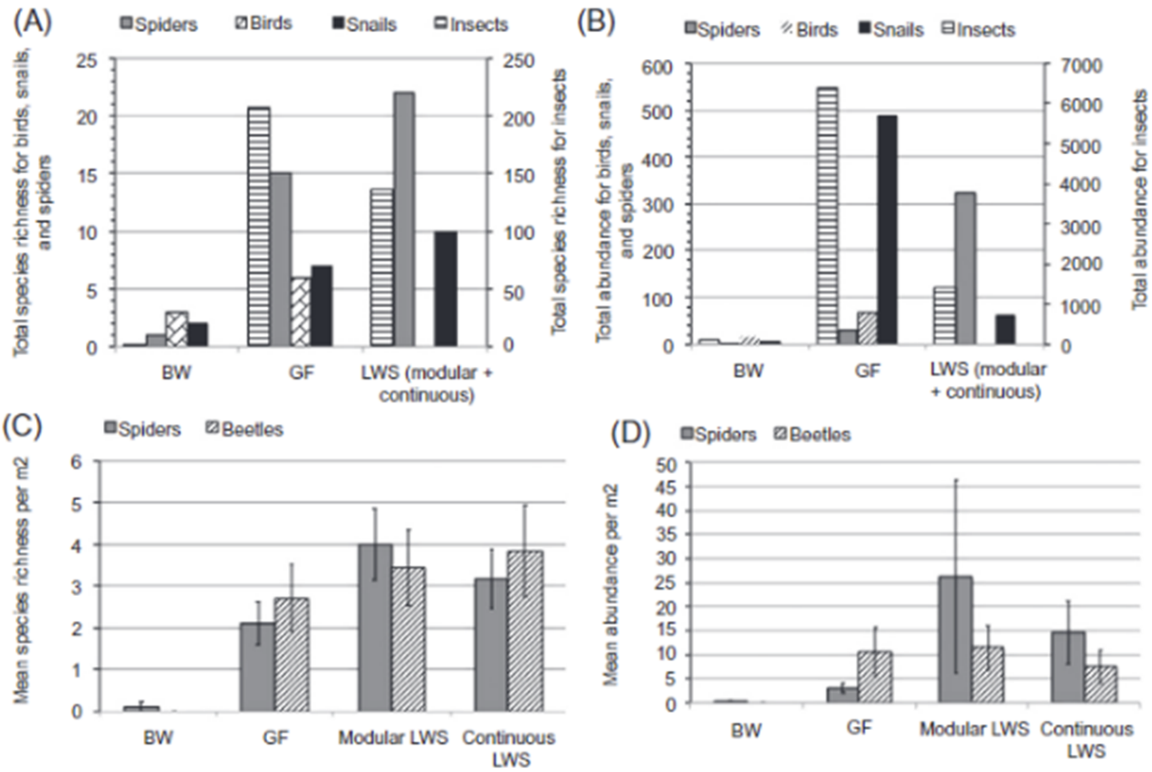


Figure 5.26: Diversity of fauna on VGS and bare walls, with BW = bare wall, and GF = mesh climber (IGFT) ([180]; [186])

Connectivity and public perception

In general, sufficient ecological connectivity between scattered habitat patches can prevent a rapid declines in biodiversity or ecological functions, for example by contributing to movement patterns of pollinators, butterflies or seed dispersers ([6]). Oftentimes, VGS are presented to be part of stepping-stone corridors that establish this connectivity, which is crucial to enhance biodiversity and important to generate ES in fragmented urban landscapes. However, Mayrand [180] disagrees, pointing out that "no study has effectively determined the mechanisms at play, nor the connectivity with other urban green spaces". Another study relates this low connectivity potential to limited VGS patch sizes, abundance and redundancy of patch quality within the landscape ([187]). Despite the fact that VGS can act as exclusive habitats, their potential as a component of urban corridors remains questionable ([180]).

Citizens perceive LWS to have a slightly higher potential value for urban biodiversity than green facades, regarding their willingness to pay (5.16 million pounds for LWS; 4.81 million pounds for GF; 3.40 million pounds for alternative policy (mean values); [188]). Although estimates are likely to be specific for the case in Southampton (UK) and the difference in welfare estimates is not significant, this study does suggest a biodiversity value associated with VGS, and especially LWS. Interviewee C also points out that VGS enables citizens to be close to green urban elements, which could lead to more public support and protection of natural values.

5.7.4 Parameters

The impact of VGS on biodiversity is dependent on particular typology-specific characteristics, including the area of vegetated surface, plant characteristics such as variety and density, seasonality and surroundings ([186]; [189]).

Few studies investigate have investigated how surroundings, such as adjacent land, vehicle and pedestrian traffic, may interact with wall biodiversity ([180]). Still though, the percentage of green areas around VGS has a significant positive impact on the richness and abundance of low-dispersal micro-fauna ([185]). Landscape configurations had a smaller impact on high-dispersal micro-fauna (spiders). Hence, Francis and Lorimer [57] and interviewee C advocate for a landscape scale approach to maximise the biodiversity potential of VGS. For example, for habitat provision for birds, a quiet environment is also necessary, which can be created by placing walking paths at a distance of the VGS. Since VGS can have ecological value to the local ecosystem they are part of, adjusting VGS design to be compatible with the (needs of) species in the environment is key.

In this regard, studies have identified total cover as an important enhancing parameter in the development of the structural complexity of GI ecosystems ([179]; [186]). Moreover, surface area of the VGS is most important for impact on urban biodiversity, as it adds biomass and food for nearby species (Interview C). It should be noted that for habitat provision for birds is limited above a certain height, which indicates that biodiversity potential in that sense is limited for high-rise application (Interview C).

Besides landscape configurations and patch size, micro-climatic ecological conditions affect biodiversity impact. Both GF and LWS provide homogeneous abiotic conditions driven by engineering ([180]). Green facades are often warm and dry habitats, while LWS are fresh and damp habitats resulting from frequent irrigation, evaporation and shade ([180]; [45]). Both conditions are suitable for certain animal species, making species-specific objectives necessary to select a VGS type with the right conditions ([45]). These objectives should also align with the function of the building, and the corresponding desirability of insects or small animals, especially near facade openings such as windows (Interview B).

Species selection with certain vegetation traits has a positive impact on the preference of targeted species. For example, flowers and foliage enlarge insect populations ([181]). And *Ivy* blooms in winter, so it can provide nectar for winter-active insects (Interview C). Also, many, especially bushy, plants are good for nesting birds, and most produce nectar and pollen for bees ([15]; Interview C). High growing evergreen climbers are recommended for birds specifically ([186]; [45]). This relates to the choice of evergreen or deciduous plants, affecting the coverage and therefore habitat functionality. Selecting plant species that support certain animal species is therefore an effective approach.

In addition, choosing native or established plants is beneficial for the associated native animal life, but not a common practice for LWS ([30]; [181]). Interviewee C therefore recommends to use native or established plants to enhance biodiversity. Purely native species are not necessary, because the urban conditions are man-made.

Plant diversity in VGS is an important design measure, because a more diverse range of plants is likely to have a greater positive effect on biodiversity by attracting more animal species ([30]; Interview C). GF use very few species in general, leading to mono-specific covers and low variety, whereas the plant cover in LWS is often diverse ([180]). Mayrand [180] suggests to increase GF functional diversity by selecting plants with different functional traits (e.g., deciduous and evergreen plants). Similar to variety, the thickness or density of the foliage is important for VGS ecological value (Interview C).

With regards to the substrate in LWS, decayed plants can accumulate organic matter, which can improve the microbiological activity and the habitat for preys and predators ([180]). For modular LWS, the relatively small container size and substrate quantity decreases rooting opportunities for flora ([180]).

All in all, design for biodiversity could entail a 'bottom-up' or multi-trophic approach which focuses on growing media that enhance plant abundance, as well as on selecting varied and native plant species that attract target species and that suit the local ecosystem ([179]; [45]).

5.7.5 Key findings

Research shows that VGS influence local biodiversity, especially through habitat provision for fauna and flora. Key takeaways are:

- Indirect green facades have a better average climber performance grade (based on cover, density, and flowering) than direct green facades, presumably providing better flora abundance and enabling more fauna habitats, such as for pollinators.
- LWS have a significantly larger potential plant richness, as they allow for integration of up to 250 different species, whereas GF have 10 suitable species.
- IGFT and LWS generally support a much more diverse and abundant fauna than bare walls.
- Regarding invertebrates, beetles have highest occurrence and abundance in continuous LWS, followed by IGFT and modular LWS (table 5.24). LWS provide the best habitat for spiders, as do IGFT to a lesser extent.
- Indirect green facades show a significantly higher abundance of insects and snails, while LWS show a slightly higher variety of snails.
- IDGF provide a notable habitat to birds. LWS are assumed to be a less attractive habitat for birds, as they provide a less bushy environment.
- Direct green facades are considered to deliver similar biodiversity value as indirect green facades, except for a reduced value due to their lower climber performance.

Therefore, a qualitative, discrete scoring on a seven-point scale best describes the aggregated potential biodiversity value for different VGS (table 5.24).

Besides typology differences in biodiversity potential, plant species selection based on target animals, that also suit the local ecosystem, is key in providing effective habitat functionality. As such, recommendations to design for biodiversity include to design for certain target species (e.g. birds, pollinators, beetles and spiders), taking into account landscape configurations, patch size and plant variety.

Table 5.24: Performance for biodiversity (fauna habitat estimations adopted from \cite{Hartog2022}, based on \cite{Mayrand2018} and \cite{Madre2015})

Sub-criterion	**Indicator**	**Performance value**						
		DGF	**IGFC**	**IGFT**	**LWSC**	**LWSMT**	**LWSMB**	**LWSL**
Maximize plant heterogeneity	Maximum number of possible species	10	10	10	250	250	250	
Maximize fauna habitat	Total species richness (est.)							
	Birds			6				
	Snails			7	10	10	10	
	Insects			210	130	130	130	
	Total abundance (est.)							
	Birds			60				
	Snails			495	60	60	60	
	Insects			6200	1100	1100	1100	
	Mean species richness (m-1, est.)							
	Beetles			3.7	3.9	3.5		
	Spiders			2.1	3.1	4		
	Mean abundance (m-1, est.)							
	Beetles			11	12	7		
	Spiders			3	26	15		
Maximize cover, density, and flowering	Average climber performance grade, scale 1 - 5	1.9	3.9	3.9				
Overall biodiversity potential	Potential (7-point scale)	**2**	**3**	**3**	**5**	**6**	**6**	**5**

Table 5.25: nfluence of parameters on VGS efficacy in enhancing biodiversity (+++ = strong, ++ =intermediate, + = small effect, brackets = assumed

Level	**Parameters**	**Effect on biodiversity potential**
Environment	District vegetation coverage	(+)
Systems design	Building vegetation coverage	+++
	Height threshold	+
	Vegetation density (LAI)	++
	Plant species	+++
	Substrate	
	Depth	+

5.7.6 Future research

Whereas green infrastructure can significantly improve biodiversity, Filazzola, Shrestha, and MacIvor [179] showed in a meta-analysis that VGS do not have significant effect on biodiversity. However, they concluded more research is needed before quantitative conclusions can be drawn. As valuing biodiversity is associated with complexity ([45]) and the specific contribution of VGS is hard to point out, the evidence base of VGS as biodiversity boosters has yet to be extended.

Thus, future research should examine topics such as:

- Habitat functionality for birds in LWS
- Influence of landscape configurations on biodiversity value provision
- Value of VGS as urban wildlife corridors that improve large-scale ecological network connectivity within fragmented areas, for example together with green roofs.

5.8 Rainwater runoff control

Vertical greening systems can contribute to sustainable urban water management through rainwater run-off control and the filtering and use of greywater. Their potential is discussed sequentially.

5.8.1 Issue

The increased area of sealed, impermeable surfaces in urban areas reduces the infiltration of rainwater into the soil ([8]). Rainfall is therefore diverted to drains and sewer systems. Heavy rainfall during storms may overload the sewage system and cause flash flooding with contaminants being flushed above-ground, especially in lower urban areas ([8]; [189]; [7]). Given climate change predictions of increased precipitation in some areas and more frequent extreme weather events, stormwater runoff management is a pressing issue.

In addition, VGS's extensive use of water for (automated) irrigation is at odds with global water scarcity as well as the environmental footprint and energy use of buildings. As such, the lack of water efficiency is one of the main implementation barriers for VGS ([47]).

5.8.2 Mechanism

Vegetation is an integral part of sustainable urban drainage systems, which are used to reduce the amount of water entering sewers by enabling either direct rainwater infiltration, or rainfall capture, containment and slow release ([8]). This section explores how VGS can retain and use rainwater to reduce pressure on urban drainage and to reduce drinking water use for irrigation.

5.8.3 Performance

Several studies suggest that VGS can retain, use and slow down rainwater, similar to green roofs ([119]). VGS can be a control source of water management at urban catchment scale, as they are able to retain and reduce the water runoff from the roofs ([190]). A retention capacity for modular LWS was found in an experimental study by Wouw, Ros, and Brouwers [191]. Expressing the retention capacity of a vertical sqm of VGS as an equivalent percentage to a horizontal sqm, a LWSMT performed on average 33.0% and a LWSMB at 18.8% (table 5.26). Qualitatively, Loh and Stav [192] describes how rainwater percolates and later partly transpires through a LWS, not only delaying the peak of sudden rainfall discharge, but also lowering rainwater flows.

Possibilities for retention of intense rainfall that causes heavy flooding are limited, because the volume for storage in VGS substrates is restricted, according to interviewee A. This is in line with the partial storage capacity found. For less intense - more average - rainfall, VGS with substrates perform well in retaining a larger percentage of rainwater (Interview A).

Besides causing a cooling effect, the evapotranspiration process from plants and substrates in VGS consumes water. When rainwater is absorbed, partial evapotranspiration reduces the rainwater runoff. An empirical study calculated the potential to reduce the stormwater runoff by 4% on average

Table 5.26: Study results for rainwater retention and runoff reduction

Indicator	Value	VGS type	Climate	Type of study	Source
		Retention			
Retention capacity of a vertical m2	18.8	LWSMB ('panels')	Cfb	Exp.	[191]
(equivalent % to a horizontal m2)	33.0	LWSMT ('planter box')	Cfb	Exp.	[191]
		Runoff reduction			
Stormwater runoff	4	LWSC (geotextile felt system)	Cfb	Mod.	[193]
reduction (%)	55	LWSMB (modular)	Af	Mod.	[190]
Evapotranspiration	18 (±3)	LWSMB ('panels')	Cfb	Exp.	[191]
power (kW/m2/y)	11 (±3)	LWSMT ('planter box')	Cfb	Exp.	[191]

for a 30% covering of a neighbourhood in Vancouver with geotextile felt systems and green roofs ([193]). More recently, a LWSMB was found to reduce runoff by 55% for a rainfall simulation with an average recurrence interval of 1 year and a 5-minute storm duration ([190]). As the runoff reduction rate is equivalent to the evapotranspiration rate ([193]), the evapotranspiration (ET) capacity can be suitable indicator of runoff reduction. Unlike the retention capacity, the total ET power was estimated higher for LWSMB at 18 (±3) kW/m2/y than for LWSMT at 11 (±3). This corresponds to 650 ± 100 mm/y and 380 ± 120 mm/y, respectively [191].

Because vertical greening systems have limited possibilities to directly capture rain, the proper connection of VGS to the nearby roofs on which rainwater is captured is crucial to control punctual excesses of water during heavy rainfall events ([194]).

A related feature at building level is the use of rainwater collected on roofs for irrigation of VGS, e.g. in a LWS drop-by-drop system, which can reduce potable water use ([15]; Interview A). Another, more common, measure beneficial for water use efficiency is a drainage system which collects excess water (e.g. in a storage tank) and returns it back to the irrigation system ([15]; Interview B). The impact of VGS on hydrology can improve the city's water cycle, therefore future research can quantify the consequent reduction of the necessary investments in the urban rainwater drainage system ([15]).

5.8.4 Parameters

The water storage capacity of the substrate and the vegetation, as well as rain events, have an influence on the VGS storm-water retention efficacy ([6]).

Substrate

For green roofs, the retaining capacity of the substrate depends on substrate thickness, moisture content at the start of the rain event, the composition and pore volume of the substrate([7]). Regarding substrate dimension of VGS, Wouw, Ros, and Brouwers [191] reasons that the larger enclosed horizontal surface of the substrate, and relatively large volume of potting soil substrate (of the LWSMT system, compared to LWSMB) allows for a better and larger buffering capacity.

Geotextile felt systems (LWSC) are expected to have a smaller retention capacity than modular LWS, due to their smaller growth medium volume ([191]). The absence of a substrate for GF makes their effect minimal, while GF with planter boxes do have some water retention capacity, determined by the size of substrate and planter box ([45]). Therefore, capturing rainwater is possible to varying extents for different VGS types, with substrate volume being key for retention capacity (Interview A).

In addition, the water infiltration rate – and thus the water retention capacity – increases both with an increase in porosity or in void between soil particles ([190]). Yet, the runoff reduction remains nearly equal in terms of soil types between sandy and loamy ([190]).

Vegetation

To a lesser extent, the vegetation canopy adds to the total water retaining capacity. A greater delaying action is related to a more complex vegetation structure ([8]). As such, a thicker plant layer with higher vegetation density can be considered to improve water retention ([45]).

Climate

The intensity and duration of the rain events affect the relative runoff reduction ([6]). Both considered studies were based on the locally observed daily rainfall data ([193]; [190]). A higher rainfall intensity and duration reduces the water retaining performance, as an increase in average rainfall intensity of 2.0 to 42.5 mm/h resulted in an average reduction decreasing from 87% to 52% ([190]). Hence VGS perform better in retaining rainfall during less intense rainfall events (Interview A). Still though, the tropical climate in this study might have a limited effect on the water retention capacity due to larger substrate saturation and air humidity than in drier climates ([7]). Other parameters, including wind speed, humidity, air temperature and solar radiation were neither independent nor dominant, and are therefore not considered crucial ([191]).

Evapotranspiration rate

The ET rate, equivalent to runoff reduction, is strongly influenced by evaporation from the wet substrate, as well as water transpiration rate from plants ([194]). Especially the foliage density in summer periods has a great influence on the final performance, with *Hedera helix* showing higher cooling capacities ([194]). Besides this, the exposed area, climatology (dry or windy conditions will increase transpiration), the available amount of water and substrate properties affect transpiration from plants. This influences ET and thus the runoff reduction rate.

5.8.5 Key findings

- VGS can provide water retention of rainfall, which slows down the runoff and reduces peak pressure on sewer systems ("retain and slow down"). LWSMT performs best on water retention capacity, owing to large substrate dimensions.
- In addition, rainwater flows can be reduced through evapotranspiration and use for irrigation ("use and reduce"). Foliage density greatly enhances the plant transpiration rate.
- The criterion 'maximize rainfall runoff control' is considered suitable, which is assessed on a seven-point scale, given the lack of quantitative data for all VGS types. The overall rainfall runoff control potential is derived from the average of retention capacity and runoff reduction (with runoff retention being the deciding factor), as visualised in figure 5.27.

Table 5.27: Rainfall runoff control performance per system type

Sub-criterion	**Unit**	**DGF**	**IGFC**	**IFGT**	**LWSC**	**LWSMT**	**LWSMB**	**LWSL**
Retention capacity	7-point scale	1	1	1	4	6	5	4
Runoff reduction	7-point scale	1	1	1	3	5	7	3

Criterion	**Indicator**	**DGF**	**IGFC**	**IFGT**	**LWSC**	**LWSMT**	**LWSMB**	**LWSL**
Maximize rainfall runoff control	Potential (7-point scale)	**1**	**1**	**1**	**3**	**5**	**6**	**3**

Table 5.28: Influence of parameters on VGS efficacy in rainfall runoff control (+++ = strong, ++ = intermediate, + = small effect, − = intermediate negative effect)

Level	Parameters	Effect on rainfall runoff control
Environment	Climate type	+
	Vegetation density (LAI)	++
	Plant species	+++
	Substrate	
	Moisture content	- -
	Depth	+++

5.9 Greywater treatment

5.9.1 Issue

VGS's extensive use of potable water for automated irrigation is at odds with global water scarcity and one of the main implementation barriers for VGS ([47]). In addition, increasingly stringent requirements for the removal of contaminants increase the energy consumption and costs of wastewater treatment ([195]). Sustainable water management is therefore vital.

5.9.2 Mechanism

Greywater (GW) is defined as household wastewater consisting of all domestic wastewater with the exception of toilet flushes, such as water from showers and laundry machines ([195]). GW may represent up to 75% of the total domestic wastewater, equalling up to 100-150 L/person/day in the EU and high-income countries ([196]).

Types of pollutants in GW are organic pollutants, including biochemical oxygen demand (BOD) and chemical oxygen demand (COD), as well as suspended solids (SS), nitrogen (N) and phosphorus (P) ([189]). GW requires simpler treatment and has less public health risks than wastewater.

LWS function as a biofilter and can remove pollutants from GW through physical (sedimentation, filtration), chemical (adsorption) and biological (microbial assimilation in plant and biofilm) processes, as water percolates vertically down through the substrate ([195]; [197]).

Integrated greywater treatment in VGS provides the opportunity to lower potable water consumption, while irrigating and providing plants with necessary nutrients and organics ([35]). At the same time, the GW is treated in a simpler treatment system than the centralised treatment systems for wastewater. This minimizes the pressure on urban municipal wastewater treatment plants and provides treated GW which meets effluent standards for reuse applications, such as toilet flushing ([189]). Approximately 40%–50% of water could be conserved with its implementation ([189]).

5.9.3 Performance

Review studies of GW treatment by VGS conclude that overall data indicated a substantial reduction in BOD and COD concentrations, and an appreciable decline in TN (total nitrogen) and TP (total phosphorous) concentrations ([189]).

Table 5.29 shows removal efficiencies found for VGS GW treatment. Organic pollutants (BOD and COD) can be removed at very high rates by VGS, with removal rates up to 90-98% and outlet concentrations that fulfil limitations for most non-potable water use ([198]; [199]; [195]). VGS can remove high amounts of total suspended solids (TSS), up to 90-100%, varying amounts of phosphorous (TP) and considerable amounts of Escherichia coli (E-coli), up to 90-100%. For nitrogen removal, removal efficiencies are somewhat lower, with predominant determining factors being both plant assimilation and media adsorption ([199]).

5.9.4 Parameters

The variability in removal efficiencies is explained by the different parameters determining GW treatment by VGS. Even more so, appropriate choice of substrate and vegetation, and setting of operational conditions can significantly improve the overall performance ([189]). Table 5.29 provides an overview of parameter values for the studies discussed in this section.

Table 5.29: Removal efficiencies from literature

Study	**Removal efficiency (%)**						**Source**
	BOD5	**COD**	**TSS**	**TN**	**TP**	**E-coli**	
1	95-98	82-88	-	31-34	69-77	98-99	[**Svete2012**]
2	97	-	-	7-92	-13-99	-	[199]
3	-	-	-	82	91	-	[200]
4	-	20-85	35-93	15-80	-156-42	60-100	[201]
5	-	-	90-100	88+-3	27-53	32-90	[202]

Substrate

The effectiveness of VGS in GW treatment is highly influenced by the performance and choice of substrate material ([189]). While natural porous media, such as soil and sand, have been generally well studied for pollutant removal, newer light-weight media, such as perlite, coir or rock-wool, are less well understood ([203]; [201]). Nevertheless, different studies investigated optimal substrate characteristics. According to Addo-Bankas et al. [189], major factors are physical properties, such as porosity, surface area, absorption capacity and water retention capacities of substrates.

Substrates are major contributors in removing excessive nutrients such as nitrogen and phosphorous ([189]). Prodanovic et al. [201] experimentally evaluated the pollutant removal performance of a variety of lightweight media in LWS. Among organic, or 'slow' media, coconut coir was found to have the best hydraulic and treatment performance. Also, organic substrates achieved higher pollutant removal of COD, T and N. Mineral, or 'fast' substrates, provide high porosity to avoid clogging, and among them perlite was most suitable. Thus, a combination of organic and mineral substrates is suggested to be the best option. This is confirmed by an in-situ study by Masi et al. [200], which found maximum removal efficiencies or organics for mixtures of LECA (light-weight clay aggregate) with coir or sand as well. Therefore, there is a balance need between high porosity to avoid clogging and sufficiently high contact surface to promote treatment, that can be achieved using hybrid materials.

In addition, bio-film formation on the surface of substrates, promoted by the addition of bio-absorbents in substrates, resulted in greater pollutant removal ([200]).

Vegetation

The influence of vegetation on pollutant removal efficiencies has been examined as well. Plants influence pollutant removal directly through adsorption and biosorption or indirectly through increasing microbial activity in the root zones by oxygenation or increasing exposure times of pollutants ([204]). Fowdar et al. [199] found that most species are effective for nitrogen removal, whereas specific ones are needed for phosphorous removal. Plant species selection should be carefully considered for greywater treatment, as requirements include high tolerance for water-logged, high-nutrient environments, which eliminates most ordinary VGS species ([189]).

Systems design and operation

Design parameters such as wall height, media height and the treatment capacity have been studied to influence the performance of the overall LWS in pollutant removal ([205]). For media height, another study found that a height of 60 cm resulted in the highest removal across all pollutants compared to 40 cm and 15 cm height ([197]).

Operational parameters, such as hydraulic loading rate and retention time, control the biogeochemical and physical processes occurring along each pathway, affecting the treatment efficiency ([195]).

The hydraulic loading rate (HLR), i.e. the ratio of flow rate per surface area, affects removal of BOD5, COD and TN. For BOD and COD, higher removal efficiencies were found when low HLR values were applied. This can be explained considering that organic matter is mostly removed by microbial degradation, for which retention time is stimulating. A low hydraulic loading rate results in higher hydraulic retention time (HLT). This results in increased removal of nitrogen ([189]). For phosphorous, no clear trend between HLR and TP removal is found ([195]).

Boano et al. [195] provides a threshold indication that values of HLR of up to 500 L/m2/day can be employed without reducing the removal efficiencies. Their argumentation for this guideline consists of a total nitrogen removal around 60-80% for HLR up to 500 L/m2/day, and high removal efficiency (around 80%) for organic matter for up to 800 L/m2/day.

5.9.5 Key findings

Key findings for greywater treatment are:

- VGS have a considerable potential to remove pollutants from greywater, given that their design is adapted to this functionality.
- Removal efficiencies (%) in BOD, COD, TSS, TN, TP and E-coli show this potential.
- Performances are mainly considered given the results form Fowdar et al. [199]. Only modular LWS are considered suitable for GW treatment, as their can provide sufficient media contact time given their relatively large substrate volume ([203]).
- For simplicity, for LWSMT and LWSMB, the average of all removal efficiencies is considered to well describe the effectiveness of VGS in greywater removal efficiency (table 5.30). All other types are assumed not suitable for GW treatment.
- The choice of substrate, vegetation and operational factors are crucial to the efficiency of LWS to treat greywater for re-use purposes. For example, hybrid substrates that have a balance between high porosity and sufficiently high contact surface promote treatment (table 5.30).

Table 5.30: Performance for greywater treatment

Aspect	**Unit**	**DGF**	**IGFC**	**IGFT**	**LWSC**	**LWSMT**	**LWSMB**	**LWSL**
Greywater removal efficiencies	BOD removal efficiency (%)	0	0	0	0	95	95	0
	COD removal efficiency (%)	0	0	0	0	80	80	0
	TSS removal efficiency (%)	0	0	0	0	90	90	0
	TN removal efficiency (%)	0	0	0	0	60-80	60-80	0
	TP removal efficiency (%)	0	0	0	0	60-80	60-80	0
	E-coli removal efficiency (%)	0	0	0	0	90	90	0
Criterion	**Indicator**	**DGF**	**IGFC**	**IGFT**	**LWSC**	**LWSMT**	**LWSMB**	**LWSL**
Maximize greywater removal efficiency	Average removal efficiency P (%)	0	0	0	0	82,5	82,5	0

Table 5.31: Influence of parameters on VGS efficacy in greywater treatment (+++ = strong, ++ = intermediate, + = small effect)

Level	**Parameters**	**Effect on greywater treatment**
Systems design	Substrate	
	Material	+++
	Depth	+++
	Plant species	++
	Water suitability	
Operation	Operational parameters	++
	Flow	
	Hydraulic loading rate (HLR)	
	Organic loading rate (OLR)	

5.10 Aesthetic value

Additionally, amenity value is an ecosystem service from a social and economic point of view that does not necessarily solve an urgent urban issue but does make VGS more attractive for citizens and economically viable.

The aesthetic experience of VGS has been researched through descriptive studies or surveys with passers-by. Preferences and perceptions of beauty rely on the visual appeal of systems [7, 181]. White and Gatersleben [206] showed that houses with integrated vegetation in some form are "more preferred, beautiful, restorative and had a more positive affective quality than those without". Other studies pinpoint the visual perception towards VGS system characteristics, such as plant diversity, size, naturalness and colourfulness [15] (Interview C). According to the hypothesis of "biophilia", humans especially appreciate the complex geometry of natural forms [207].

Similarly, another study suggests a wider variety of plants may be more appealing [208]. In urban green spaces, a flower cover over a critical threshold of 27% generates a 'wow factor' in terms of perceived attractiveness, in a more stimulating way [208]. Thorpert et al. [181] proposes planting arrangements that apply variation and contrast in foliage colour, as these are associated with better visual preferences. Crucial to a year-round green VGS is the use of evergreen plants (Interview C). When considering this importance of vegetation diversity to aesthetic appeal, studies indicate that LWS offer more creative potential than GF [71].

Environmental conditions play a dual role in aesthetic perception. The potential to integrate buildings with VGS into natural surroundings can improve landscape aesthetics [127], though VGS might be more valued in urban dense areas with lack of greenery [7]. Therefore, the character of the (urban) environment plays a dual role.

The aesthetics of vertical greening systems are recognised to increase the property value of buildings [209]. Even more so, the aesthetics and protective screening of green facades are means to increase the amenity value [8]. Giordano et al. [39] refer to this phenomenon as the value-property increment. It is further discussed in section 5.13 about economic impact. The economic impact of improving aesthetic is an effect on building level, whereas improving urban aesthetics for the public is discussed in this section.

In a more generic way, public perception of VGS can help in increasing public acceptance. Surveys aimed at citizens and urban planning specialists show that they perceive walls covered with greenery as more pleasant than bare walls, but with differences between countries and target groups [210]. This mixed perception was also evident in another study [211], where professionals and end-users did not mutually agree on all VGS benefits and concerns. For example, professionals emphasize environmental quality improvement, while building occupants also fear insects climbing on LWS [207].

Still though, another survey showed positive emotions reported in 87.7% of the respondents for a LWS at a hospital in Seville, Spain ([212]). The same survey shows that 40% of respondents did not completely understand VGS, emphasizing the importance of the informing and engaging with the public. Even more so, Francis and Lorimer [57] and interviewee A both state that successful implementation of VGS heavily relies on the participation of urban citizens.

Key findings

Key takeaways on the aesthetic potential of VGS are:

- Some studies on aesthetic value of VGS indicate that aesthetic appeal is mainly based on the diversity and flowering in vegetation cover.
- Therefore, a 7-point scale for qualitative assessment is adopted, mainly based on the potential vegetation diversity for different VGS systems.
- Since LWS can integrate up to 250 species (chapter 4), their diversity potential is larger.
- Since green facades have smaller possibilities for diversity of vegetation than LWS (chapter 4), and can have lower facade coverage (section 5.7), they score less well than LWS.
- The flexible felt of LWSC enables different shape possibilities, adding complexity to the VGS form - which is aesthetically appreciated [207], so LWSC are assumed to score highest.

Table 5.32: Criterion, indicator and performances for aesthetic value

Criterion	Indicator	DGF	IGFC	IGFT	LWSC	LWSMT	LWSMB	LWSL
Maximize aesthetic value	Potential (7-point scale)	3	3	3	7	6	6	4

Table 5.33: Influence of parameters on VGS efficacy in aesthetic value (+++ = strong, ++ = intermediate, + = small effect)

Level	Parameters	Effect on aesthetic value
Systems design	Building vegetation coverage	++
	Plant species	
	Diversity of plant species	+++
	Flowering coverage	++

5.11 Human health and well-being

5.11.1 Issue

Urban upbringing and living brings with it the potential for negative impacts on mental health and well-being, in particular mood and anxiety disorders, increased incidence of schizophrenia, and mental fatigue [8]. Physical health in cities is also under pressure, as laid out in the section about urban heat island, air pollution and noise hindrance. At the same time, rising costs for health care is an urgent theme too [17].

5.11.2 Mechanism

Green infrastructure provides ecosystem services related to human health and well-being. On the one hand, greener cities improve physical health by controlling pollutants – provided that human allergenicity to specific plant species is taken into account –, by reducing urban heat, air pollution and noise, and by stimulating exercise, which is most true for green streets [3]. On the other hand, urban green has been proven to enhance psychological well-being regarding stress relief. This is often related to the hypothesis of "biophilia", in which natural elements that are brought more closely in contact with humans is necessary for human well-being [207, 213]. Some urban policies already acknowledge the mental need for greenery by transforming public space, e.g. in Barcelona [23]. From a societal perspective, integration of vegetation in urban areas can play a valuable role in crime reduction as well as social integration, cohesion and justice [3, 8].

5.11.3 Performance

The restorative effects of urban green were found by famous research by Ulrich et al. [214], who found that hospital patients with a view on greenery out of the window could recover more quickly than those who cannot. Other physical health effects of vegetation include reduced exposure to noise, air pollution and heat, as discussed in previous sections [13].

Most positive effects of nature on human health and well-being are demonstrated qualitatively through surveys. Studies confirmed that natural scenery helps people to cope with stress-related psycho-social symptoms [215]. Simply viewing a green space, even if not accessible, has a positive psychological effect [7]. Exposure to vegetation, or a view of natural scenery, is known to provide psychological relaxation and reduce mental distress, stress levels, tension and anxiety [8].

Characteristics of green influence the impact of GI on mental well-being. "Can Even a Small Amount of Greenery Be Helpful in Reducing Stress? A Systematic Review" [216] found that the stress-reducing effect of indoor greening facilities is not necessarily proportional to their size, because a tree cover at higher densities was not associated with pressure recovery. Hoyle, Hitchmough, and Jorgensen [208] identifies subtle and 'natural' green to induce higher restorative effects. The latter refers to the fact that planting moderately and most natural in structure was perceived significantly more restorative than highly designed planting.

Although this evidence of positive health effects of GI may be extended to VGS, the psychological benefits of VGS specifically are rarely scientifically addressed [212]. Yet, in a recent study on VGS, the beneficial effect of viewing a green facade landscape instead of a bare building wall was demonstrated to enhance physiological and psychological relaxation [217]. Also, visually attractive LWS can be beneficial for human health [181].

Whereas societal benefits, such as crime reduction or sense of community, have been explored, much more research is needed on how VGS can contribute to those before a relationship can be established.

5.11.4 Key findings

For effects on human health and well-being, the key findings are:

- A natural scenery, including VGS, brings people psychological and physical relaxation, especially for subtle and 'natural' green.
- As the extent of mitigating urban heat, noise and air pollution is already reflected in other criteria, the performance for human health below focuses on the relaxation effects.
- As GF are more likely to be perceived as a natural structure, and its vegetation as subtle and less flowering, GF are considered to perform better in terms of potential relaxation effects. Similarly, LWSL also contain vertically growing climbers, providing a more 'natural' look.

Table 5.34: Criterion, indicator and performances for relaxation effects

Criterion	Indicator	DGF	IGFC	IGFT	LWSC	LWSMT	LWSMB	LWSL
Maximize relaxation effects	Potential (7-point scale)	6	6	6	3	3	3	5

Table 5.35: Influence of parameters on VGS efficacy in relaxation effects (++ = intermediate effect)

Level	Parameters	Effect on relaxation effects
Systems design	Plant species	++

5.12 Environmental impact

Regarding environmental impact, VGS can have a high influence on the environmental profile of a building envelope [70]. Life cycle assessment (LCA) methodology can be used effectively to demonstrate if a VGS can be considered environmentally sustainable or not (Perini, 2021). LCA techniques compare environmental impacts from construction, installation, maintenance and disposal phases (figure 5.27) [3]. As an LCA quantifies sustainability, the environmental impact is translated into environmental (shadow) costs per square meter, i.e. an environmental cost indicator (ECI) value [171].

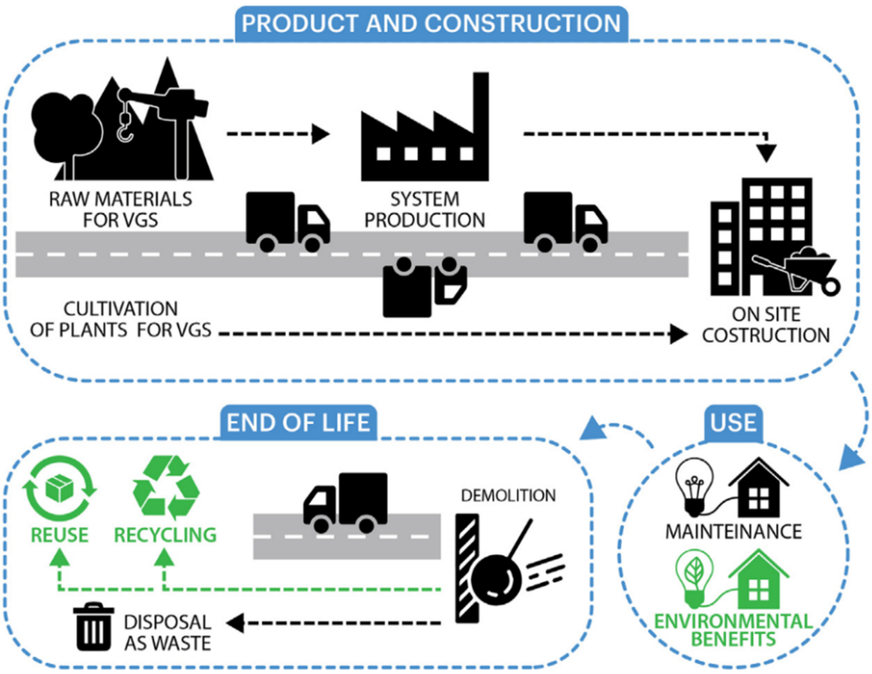


Figure 5.27: Main life cycle phases of VGS [218]

VGS can be sustainable design strategies when environmental benefits are higher than environmental costs [218]. However, Rowe et al. [30] concludes that uniform guidelines or practices exist for environmental impact assessment of VGS. Thus, this section explores the main environmental burdens and benefits, and interprets these to integrate them in an MCDM approach.

5.12.1 Environmental burdens

Negative environmental impacts, i.e. burdens, are calculated according to selected impact categories, often greenhouse gas emissions and climate change, and sometimes also global warming, human toxicity and fresh-water aquatic eco-toxicity [218].

Materials

The environmental impact of VGS is most enlarged by the materials and components used, as well as their related dimensions and weight, for example of the supporting system [3]. For example, the supporting system can be made of a steel mesh, wooden trellis, plastic mesh for IDGF or felt, HDPE planter boxes or geotextile for LWS [3].

Concretely, the material stage contributes in a range of 47-97% to all the environmental impact categories [219].

Different assumptions for system lifespan are made in LCA studies. Felt-based systems (LWSC) are generally considered to have the lowest lifespan, around 10 years [30]. This implies panel replacement every 10 years, increasing the environmental burden. Most often, for other LWS an in-service life of 50 years is assumed, including LWS based on plastic planters and IDGF with steel support [7, 30]. This is comparable to the lifespan of conventional facades, which is 45-50 years [220].

Different assumptions are also made for whether materials are re-used or recycled in the end-of-life phase. When re-use and recycling is not assumed for a stainless steel mesh in IDGF, the environmental burden is higher than for other mesh materials, e.g. coated steel or HDPE [70]. However, interviewee B expects that steel or aluminium elements of IDGF and LWS could be re-used after the lifetime of the VGS has expired, which would improve both environmental and economic (disposal) impact. On the other hand, felt systems are considered less likely to be re-used, because it is directly fixed to facade layers. The recycling potential can lower the environmental burden, as 50% of the total substrate volume could be made of recycled materials, though these innovations are not widely available yet [218].

Maintenance

In addition, maintenance issues play a large role and affect the environmental burden. For example, pruning takes place from twice to several times a year and dead plants or ruined panels need replacement [218].

The yearly replacement rate of plants is assumed between 0 to 28.6% [30]. This range can be attributed to uncertainty due to dependencies on specific systems and difficulty of gathering data on all influential parameters [30]. Living wall systems often need 5-10% yearly replacement of plants [7].

Due to salt crystallization, irrigation water pipes can be blocked and need to be replaced every 7.5 years [221]. Three papers agree on an irrigation pipe lifetime of 7.5 years, while three others assume 10 years [164]. Besides costs, this adds to the environmental impact as well.

Water use

Tap water demand for irrigation of LWS lies around 3 L/m2/day and affects especially eutrophication potential and freshwater aquatic eco-toxicity [219]. Rowe [164] analyses that water demand is dominantly determined by the type of VGS, local climate and orientation. Yet there is no consensus between studies on which type of VGS uses most water. Generally, green facades are assumed to need no to little irrigation because of plants rooted in ground-level soil. For LWSC (felt-based), water use ranges between 730 and 2190 L/m2/year, while for VGS based on plastic planters this lies between 146 and 2920 L/m2/year [164]. The future potential of lowering environmental burdens by reducing the irrigation demand by half was shown by Natarajan et al. [222], who claims that this can save 46% energy usage and 37% carbon emissions. For this purpose, drought-tolerant plant species with a low water demand could be considered.

5.12.2 Environmental benefits

The most widely considered benefits in LCA studies are energy savings, CO2 uptake and air cleaning potential [30].

The potential energy reduction from reduced cooling and/or heating form the most influencing benefit lowering the environmental impact of VGS [3]. Studies often use single thermal resistances to assess potential energy savings, resulting in energy savings varying from 6% to 60% [30].

Three LCA studies include CO2 uptake, i.e. carbon sequestration potential of VGS [30].

The air cleaning potential relates to the impact categories of the LCA methodology, too (Perini, 2021). The one model that estimates a payback period for air pollutants (NO2, SO2, O3, PM10) is based on green roof capture results. As such, more data would be needed for integration in LCA studies.

Rowe et al. [30] determines that for impacts on biodiversity, noise reduction and psychological and health effects, quantitative data is lacking for integration in LCA studies.

5.12.3 Key findings

Despite the academic knowledge on the environmental impact of VGS, it remains difficult to fully understand the sustainability level during the life cycle [40], especially due to different assumptions and boundary conditions in LCA studies [30] and limited available data [223].

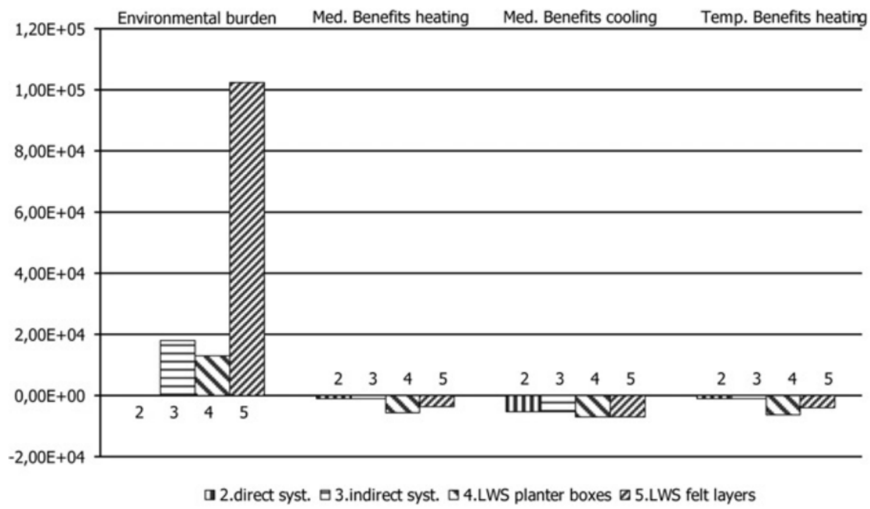


Figure 5.28: Total environmental burden for four VGS, benefits for heating and cooling in Mediterranean climate, and benefits for heating for temperature climate [70]

Therefore, this study considers a 7-point scale performance for total environmental burdens per system typology. Environmental benefits, on the other hand, are considered separately in terms of the indicators identified in other sections.

The main takeaways for environmental burdens, based on [70], [36] and interviewee B are:

- Direct green facades have a very small influence on the total environmental burden of the building facade and are almost always a sustainable choice because they only contain vegetation. Therefore, they score high on the 7-point scale.
- Indirect greening systems with a stainless-steel support have a higher environmental burden due to material use.

- Living wall systems have a significant influence on the environmental profile, but often the benefits of LWS can balance their environmental burden [3].
- LWS with a cloth system of felt (LWSC) have the highest environmental burden, due to a low lifespan and low recyclability (figure 5.28).
- LWS with planter boxes (LWSL) have a smaller footprint than other LWS owing to the positive effect on the thermal resistance.
- Two important factors determining differences between different LWS systems are the mass of materials involved, and recyclability and reusability of each component.

Table 5.36: Criterion, indicator and performances for environmental burdens

Criterion	**Indicator**	**DGF**	**IGFC**	**IGFT**	**LWSC**	**LWSMT**	**LWSMB**	**LWSL**
Minimize environmental burdens	Potential (7-point scale)	7	6	6	1	3	3	4

Table 5.37: Influence of parameters on VGS environmental burdens (+++ = large, ++ = intermediate, + = small, - - = negative intermediate, brackets = assumed)

Level	**Parameters**	**Effect on environmental burdens**
Systems design	Building vegetation coverage	(- -)
	Plant species	++
	Substrate	
	Material	++
	Supporting structure	+++

5.13 Economic impact

Assessing economic sustainability, by balancing costs and benefits, is essential for the large-scale deployment of VGS [20, 41]. Whilst presenting the benefits of ES in monetary terms makes them easily understood by decision-makers, research on economic sustainability is limited [6, 43].

Cost-benefit analysis (CBA), which compares the life-cycle costs and benefits of a project to determine its feasibility, is applied by most economic studies [20]. Although CBA can provide insight into associated costs and benefits, it cannot capture all the value created by VGS. Not all benefits can be included due to difficulty and uncertainty in quantification and monetization of 'soft' benefits [7].

This section examines the economic costs and benefits that can be appropriately included in a holistic MCDM approach. Private costs and benefits are laid out, whereas noise insulation, air quality improvement and carbon reduction are integrated into this study's approach as quantified benefits in terms of indicators that best represent their value, instead of monetised values with large uncertainty and largely based on assumptions.

5.13.1 Private costs

Typically, private life cycle costs are divided into installation, maintenance and disposal costs. This section discusses those costs, with key findings at the end of this chapter, and a detailed derivation of cost (ranges) in appendix 11.7.6.

Installation

Review studies compare the costs for different VGS available through manufacturing companies on the European market [7, 15, 41]. System type, and accordingly plant type, is the main determinant of the cost range. Variation within installation and maintenance cost ranges depends on factors such as location (urban or peripheral, local climate) and detailing (connections, height) [41, 71].

Installation costs consider the initial investment for the application of a VGS, including design, materials, transportation and labour costs [7]. Rosasco [41] presents an elaborate cost breakdown (Appendix 11.7.6), presumably mainly based on the cost-benefit analyses performed by Perini and Rosasco [221] and Perini and Rosasco [224].

For direct green facades (DGF), the costs for design, digging and potting, plant species, installation and the irrigation system make up the total installation costs. The required dig at the base of the facade, as well as plant species and installation, are expressed in a cost range per linear metre facade [41]. To arrive at a total cost range for installation per square metre of facade, a facade height of 15 metres is assumed for a DGF (similar to [221]). Besides, design costs depend on the complexity of the green facade solution, and are considered between 6% to 10% of the total initial costs for all VGS [41]. This results in total installation costs of 37 – 51 €/m2 for DGF. These values are in line with other estimations at 30 – 45 €/m2 as disposition costs for grown climbing plants as a DGF [71].

In the case of indirect green facades, additional installation costs include the irrigation and supporting system materials, transportation and installation. Based on costs estimated in earlier studies [221, 224], a distinction for supporting system and transportation costs between HDPE (35-45 €/m2) and steel (95-110 €/m2) is made. It is noted that transportation costs depend on the distance between the building and the manufacturing companies' location, for which the earlier studies were based on the city of Genoa, Italy, with production 300 -340 km away [221]. Choosing local, more close, suppliers would lower the transportation costs (Interview B). When the same height of 15 metres is assumed, the total installation costs for IFGT are 146 – 219 €/m2 and 206 – 284 €/m2 for HDPE and steel, respectively. Similar values are considered for indirect green facades with continuous rather than mesh supports, as those specific costs have not been discussed in literature.

The estimates for IDGF are roughly in line with the cost estimates of 125 €/m2 for HDPE and 240 €/m2 for steel mesh by Rosasco [41]. Discrepancies between the estimates may be due to differences in scope, such as the exclusion of design or digging costs.

For IDGF with planter boxes, a similar derivation results in total installation costs of 202-306 €/m2 for HDPE and 293-406 €/m2 for steel as material of supporting structure and planter boxes. This is approximately in line with earlier estimates (Appendix 11.7.6).

For living wall systems, the costs for plant species and panels vary largely between 185 – 500 €/m2 [41], as many different systems are available on the market. This results in 224 – 594 €/m2 as installation costs for LWS.

These values are to some extent comparable to ranges found in other studies, such as 400 – 570 €/m2 [47]. Another study shows LWS installation costs at 750 €/m2 as the average of two studies with values far apart (around 400 and 1000 €/m2 [7]), which makes the average a highly uncertain value. Perini et al. [71] presents installation costs range estimates for trough planters, felt and modular framed boxes LWS, at averages of 500, 550 and 975 €/m2, respectively. This suggests higher costs for modular than for linear or continuous LWS, yet because of the wide ranges and old reference year these values are not adopted in this study. Also, installation costs of modular LWS could be lower because of using pre-fabricated modules with short installation time, while IDGF require longer installation time and thus more labour costs (Interview B). Thus, the cost ranges found by Rosasco [41] are adopted.

Maintenance and operation

Maintenance costs are to a large extent comprised of pruning costs. Those costs and pruning frequency depend on VGS type, species and local climate [41]. Annual pruning costs vary from 2.5 to 18 €/m2, for green facades and living wall systems (including panel adjustments) (Appendix 3.1). Replacement of dead plant species in planter boxes and LWS usually varies between 5% to 15% annually [70, 221].

Operational costs relate to irrigation costs at 1 – 1.5 €/m2/y, for which water demand depends on the local climate (air temperature and humidity, incoming solar radiation, wind speed) and vegetation type. For example, GF in climates with dry and warm winters would need more intense irrigation, increasing irrigation costs (Interview B). This insinuates that the water demand of LWS is more independent of climate (since automated watering is necessary anyway) than of GF. Irrigation pipes replacement is needed due to clogging by crystallized salts and can reach 15% of the total length of pipes annually, corresponding to a variation between 0.3 to 3 €/m2/y [41].

Total annual maintenance and operation costs come down to 3 – 4.4 €/m2 for (in)direct GF, 10.5 – 15.5 €/m2 for GF with planter boxes, and 23.5 – 35.5 €/m2 for LWS. This is comparable to values found by other review studies, that estimated 5,57 €/m2 for GF and 18,98 €/m2 for LWS [7].

Disposal

Disposal costs at the end of the lifespan consider the plant and structure removal, transport to landfill and dump taxes (in case of no recycling or re-use). These vary from 30-45 €/m2 for DGF, 160 – 220 €/m2 for IDGF to 180-240 €/m2 for LWS, due to the diversity of materials involved [15].

5.13.2 Private benefits

The installation and maintenance costs within the lifespan can be counteracted with economic private benefits, such as energy savings, increased building plaster durability and real estate value [209].

Energy savings

The energy savings from reduced energy demand for heating and air-conditioning greatly influence the total benefits of VGS [3] and are considered in most economic analyses. The reader is referred to the section about thermal control for assumed performances regarding energy savings (%), as an indicator of this aspect.

Facade longevity

Several studies hypothesize that VGS application can prolong the service life of the building facade underneath.

VGS protect the exterior building plaster from UV radiation and corresponding exterior surface temperature fluctuations, rain-off along the facade and wind pressure, which decreases facade deterioration or weathering of exterior painting or cladding layers [9, 97, 225]. As such, the more minor plaster reconstruction works and the postponement of the intervention over time create cost savings [41].

Still though, extensive quantification of life cost savings because of the longevity of the facade has not yet been done in the research field [40]. One case study quantifies facade longevity benefits, by comparing the discounted cost of facade plaster renovation without the VGS at the 'regular' end-of-service-life (usually 25-30 years) with the same cost at the increased life span (usually 10 to 15 years later) [221]. Assuming a regular service life of 35 years, an extended service life of 50 years, and different extents of renovation for different VGS (more protective action results in less extensive renovation), the study resulted in the values in table 5.38.

Table 5.38: Plaster renovation saving for total area of 215 m2 and per m2 (based on [221])

Indicator	DGF	IDGF	LWSL	LWS
Plaster renovation saving (€, at t = 50)	61.164	107.354	113.326	133.793
Plaster renovation saving (€/m2, t = 50 y)	284	499	527	622

Real estate value

The increase of real estate value due to the application of VGS, varying between 1.4% and 20.0%, has been non-completely investigated [3]. Studies have employed hedonic pricing of greenery, estimating that an increase in greenery quality level would increase the land price by 1.4-2.7% [226], which would increase the property value. Other studies found generic values for green roofs and walls, as shown in table 5.39 below. Manso et al. [7] derived an average increase of 8.24% from past studies, albeit for green roofs and VGS. This is nearly equal to the average of 8.3% increase as average from the results in the table.

An Italian study in the city of Genoa found higher increases for more peripheral areas within the city [230]. Possibly, this could be related to the fact that highly urban city centres already have other aesthetic features and real estate prices are already higher so a VGS application will increase the real estate value relatively less. Perini and Rosasco [221] considers greening on one side of the building, and appreciation, besides aesthetic value, also depending on factors such as building type, number of floors and presence of nearby green. Therefore, they assume $\frac{1}{4}$ fraction of these values, equal to 2.0 to 5.0%.

This study follows this reasoning. Since Bianchini and Hewage [79] found that extensive green roofs can increase property value by 2-5% and intensive green roofs by 10-20%, it is assumed that intensive LWS (LWSC, LWSMT, LWSMB) will result in higher value increases (4.0-10.0%) than extensive GF (2.0-5.0%). LWSL, being a hybrid of extensive and intensive systems, is considered to increase with a value in between the two extremes (3.0-7.5%).

Table 5.39: Real estate value increases (%) in literature

Real estate value increase (%)	Assumptions	Source
1.4 – 2.7	Hedonic pricing of greenery through hedonic pricing, for two Japanese cities	[226]
3.9 – 15.0	For VGS and green roofs, based on local market demand	[227]
6 – 15	Green roofs and walls yield same property increase as a 'good tree cover'	[228]
6 – 15	Aesthetic appreciation of 5.8 €/household, equal to 2.4 €/person/year, in Toronto, Canada	[229]
8.0 – 20.0	8.0% for located in central city area, 12.0% in semi-central city area, 20.0% in peripheral area	[230]
2.0 – 5.0	2.0% for located in central city area, 3.0% in semi-central city area, 5.0% in peripheral area	[221]

In chapter 6, a parametric scoring is adopted which the reflects the dependency on the degree of urbanity [230]. There, value increases at the upper end of the range are considered for peripheral areas within the cities, and lower values within the range for highly urban areas. VGS in non-urban areas are assumed to result in a value increase at the average of the range, because not many citizens see the VGS.

Tax incentives

It is worth mentioning that the research by Rosasco and Perini [209] resulted in the conclusion that VGS are economically sustainable when a tax reduction on installation costs is considered. Tax incentives or subsidies by public administration, that take into account social or public benefits, can support private investments, and as such increase economic sustainability and promote the implementation of VGS at urban scale [40, 209] (Interview A). Since incentives are not uniformly applicable throughout the Netherlands, an explicit score on incentives is not integrated into the tool. However, a recommendation is made to check on the applicability of incentives, whether for existing residential projects [231] or other building types such as offices or social housing [232].

5.13.3 Total economic sustainability

A main economic sustainability indicator is the net present value (NPV), which illustrates the total economic impact of the project during its lifetime. Although the NPV can indicate cost-effectiveness, economic studies have dealt with different scopes (e.g. for included benefits) and assumptions, which makes it difficult to compare values.

In a sensitivity analysis, Rosasco and Perini [209] found that the main economic costs that negatively influence the NPV are increases in installation and maintenance costs. Therefore, these costs are incorporated as one of the indicators of economic costs, being more determining than e.g. discount or inflation rates. Also, this makes careful design and optimal material choice specifically relevant in order to optimize material choice, thereby reducing installation and maintenance costs [57, 209].

5.13.4 Key findings

Private costs include installation, maintenance and disposal costs. For clarity and one overall value in the MCDM approach, the average of cost ranges is considered to represent an approximation of the magnitude of the costs. Similarly, the costs for IGFC/IGFT and LWSL are averaged for using HDPE and steel. Still though, the detailed results in the tool will represent the exact ranges found, as well as the distinction between HDPE and steel. Figure 5.40 (next page) shows the cost ranges found in the literature study, and the values assumed in the overall performance aggregation.

Private benefits include energy savings (see section 5.3), plaster renovation savings and real estate value increases. Their respective performances for different VGS types are shown in the table. For real estate value increase, parametric scoring is adopted in chapter 6, to account for the influence of urbanity on the performance. Figure 5.41 shows an overview of the environmental and design parameters affecting private costs and benefits.

Table 5.40: Economic performances (bold = adopted in framework/tool scoring)

Criterion	Indicator	DGF	IGFT, IGFT		LWSC, LWSMT, LWSMB	LWSL	
			HDPE	Steel		HDPE	Steel
Minimize private costs	Installation costs, range (€/m2)	37-51	146-219	206-284	224-594	202-306	293-406
	Installation costs (€/m2)	**44**	**214**		**409**	**302**	
	Maintenance and operation costs, range (€/m2/y)	3-4.4	3-4.4		23.5-35.5	10.5-15.5	
	Maintenance and operation costs (€/m2/y)	**3.7**	**3.7**		**29.5**	**13**	
	Disposal costs, range (€/m2)	30-45	160-220		180-240	160-220	
	Disposal costs (€/m2)	**38**	**190**		**210**	**190**	
Maximize private benefits	**Plaster renovation saving (€/m2, t = 50 y)**	**284**	**499**		**622**	**527**	
	Real estate value increase (%)	**2.0-5.0**	**2.0-5.0**		**4.0-10.0**	**3.0-7.5**	

Table 5.41: Influence of parameters on VGS private costs and benefits (+++ = large, ++ = intermediate, + = small effect, - - = negative intermediate effect, brackets = assumed)

Level	Parameters	Effect on private costs	Effect on private benefits
Systems design	Building vegetation coverage	(- -)	(++)
	Plant species	++	
	Supporting structure	+++	

5.14 Functionality

Designing for functionality is a base-line requirement, since it needs to be taken into account regardless of location, objectives and system type to obtain a healthy and green VGS. A functioning VGS is a condition necessary to provide the benefits covered by the criteria. Therefore, this section analyzes what main aspects are important for functionality, and formulates generic design recommendations to be part of the MCDM framework.

5.14.1 Structural suitability

The load-bearing capacity of the primary structure should be able to handle the loads of the structural weight of the VGS. For new-built projects, the weight of VGS is 'not a limiting factor' in the case of a concrete or steel load-bearing structure (Interview B). Even more so, the choice for a light-weight VGS, e.g. green facades, can inform the design choices for the load-bearing structure (Interview B). When applying VGS on existing buildings or in renovation projects, the load-bearing capacity of the existing structure needs attention (Interview A). In some cases, this might imply that the heavier LWS are not suitable. To include this consideration, a first check on structural suitability is part of the design recommendations at the end of the framework. Because determining the existing load-bearing capacity is challenging in early facade design phases, an elaborate structural check during these phases is considered out of the scope of this study. The recommendation is:

- For existing buildings or renovation projects, check the suitability of load-bearing capacity of the existing structure for the structural weight of different VGS systems.

5.14.2 Vegetation

There are various choices and considerations associated with plant species in VGS. A deliberate choice for plant species is important for functionality, as Bustami et al. [48] states that *"the success of a VGS relies partly on the ability to select suitable plant species that can maximise the capacity and performance of VGS"* . Recommendations for plant species contributing to benefits are covered in the systems design parameters described before. This section discusses vegetation considerations for functionality.

The selection of most suitable plant species has a significant impact on the green system behaviour [40], especially in aesthetic and functional aspects [67]. Depending on the desired effect, the textures and colours offered by diverse plant species produce completely different designs and appearances [62].

Plant species for GF and LWS

For climbers in green facades, considerations include the varying attachment methods, plant size and growing speed of climbing species for green facades, also depending on whether a support structure is used [62]. Commonly used species for direct green facades are Ivy (*Hedera helix*) as evergreen species and Boston Ivy (*Parthenocissus tricuspidata*) as deciduous species [61]. Indirect green facades allow a greater variety of climbers with different attachment modes and other characteristics (figure **??**).

Multiple climber-plant traits for greenwall design and management			
Biological	**Provenance**	**Life-cycle**	**Growth-form**
	Native	Perennial	Stout-woody
	Naturalized	Biennial	Slender-woody
	Exotic	Annual	Herbaceous
Ecological	**Seasonality**	**Light-preference**	**Moisture-preference**
	Evergreen	Full-sun	Hydric
	Semi-deciduous	Semi-shade	Mesic
	Deciduous	Shade-tolerant	Xeric
Growth-habit	**Growth-rate**	**Attainable-height**	**Green-coverage**
	Fast	Tall >20 m	High >75%
	Medium	Medium 10–20 m	Medium 50–75%
	Slow	Short 3–10 m	Low 25–50%
		Dwarf <3 m	Sparse <25%
Foliage	**Leaf-size**	**3D-foliage**	**Seasonal-color**
	Large >8 cm	Cantilever	Vivid change
	Medium 4–8 cm	Normal	Moderate change
	Small <4 cm	Veneer	Little change
Flower	**Showy-flower**	**Flower-size**	**Bloom-duration**
	Conspicuous	Large >8 cm	Long >4 weeks
	Moderate	Medium 4–8 cm	Medium 2–4 weeks
	Non-showy	Small <4 cm	Short <2 weeks
Climbing	**Attachment-mode**	**Training-system**	**Climbing-surface**
	Sticking[a]	Bare wall	Wall
	Gripping[b]	Mesh (trellis)	Wall-like frame
	Twining[c]	Netting (web)	Pergola (arbor)
		Cable (wire-rope)	Post-pole

[a] Direct attachment to bare wall surface with sticky pads or sticky aerial roots.
[b] Attaching to wires of a training system of mesh or netting by tendrils, hooks, thorns, etc.
[c] Spiral twinning around the a cable (wire-rope) of the cable training system.

Figure 5.29: Examples of climber characteristics to consider [182]

For living wall systems, the choice of plant species is influenced by the characteristics of the type of VGS, climate and environmental conditions [62, 67]. LWS offer a greater variety of species to choose from. Usual types are herbaceous perennials and shrubs, owing to to the desired aesthetic effect in terms of variation in color, texture, foliage forms and density, vitality, and growth [61]. Another option are grasses. In LWSC, a large number of plants incurs a high probability of poor performance and more need for replacement [65], making a deliberate plant choice even more important.

Seasonality

Depending on the micro-climatic benefits required, evergreen of deciduous plants can be used. Evergreen plants can protect the facade from wind flow, snow and rain in wintertime, which can be specifically relevant in temperate climates or north-facing facades [67].

Deciduous plants affect its performances in winter, as direct solar radiation can reach the facade [67]. Bellomo [72] states that deciduous plants can be more suitable for Mediterranean climates, or southern facades. Although deciduous plants allow the building envelope to change visually, they are less favourable for aesthetic value (Interview C). The design recommendations for specific criteria, therefore, include using evergreen or deciduous species.

Environment

For each vertical greening system, the selection of species should be adapted to the specific local environment in which they will grow, in terms of light and shadow (e.g. sun-tolerant species), temperature and water conditions (e.g. drought-tolerant species) [36] (Interview C). Also wind exposure, especially on high buildings, needs to be taken into account (Interview C). In that way, this offers an opportunity for good biomass development, which is important for benefits such as noise reduction.

Other parameters for plant selection include low allergenicity, suitability to grow in the substrate, maintenance needs (such as pruning), biomass production (growing speed), space available within the urban area and stock availability in nurseries in the area of installation [**Perni2013**, 41, 62].

Local plants

Whereas Scheuermann et al. [5] recommend to generally use a variety of local plants to overcome survival difficulties related to climatic conditions, Fernández-Cañero et al. (2018) and interviewee B describe that for LWS this strategy has mixed results as native plants sometimes do not grow properly in the artificial ecosystem. For biodiversity, the use of native or established species is recommended (Interview C) [181]. Anyway, the use of local plants is recommended for better survival chances in the local conditions (sun, drought etc.).

To facilitate plant selection, the development of plant catalogues by climate would be useful [19]. The above results result in the following design recommendation for functionality:

- Choose local plants for better survival chances.
- Choose plant species that are well-adapted to local conditions (e.g. wind, amount of sun/shadow, temperature) for good biomass development.
- Choose plants with low allergenicity.

5.14.3 Substrate

The substrate choice can be based on characteristics such as well-draining behaviour, i.e. the water-holding capacity, and proper organic content [40, 233]. These two characteristics contribute to the survival of the plants through water and nutrient provision. The functionality recommendations are:

- Consider the suitability of the substrate conditions for the plant species.
- Use a substrate with well-draining behaviour and proper organic content [40].

5.14.4 Supporting structure

Materials for the supporting structure have different environmental impacts, while recycling of supporting structures at the end-of-life can also reduce the environmental impact of a system (Ottelé, 2011). This is expressed in design recommendations for minimizing environmental burdens.

Another consideration for the supporting structure is the integration with the structure and surface of the building envelope[40]. Especially water-tightness and mounting the VGS on the primary structure to maintain structural integrity are important to consider (Interview B). Also, Fernández-Cañero, Urrestarazu, and Perini [62] point out that the supporting systems made of stainless steel can be installed outdoors in any climatic condition.

This results in the recommendation:

- For designing the supporting structure, consider the water-tightness, mounting and suitability to climatic conditions.

5.14.5 Operation: Irrigation and maintenance

During the operational phase of the VGS, irrigation and maintenance are important for 'a good state and performance' [233].

Adequate irrigation is essential for provision of water for plant development [194]. On the other hand, water use efficiency is beneficial for the energy use of LWS irrigation systems and environmental footprint [222]. Overwatering of LWS is often an issue [47], so adaptive irrigation is advisable [40].

For water distribution in a LWS, two approaches can be applied: either plant species should be placed bearing in mind their water requirements as there will be a gradient of humidity along the living wall, or a higher frequency irrigation with lower flows and shorter irrigation time is applied to achieve a uniform water distribution [234].

For maintenance, the (costs of) replacement of system components and other maintenance is discussed in section 5.13. A challenge for VGS maintenance, such as pruning, is associated with working at a height. Therefore, a maintenance strategy with planned maintenance, e.g. through a service contract, is needed to properly maintain the VGS.

Operational recommendations for functionality are:

- Design an irrigation system that ensures adaptive irrigation (avoid over-watering).
- Place plant species bearing in mind their water requirements as there will be a gradient of humidity along the living wall, or apply higher frequency irrigation with lower flows and shorter irrigation time to achieve a uniform water distribution [234].
- Implement a maintenance strategy, with planned maintenance (e.g. with a service contract).

Above aspects are crucial to take into account to make sure the system, and especially the plants, are in good condition. As such, these design considerations are necessary for performance in delivering ecosystem services. It should be noted that the above aspects of designing for functionality are non-exhaustive, and based on the systematic literature study performed to answer RQ2-4. Thus, the design for functionality recommendations form an initial overview of important aspects to take into account in schematic design phases.

5.15 Synthesis and conclusion: A holistic set of criteria for sustainable buildings and cities

5.15.1 Criteria

This chapter has collected the wide range of impacts of VGS. These include ecosystem services that help solve issues that are often predominant in urban settings, as well as other benefits and burdens. Combining the criteria creates a set of criteria on which the VGS types can be assessed. The value tree in figure 5.30 provides an overview of the criteria and corresponding indicators adopted in this study. The set of criteria represents the different dimensions from which the alternatives can be viewed, and it reflects the value associated with the consequences of each VGS system alternative [51].

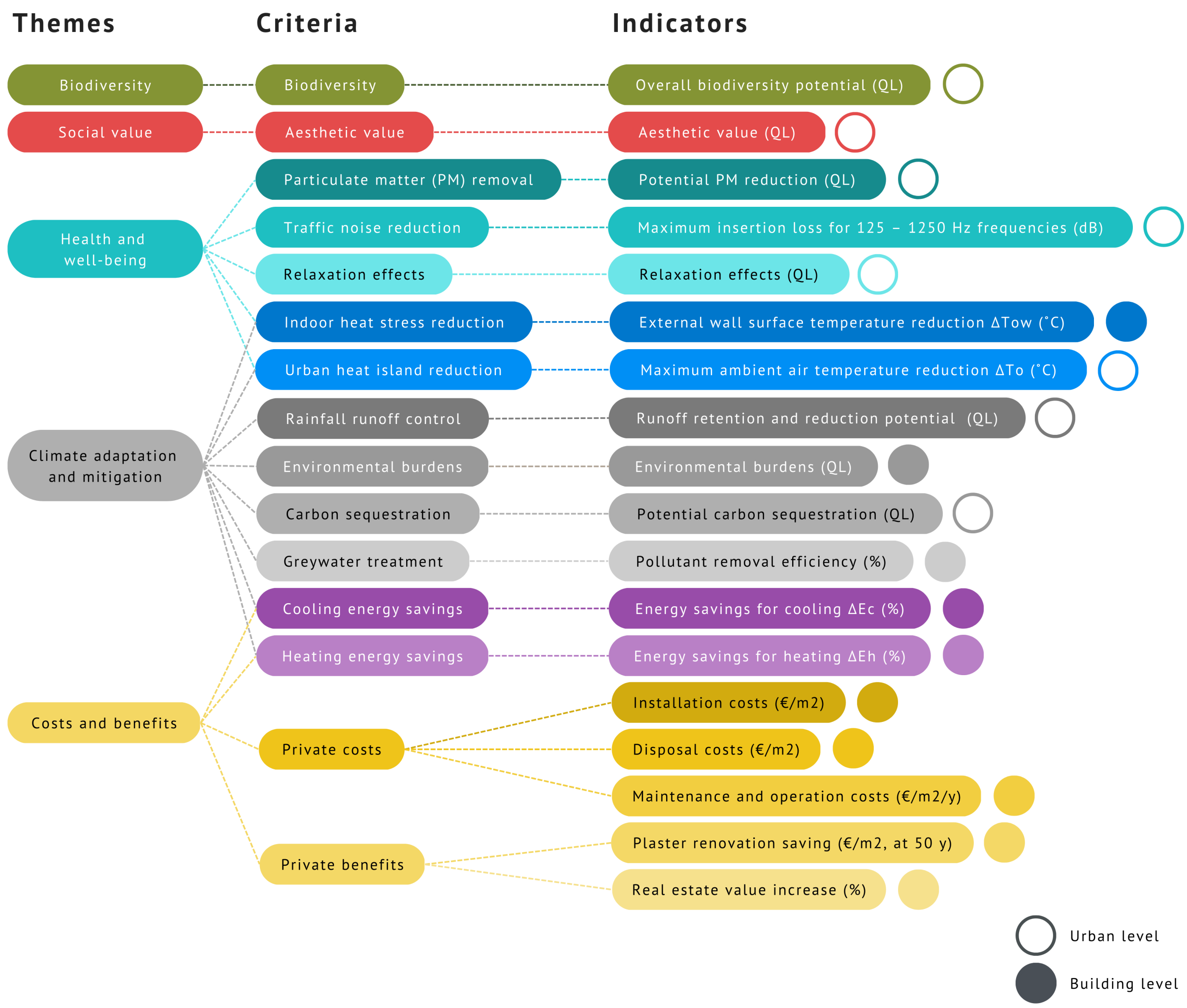


Figure 5.30: Value tree with themes, criteria and indicators (own work)

In developing an MCDM approach, it is necessary to assess the provisional set of criteria against a range of qualities [50]. These qualities are:

- **Measurable.** The criteria define project objectives in more detail.
- **Operational**. The criteria should be a sound basis for evaluation.
- **Understandable.** The criteria should be defined clearly enough to be assessed.

- **Complete.** The set of criteria needs to capture all key aspects of the objectives, but should not be larger than it needs to be.
- **Distinguishable**. MCDM assumes mutual independence of preferences on different criteria (to use the sum of weighted averages to combine preference scores across criteria). Therefore, the performances on different criteria should not overlap, to avoid double counting.

The quality of the set of criteria in the MCDM framework and tool was reviewed by performing a case study (chapter 8) and expert interviews. All three interviewees (A, B and C) confirmed the criteria to be understandable and complete. The use of the criteria in the framework validated that the criteria are measurable (performance expressed in indicators with a unit measure) and operational. The systematic literature study resulted in delimited criteria and indicators for the different impacts of VGS (e.g. the distinction between cooling and heating energy savings), which improves the criteria to be distinguishable. However, the approach suggests that there are no dependencies between performances on different criteria at all. This might not always align with reality, because, for example, a high aesthetic value might correlate with - or even cause - a high real estate value increase. Yet this (in)dependence of criteria is considered sufficient to achieve reliable scoring, but it needs attention in future research.

5.15.2 Themes

To structure the criteria, make them more intuitively understandable and to reflect different aspects of sustainability, the criteria are grouped in 5 themes. Different perspectives on sustainability inspired the structuring of the themes.

Sustainable development as defined in the 3-P notion by Elkington [235] refers to ‘people’ (social aspects), ‘planet’ (environmental aspects) and ‘profit’ (economic growth). This triple perspective on sustainability is also reflected in the Green Design and Building concept for civil engineering projects by Jonkers [171], which takes durability, functionality and sustainability into account. First, construction design should be tailored to the required service lifetime of the construction. Second, the application of renewable materials adds to a sustainable practice. Third, implementation of ecosystem functionality in the construction can deliver added value to the environment, resulting in a net positive influence of the project.

Other VGS or sustainability frameworks [46] identified several sustainability themes to classify monetary VGS impacts or sustainable building strategies, respectively. Some include climate change and adaptation, resources and circularity, and biodiversity and natural systems. Interviewee B also stressed the wide definition of sustainable construction, including social and well-being aspects. All combined, this led to the five themes in figure 5.30, which also indicates whether a criterion has the most impact on building or urban level. The five themes can also be seen as main (project) objectives, with multiple corresponding criteria, and can clarify the purpose of applying VGS.

5.15.3 Conclusion

In answer to RQ2 and RQ3, this research adopts a holistic set of evaluation criteria that integrates the main benefits and burdens associated with VGS. The five themes 'biodiversity', 'social value', 'health & well-being', 'climate adaptation and mitigation' and 'costs and benefits' provide a structure for the effects of VGS at building and urban scale.

From an extensive literature study, 18 evaluation criteria are identified that either answer building and urban sustainability challenges, such as heat, air and noise pollution, or create value, such as economic benefits. As such, the study proposes that the choice of VGS should be based on a wide range of criteria that reflect the full scope of sustainable construction.

For every criterion, an extensive review and analysis of past research inform the (potential) performances per system type adopted in this study. The role and integration of these performances is elaborated in chapter 6.

5.16 Synthesis and conclusion: Environmental input and design recommendations

This section describes how the parameters found in the literature study can be integrated in the MCDM approach.

5.16.1 Environmental parameters

Table 5.42 shows how environmental parameters affect VGS performance on criteria. In the MCDM approach, environmental parameters are used as input for project-specific scoring (see chapter 6).

Table 5.42: Overview of the influence of environmental parameters on criteria (+ = small effect, ++ = intermediate effect, +++ = large effect, - - = negative effect)

		Criteria								
		BD	**PM**	**TN**	**HS**	**UHI**	**RC**	**CE**	**HE**	**PB-VI**
Environmental parameters	Climate type				+++	++	+	+++	+++	
	Temperatures				++	++		++	++	
	Solar radiation				++	++		++	(+)	
	Wind speed		- -		+	+		+	(+)	
	Street aspect ratio (H/W)		+++			+++				
	District vegetation coverage	(+)	+++	(++)		+++				
	Pollution level		+							
	Urban geometry			+						
	Degree of urbanity									+++

Table 5.43: Legend of abbreviations for criteria

Abbreviation	**Criterion**
BD	Biodiversity
AV	Aesthetic value
PM	Particulate matter removal
TN	Traffic noise reduction
RE	Relaxation effects
HS	Indoor heat stress reduction
UHI	Urban heat islands reduction
RC	Rainfall runoff control
EB	Environmental burdens
CS	Carbon sequestration
GW	Greywater treatment
CE	Cooling energy savings
HE	Heating energy savings
PC-I	Private costs - Installation costs
PC-MO	Private costs - Maintenance and operation costs
PC-DC	Private costs - Disposal costs
PB-PR	Private benefits - Plaster renovation saving
PB-VI	Private benefits - Real estate value increase

5.16.2 Systems design recommendations

Table 5.44 shows how systems design parameters affect VGS performance on criteria. In general, the systems design parameters with a large effect on performance are orientation, building coverage, vegetation density, plant species, substrate and supporting structure. Some parameters complement each other, such as increased vegetation density (LAI) which enhances thermal benefits, PM air purification, traffic noise reduction biodiversity and rainfall runoff control. Other parameters can conflict. For example, a large area of VGS is more costly, but provides more benefits, e.g. in enhancing biodiversity. Increasing the moisture content of the substrate helps traffic noise reduction, but limits the rainfall retention capacity.

On the basis of the literature findings about systems design parameters, specific design recommendations per criterion are formulated (appendix 11.8), structured by system components from coarse to fine (e.g. first orientation, then plant species and substrate) and the effect (large, intermediate, small). In that way, the recommendations can be applied in a sequential way. Depending on the ranking (relevance and priority, see chapter 7), users of the framework/tool can put more emphasis on certain design recommendations. In that way, the MCDM framework allows designers to make design choices that fulfill the potential performance.

Table 5.44: Overview of the influence of systems design parameters on criteria (+ = small effect, ++ = intermediate effect, +++ = large effect, - - = negative effect, brackets = assumed)

		Criteria																	
		BD	**AV**	**PM**	**TN**	**RE**	**HS**	**UHI**	**RC**	**EB**	**CS**	**GW**	**CE**	**HE**	**PC-I**	**PC-MO**	**PC-DC**	**PB-PR**	**PB-VI**
System design parameters	Orientation						+++	(+)					+++	+					
	Dimensions																		
	Building vegetation coverage (%)	+++	++	+++	+++		++	+++		(- -)	(++)		++	(++)	(- -)	(- -)	(- -)		(++)
	Height threshold	+						+											
	Vegetation density (LAI)	++		++	+++		+++	+++	++		(++)		+++	(+++)					
	Random arrangement of tall/short plants			+															
	Plant species	+++	+++	++	+	+++	+	(+)		++	+++	++	+	++		++			
	Substrate																		
	Moisture content				+++		+	+	- -				+						
	Depth	+			+		+		+++		(++)	+++	+	(+)					
	Density / porosity				++														
	Material									++		+++							
	Supporting structure									+++					+++				
	Air gap width						+						+	(+)					
	Reflective facade behind VGS				++														

5.16.3 Conclusion

Environmental conditions and systems design affect the performance of VGS on the evaluation criteria, which answers RQ4. The climate type, street morphology and vegetated facades in the district are key environmental parameters, specifically affecting thermal comfort, energy savings, urban heat islands mitigation and particulate matter removal. The systems design parameters with a large effect on performance are orientation, building coverage, vegetation density, plant species, substrate and supporting structure. A large VGS is more costly, but provides more benefits, e.g. in enhancing biodiversity. Increasing the moisture content of the substrate helps traffic noise reduction, but limits the rainfall retention capacity.

Chapter 6

Project-specific scoring

Based on the systematic literature research, performances on every criterion were assumed, in terms of a suitable indicator. To arrive at a project-specific total performance per system type, some MCDM steps that process scores need to be undertaken. This chapter discusses parametric scoring (section 6.1), standardization (section 6.2) and weighting (section 6.3) to arrive at one total value per system.

To visualize the data conversion and different variables, figure 6.1 (next page) shows a clarifying MCDM model. From left to right, it shows how a total score per system is derived. The green boxes refer to project-specific input. It serves as a visual guide to the steps elaborated in the following sections.

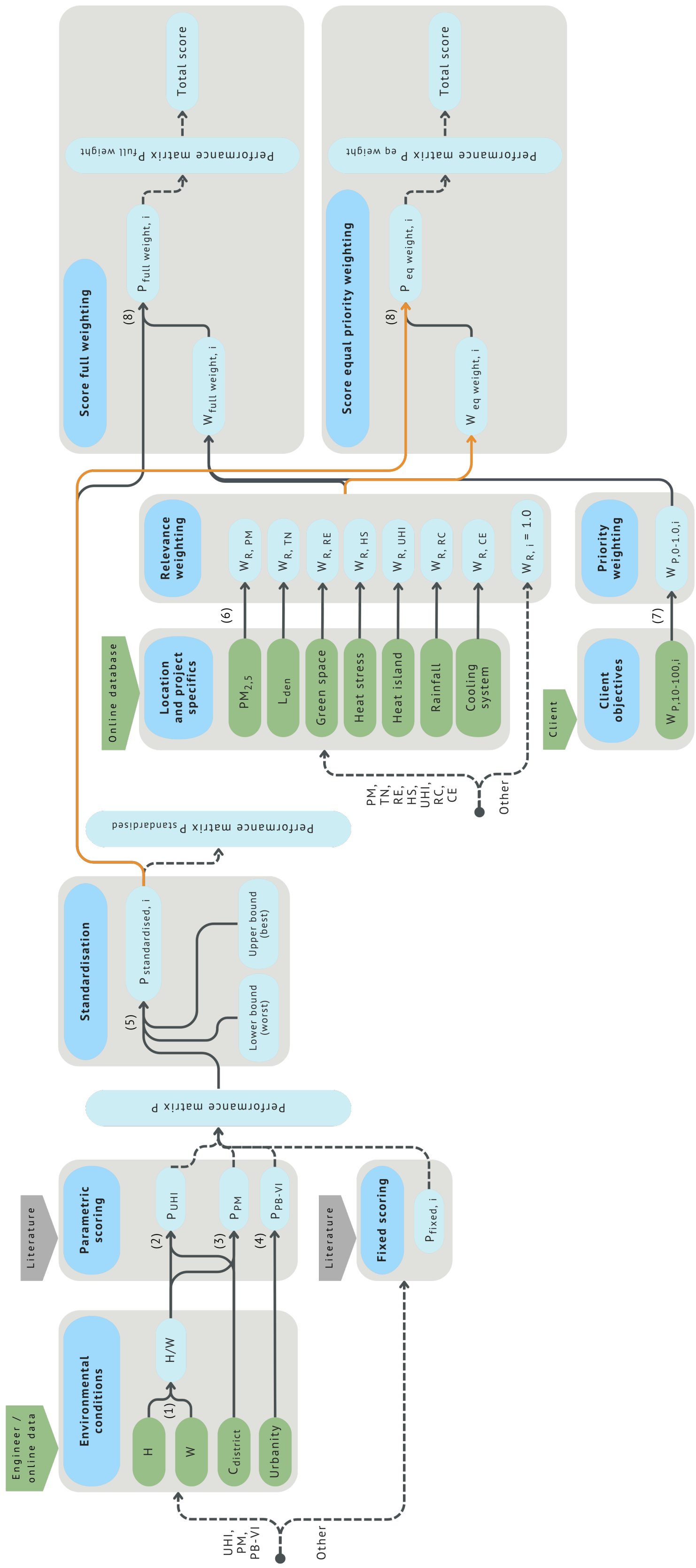


Figure 6.1: MCDM model (green = input, i = criterion)

6.1 Potential: Parametric scoring

Environmental parameters that affect the performance were identified and categorized according to their importance. Table 5.42 shows an overview of the effects of environmental parameters.

The MCDM framework intends to derive the best possible, or achievable, performance of each VGS type. Therefore, the influence of environmental parameters is explicitly taken into account through 'parametric scoring'. This determines the score on certain criteria within a performance range, based on context-specific input.

6.1.1 Climate type: Cfb

The climate type, and in specific temperature extremes (cold and hot conditions), solar radiation and wind speed, affect thermal behaviour of VGS (indoor thermal comfort and UHI mitigation). Still though, understanding of the effect of specific climate zones is lacking. Therefore, the scope of the MCDM tool is narrowed to projects in the Netherlands (Cfb climate). As such, performances specific for temperate (C) or Cfb climate are considered suitable. On top of that, for heat stress reduction, energy savings and UHI performances maximum values were obtained, which already reflect hot periods. All in all, the influence of climate is already reflected in the performances, and is therefore not made explicit in parametric scoring.

When climatic effects are disregarded, there are three environmental parameters left with a large effect on VGS performance (table 5.42): the street aspect ratio (H/W), district vegetation coverage and degree of urbanity. Whereas the first two affect UHI and PM mitigation, the latter affects real estate value increase. These dependencies are made explicit in parametric scoring, as explained here-after.

6.1.2 UHI mitigation - Street aspect ratio

To include the effect of the street aspect ratio in the MCDM tool, the average building height and width of the neighbourhood is needed, according to the following equation (see model in figure 6.1):

$$H/W = H/W \tag{1}$$

where H/W= Street aspect ratio (-),
and H = Average building height (m) in 500 m radius,
and W = Average street width (m) in 500 radius.

To characterise the correlation between UHI mitigation and aspect ratio, a performance function per system type has been derived. Linear regression of data points obtained by two studies (table 6.2; R^2 = 0.80) reveals that for an increase of 1.0 in aspect ratio, the maximum ΔT_o grows by 2.0 °C (figure 6.2).

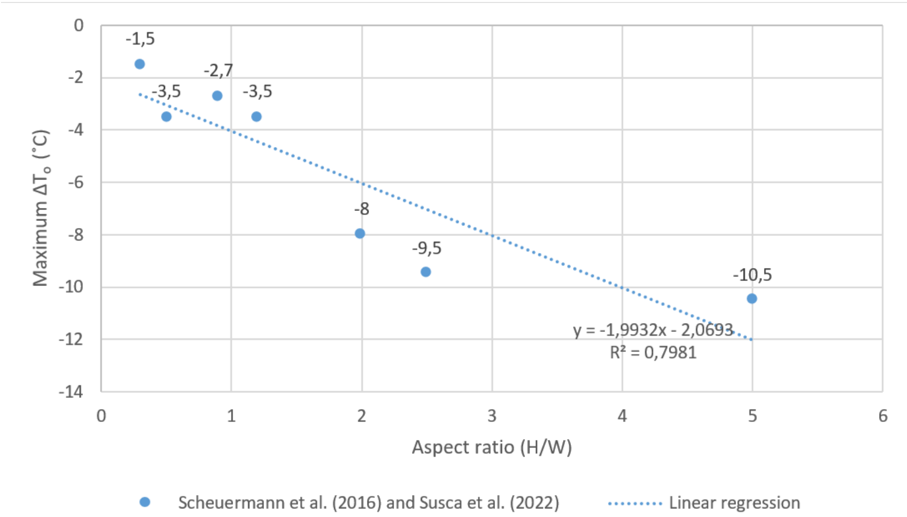


Figure 6.2: Linear relation between UHI mitigation (ΔT_o) and aspect ratio

When assuming that the performances per VGS type before were obtained for an aspect ratio of 0.5 (since the values lie around 3 °C), this results in the performance functions below (figure 6.3). The middle data point for all functions displays the previously obtained performance. Between an aspect ratio of 0 and 5, a type-specific linear performance function is established that cuts through this performance from literature, and that has the same slope as the linear regression function from the data points. For consistency and clarity, ΔT_o is considered a positive value in the framework. As such, the performance $P_{UHI-H/W}$ (°C) follows from system-specific performance functions (figure 6.3) with input H/W.

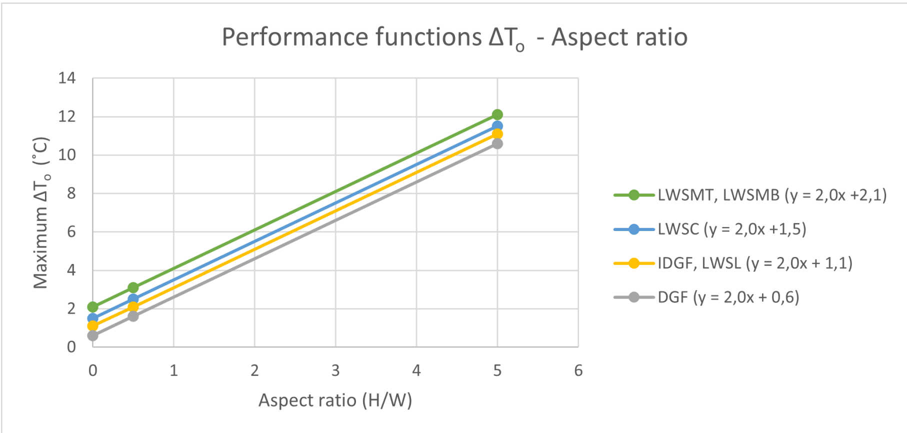


Figure 6.3: Performance functions UHI mitigation - aspect ratio (y = ΔT_o, x = H/W)

6.1.3 UHI mitigation - District vegetation coverage

In a similar way, performance functions for the influence of district vegetation coverage on UHI mitigation are derived . Linear regression by a previous study (table 5.15; $R^2 = 0.91$) reveals that for an increase from 100% to 200% (where 100% is assumed to be the building facade), results in a ΔT_{ow} reduction from -15 °C to -18 °C (+20%) [89]. Figure 5.16 shows means ΔT_o reductions of 1.0 °C, 3.0 °C and 7.7 °C for application of VGS on building, street canyon and block-to-city scale, respectively [89].

In most experimental studies, part of a street-facing facade was greened in a mostly grey environment. Hence, it is assumed that the maximum delta To found in the literature research are valid for 0% district coverage. As a maximum value for the best performing system (LWSMT, LWSMB), the 7.7 °C for block-scale application from Susca et al. [89] is considered. Giving all performance functions the same slope, and with the performances from literature as 'starting point' at 0%, this results in the following performance functions, shown in figure 6.4. Therefore, $P_{UHI-Cdistrict}$ (°C) follows from performance functions (figure 6.4), with as input $C_{district}$, which is the facade vegetation coverage (%) in a radius of 500 m.

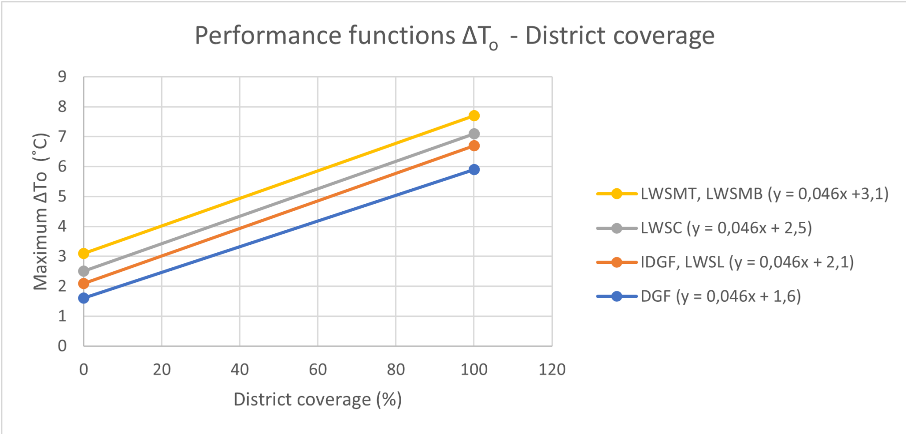


Figure 6.4: Performance functions UHI mitigation - district coverage

Since both the aspect ratio and district vegetation coverage affect UHI performance, the average of the two scores is taken as the total context-specific performance, according to:

$$P_{UHI} = (P_{UHI-H/W} + P_{UHI-Cdistrict})/2 \quad (2)$$

with $P_{UHI-H/W}$ and $P_{UHI-Cdistrict}$ following from performance functions as defined above.

6.1.4 PM removal - Street aspect ratio and district vegetation coverage

Removal efficiencies of particulate matter are retrieved from modelling studies [148] for different combinations of aspect ratio (H/W) and district vegetation coverage (%). Since performance ranges on a seven-point scale were determined for every VGS type (chapter 5), table 6.5 shows the performance within that range for different parameter combinations of H/W and coverage. As such, the performance P_{PM} (7-point scale) in the MCDM tool is determined with the performance table, with input H/W and $C_{district}$ (model equation 3 in figure 6.1).

Aspect ratio (H/W)	**District vegetation coverage (%)**	**Potential PM reduction** (seven-point scale)			
		DGF (2-4)	**IDGF, LWSL (2-5)**	**LWSC (4-6)**	**LWSMT, LWSMB (4-7)**
>1.5	>40	4	5	6	7
>1.5	20-40	4	4	6	6
>1.5	<20	3	3	5	5
≤1.5	>60	4	4	6	6
≤1.5	10-60	3	3	5	5
≤1.5	<10	2	2	4	4

Figure 6.5: Performance flow diagram for PM removal - Aspect ratio and district coverage

6.1.5 Real estate value increase - Degree of urbanity

The ranges of real estate value increases per system type were determined from the literature study (chapter 5). Given the higher increases for more peripheral areas within the city [221, 230], the values in table 6.6 are adopted in this study. The area address density in the Netherlands [236] can characterise the degree of urbanity, and is categorised in 5 descriptions, from 'non-urban' to 'very strongly urban'. Depending on this area address density [236], a relative increase is given. For non-urban areas, an intermediate value is assumed. This way, P_{PB-VI} (%) is calculated with the performance table, depending on the location-specific Urbanity category (MCDM model equation 4).

Performance PB-VI, from Urbanity

Criterion	Env. cond.	Options	DGF, IGFC, IFGT	LWSC, LWSMT, LWSMB	LWSL	Unit
PB-VI	Urbanity	Niet stedelijk	3,0	6,0	4,5	%
		Weinig stedelijk	5,0	10,0	7,5	%
		Matig stedelijk	5,0	10,0	7,5	%
		Sterk stedelijk	3,0	6,0	4,5	%
		Zeer sterk stedelijk	2,0	4,0	3,0	%

Figure 6.6: Performance table for PB-VI - Degree of urbanity

6.1.6 Excluded environmental parameters

The environmental parameters with a large effect are taken into account in the performances. However, some intermediate or small effects are not included. For PM reduction, wind and pollution level are excluded from the framework as environmental parameters affecting the potential performance (table 5.42). The above-roof wind speed is probably not known at early project starts, cannot be captured in one value and its effect is still too unclear. VGS are more effective in PM collection at locations near road traffic, but this parameter has not been studied numerically, so the PM pollution level is reflected in relevance weighting (next section).

Regarding noise reduction, the influence of urban geometry and district vegetation coverage was not explicitly researched in past studies. The character of the urban environment affecting aesthetic value potential is a descriptive parameter, and therefore not quantified in the scoring.

6.1.7 Performance matrix

Table 6.7 is the performance matrix, also referred to as 'consequence table' in MCDM. It shows the potential/achievable scoring per criterion, in terms of the unit measures of the indicators. Most criteria rely on 'fixed scoring', so their performances were derived in the literature study (chapter 5). Other scores depend on environmental input parameters through 'parametric scoring'. For those criteria, the matrix shows a range of scores (minimum-maximum).

Criterion	BD	AV	PM	TN	RE	HS	UHI	RC	EB	CS	GW	CE	HE	PC-I	PC-MO	PC-D	PB-PR	PB-VI
Indicator	Pot	Pot	Pot	IL	Pot	ΔTow	ΔTo	Pot	Pot	Pot	ΔP	ΔEc	ΔEh	Costs	Costs	Costs	Benefit	Benefit
Unit	QL	QL	QL	dB	QL	˚C	˚C	QL	QL	QL	%	%	%	€/m2	€/m2/y	€/m2	€/m2	%
DGF	2	3	2-4	0	6	9,4	1,4	1	7	2	0	20	8	44	3,7	38	284	2,0-5,0
IGFC	3	3	2-5	6,5	6	12,7	1,9	1	6	2	0	37	8	214	3,7	190	499	2,0-5,0
IGFT	3	3	2-5	6,5	6	12,7	1,9	1	5	2	0	37	8	214	3,7	190	499	2,0-5,0
LWSC	5	3	4-6	8,4	3	19,5	2,3	3	1	4	0	26	20	409	29,5	210	622	4,0-10,0
LWSMT	6	7	4-7	5,4	3	13,3	2,9	5	3	5	82,5	34	20	409	29,5	210	622	4,0-10,0
LWSMB	6	6	4-7	4,7	3	8,5	2,9	6	3	5	82,5	59	20	409	29,5	210	622	4,0-10,0
LWSL	5	4	2-5	3,1	5	8,4	1,9	3	4	3	0	34	15	302	13	190	527	3,0-7,5

Figure 6.7: Potential performance matrix, not standardised (dark-blue = fixed scoring; light-blue = parametric scoring, Pot. = potential on 7-point scale)

6.2 Standardization

Since the performances for different criteria in different units cannot be simply added, standardization of performances is necessary. A dimensionless scale of 0 to 100 is considered, where 0 represents the least preferred, and 100 represents the most preferred.

To standardise performances, local or global scaling can be applied. Table 6.8 shows the lower and upper bounds of standardised performances. For both, global scaling is applied. This means assigning a score of 0 to represent the worst level of performance that is likely encountered in a decision problem of the general type currently being addressed, and a score of 100 to represent the best level [50]. In this study, this general decision problem is choosing a building facade design measure.

For the 'worst' score, i.e. lower bound, this means assigning a score of 0 for most criteria. For private costs, the maximum costs in the ranges established from the literature study are considered representative of the most expensive facade measure.

For determining the upper bound, a score of 100 is assigned to the 'best' scoring that is assumed possible for a general facade measure. For private costs, no spending (0) are considered the best achievable score. Table 6.8 provides an explanation of the choice of 'worst' and 'best' score bounds.

Figure 6.8: Value function per criterion for standardisation (P = P_i (unit measure))

Criterion	Indicator	Unit	Lower bound (worst score)	Upper bound (best score)	Value function $P_{standardised}$	Explanation
BD	Potential	QL	0	7	(P/7)*100	7 = maximum on seven-point scale
AV	Potential	QL	0	7	(P/7)*100	7 = maximum on seven-point scale
PM	Potential	QL	0	7	(P/7)*100	7 = maximum on seven-point scale
TN	IL	dB	0	15	(P/15)*100	15 dB = reduction by tree belts and ground plantings (Scheuermann et al., 2016)
RE	Potential	QL	0	7	(P/7)*100	7 = maximum on seven-point scale
HS	ΔTow	˚C	0	23	(P/23)*100	23 ˚C = max. reduction in temperature climate (Bianco, 2017)
UHI	ΔTo	˚C	0,0	10	(P/10)*100	10 ˚C = max. reduction in temperature climate (Scheuermann et al., 2016)
RC	Potential	QL	0	7	(P/7)*100	7 = maximum on seven-point scale
EB	Potential	QL	0	7	(P/7)*100	7 = maximum on seven-point scale
CS	Potential	QL	0	7	(P/7)*100	7 = maximum on seven-point scale
GW	ΔP	%	0	100	P	100% = full removal of pollutants
CE	ΔEc	%	0	97	(P/97)*100	97% = max. saving in temperature climate (Djedjig, 2017)
HE	ΔEh	%	0	50	(P/50)*100	50% = max. saving in temperature climate (Cameron, 2015)
PC-I	Costs	€/m2	594	0	((594-P)/594)*100	594 €/m2 = upper end of cost range most expensive system type (Rosasco, 2018)
PC-MO	Costs	€/m2/y	35,5	0	((35,5-P)/35,5)*100	35,5 €/m2/y = upper end of cost range most expensive system type (Rosasco, 2018)
PC-D	Costs	€/m2	240	0	((240-P)/240)*100	240 €/m2 = upper end of cost range most expensive system type (Rosasco, 2018)
PB-PR	Benefit	€/m2	0	750	(P/750)*100	750 €/m2 = assumed maximum savings from façade protection
PB-VI	Benefit	%	0	15	(P/15)*100	15 % = max. increase in literature (Peck, 1999)

In between upper and lower bound, a linear relation is assumed, as is common practice in MCDM approaches ([50]). This is visualised in table 6.9, which shows a value function between performance (7-point scale) and standardised performance (0-100). Table 6.8 presents all value functions. As such, the standardised performance $P_{standardised,i}$ (-) per criterion (i) follows from value functions with input P_i (unit measure) (table 6.8) (MCDM model equation 5).

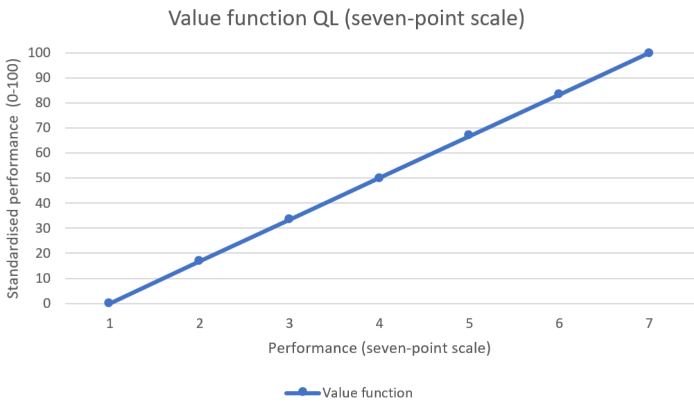


Figure 6.9: Value function for criteria expressed on a 7-point scale

6.3 Weighting

Weighting concerns assigning weights to each of the criteria to reflect their relative importance to the decision [49]. This research proposes a combined weighting method of relevance and priority weighting. On the one hand, relevance weighting accounts for the presence of issues at the project location. On the other hand, priority weighting reflects the project objectives. Whereas relevance weighting is objectively based on location-specific parameters (e.g. noise pollution level in dB), priority weighting is based on a subjective judgement by the design team. The multiplication of the two provides the total weight, which makes the total combined importance of a criterion balanced between objective and subjective judgements [237].

6.3.1 Relevance weighting

Depending on the location, mitigating issues by VGS can be more or less important. For example, when noise pollution levels are above a noise pollution indicator, it affects the well-being of citizens. In that case, traffic noise reduction is more relevant than when noise levels are quite low.

To take the relevance of issues into account, a relevance weight is introduced. This assumes that when an issue is less relevant, the contribution of the criterion performance to the total score should be lower. Still though, it is applied in weighting to not alter the potential performance (e.g. a 5 dB insertion loss).

The location-specific circumstances (and presence of a cooling system) that can serve as input parameters for relevance weighting are presented in figure 6.11. The relevance weighting variables describe to what extend a location is prone to the issue the VGS can mitigate. As such, the relevance weight $W_{R,PM}$ (0-1.0) follows from the relevance table in figure 6.11 (MCDM model eq. 6). For consistent weighting, a scale of relevance is adopted with percentiles ranging from 'not relevant' to 'very relevant' (figure 6.10).

Relevance	Not relevant	Little relevant	Somewhat relevant	Relevant	Quite relevant	Very relevant
w_R	0	0-0.25	0.25-0.50	0.50-0.75	0.75-1.00	1.00

Figure 6.10: Relevance weighting scale

For criteria for which clear indicators of the issue are available, a relevance of 0 is applied to irrelevant situations. For example, when the particulate matter level in the air is below the WHO recommended value, particulate matter removal is considered not relevant. The same goes for traffic noise reduction, when the noise in the environment is below the EEA indicator for noise pollution, and for UHI mitigation, when it is very low (below 0,5 °C).

Smaller differences in relevance have been applied to weighting variables that have a more uncertain relation to the issue at hand. For example, this study assumes that relaxation effects are more relevant when there is little green around, but relevance weight varies between 0,40 and 1,00, considering that relaxation effects are always somewhat relevant.

Besides location-specific weighting variables, a distinction is made for cooling energy savings. Depending on whether an active (energy-consuming) cooling system is present, the criterion 'cooling energy savings' is given none or full relevance.

Criterion	Weighting variable	Description	Options	Unit	Relevance	Weight w_R	Explanation
PM	PM2,5	Particulate matter (PM2,5) in air (2020)	< 5	µg/m3	Not relevant	0,00	Lower than WHO recommended value (RIVM, 2020)
			≥ 5 and < 10	µg/m3	Somewhat relevant	0,33	Between recommended value and WHO Interim Targets 3/4
			≥ 10 en < 25	µg/m3	Relevant	0,67	Between WHO Interim Targets 3/4 and WHO Interim Target 2
			≥ 25	µg/m3	Very relevant	1,00	Above WHO Interim Target 2
TN	Noise	Noise in the environment (L_{den})	< 46	dB	Not relevant	0,00	Lower than EEA indicator for noise pollution (55 dB) (RIVM, 2020)
			≥ 46 and < 51	dB	Not relevant	0,00	Lower than EEA indicator for noise pollution (55 dB)
			≥ 51 and < 56	dB	Not relevant	0,00	Lower than EEA indicator for noise pollution (55 dB)
			≥ 56 and < 61	dB	Quite relevant	0,80	Higher than EEA indicator for noise pollution (55 dB)
			≥ 61	dB	Very relevant	1,00	Possibly higher than EEA indicator for high noise pollution (65 dB)
RE	Green space	Percentage area of green space in 500 m radius	≥ 60	%	Somewhat relevant	0,40	Very good access to urban green space (RIVM, 2020)
			≥ 50 and < 60	%	Relevant	0,55	Good access to urban green space
			≥ 40 and < 50	%	Relevant	0,70	Fair access to urban green space
			≥ 30 and < 40	%	Quite relevant	0,85	Poor access to urban green space
			< 30	%	Very relevant	1,00	Bad access to urban green space
HS	Heat stress	Severely lonely elderly over 75 (2020)	< 10	# / km2	Relevant	0,55	Severely lonely elderly over 75 are the most vulnerable population group for heat stress, due to their low thirst stimulus and no other people alerting them to drink enough and cool down (Gezondheidsmonitor / RIVM, 2020).
			10-30	# / km2	Relevant	0,70	
			30-100	# / km2	Quite relevant	0,85	
			> 100	# / km2	Very relevant	1,00	
UHI	Heat island	Average ambient air temperature difference, relative to rural area	< 0,5	˚C	Not relevant	0,00	Very good (RIVM, 2020)
			≥ 0,5 and < 1	˚C	Somewhat relevant	0,25	Good
			≥ 1 and < 1,5	˚C	Relevant	0,50	Fair
			≥ 1,5 and < 2	˚C	Quite relevant	0,75	Poor
			≥ 2	˚C	Very relevant	1,00	Bad
RC	Rainfall	Yearly precipitation (2016)	< 800	mm	Quite relevant	0,80	Below average (RIVM, 2016)
			800-900	mm	Quite relevant	0,90	Average
			>900	mm	Very relevant	1,00	Above average
CE	Cooling s.	Presence of active cooling system	No	-	Not relevant	0,00	
			Yes	-	Very relevant	1,00	

Figure 6.11: Relevance weighting

6.3.2 Priority weighting

To account for project-specific objectives, such as an emphasis on sustainability aspects, costs or biodiversity enhancement, priority weighting is incorporated. The user of the tool (architect/engineer) can give relative priorities to criteria, in consultation with the client. For this, the ratio weighting method is adopted [237]. This requires the input from decision-makers (client) to rank the priority of the criteria. The least important criterion (or multiple unimportant criteria) is assigned the value of 10. Then, the other criteria are assigned multiples of 10, with a maximum of 100. This indicates their relative priority. The highest values are assigned to the criteria most important to the client. Several criteria can have the same value, indicating that they have the same priority.

The resulting weights are normalised to sum to one. This is done to make sure the 'total priority' to be divided is the same for any project, since the priority is relative. Oppositely, the relevance weights are not normalised, since the relevance is absolute. Some locations can have a larger 'total relevance', e.g. when they suffer from strong UHI effects, much noise pollution, etc.

The priority weight per criterion (i) is normalized according to the following MCDM model equation:

$$W_{P,0-1.0,i} = W_{P,10-100,i} / \sum W_{P,10-100,i} \tag{7}$$

with $W_{P,0-1.0,i}$ = Priority weight per criterion (0-1.0),
and $W_{P,0-100,i}$ = Priority weight per criterion (10-100).

Another scenario of priority weighting is applying 'mean weight' [237], also referred to as equal priority weighting. In that instance, every criterion is assigned the same normalised priority weight. This is only adopted in this study for:

- Showing the effect of (client-)assigned priorities on the total performance per system type.
- Displaying separate performances per criterion, because that represents the potential performance which is weighted 'only' for relevance.

6.3.3 Total weight

The total weight is the multiplication of the relevance and priority weights. In that way, the performance on a fully irrelevant criterion is ruled out, while low-priority criteria cannot be completely ruled out (minimum weight of 10). This improves the degree of objectivity of the total weight factor.

For the standard 'full weighting', the total weight is calculated as follows:

$$W_{fullweight,i} = W_R * W_{P,0-1.0,i} \tag{8a}$$

with W_R = Relevance weight per criterion (0-1.0)
and $W_{P,0-1.0,i}$ = Priority weight per criterion (0-1.0).

In the scenario of equal priority weighting, all priority weights are equal (1/number of criteria = 1/18):

$$W_{eqweight,i} = W_R * 1/18 \tag{8a - equal priority}$$

6.4 Overall value

To arrive at one weighted score per VGS, an overall value can be aggregated by performing a weighted linear combination [49]. Multiplying the standardised score with the total weight provides a performance per criterion:

$$P_{fullweight,i} = W_{fullweight,i} * P_{standardised,i} \tag{8b}$$

Next, the overall performance per system type is the sum of the weighted scores on all the criteria:

$$P_{total,fullweight} = \sum P_{fullweight,i} \tag{8c}$$

The overall performance scores (dimensionless) give an indication of how much more suitable one alternative is over another. The overall performance also results in a complete ordering of alternatives. This can serve as a ranking of alternatives, from the most to least suitable system.

For equal priority weighting, the total performance is calculated as follows:

$$P_{eqweight,i} = W_{eqweight,i} * P_{standardised,i} \quad \text{(8b - equal priority)}$$

$$P_{total,eqweight} = \sum P_{eqweight,i} \quad \text{(8c - equal priority)}$$

6.5 Conclusion: project-specificity in an MCDM approach

No building project is the same. Project-specific characteristics that affect the early selection and design of VGS are environmental conditions on the location of the project as well as the project objectives. Therefore, in answer to RQ5, this study suggests three complementary ways to integrate project-specificity in a multi-criteria approach:

- First, parametric scoring can acknowledge the effect of environmental conditions (e.g. climate or street morphology) on the potential performance. For example, a greater particulate matter removal is achievable in more narrow streets. This results in the achievable/potential scoring of VGS systems per criterion.
- Second, the relevance of the issues at hand can be reflected in relevance weighting of criteria. For example, traffic noise reduction is more relevant when street noise levels exceed noise pollution indicators.
- Third, client wishes and objectives can be expressed in priority weighting, to put emphasis on certain criteria.

The overall performance per system leads to a ranking of most suitable VGS in the specific project.

Part III

Framework

Chapter 7

Framework and tool

This chapter presents a conceptual framework for the selection and design of VGS, according to a multi-criteria decision-making approach. It is followed by a ready-to-use Excel tool that implements the framework in a numerical way.

7.1 Conceptual framework

Figure 7.1 shows the conceptual steps of the multi-criteria framework.

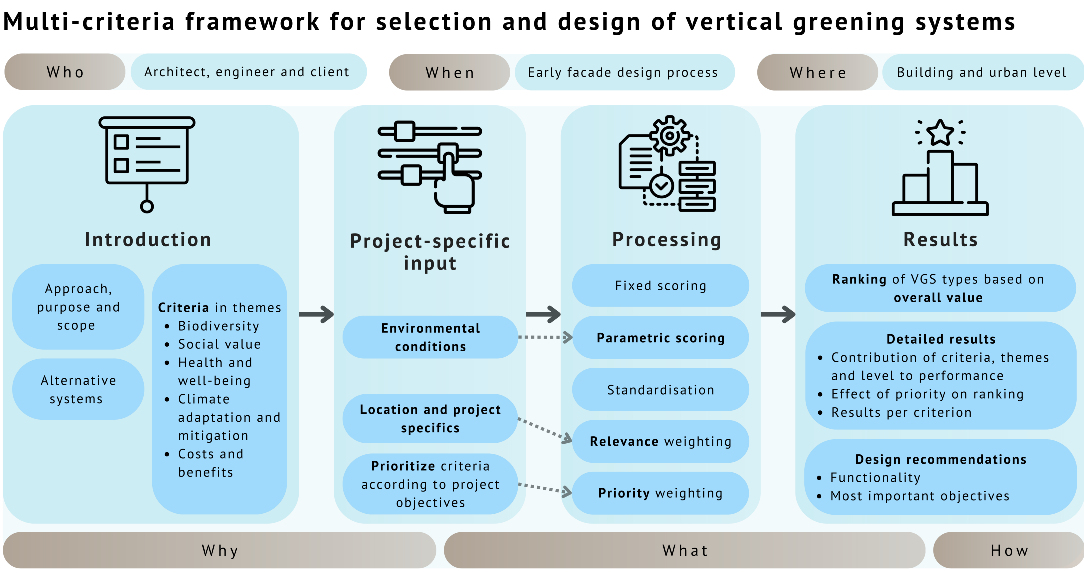


Figure 7.1: Multi-criteria framework

It exists of four phases and kicks off with introducing the purpose and scope of the framework. In short, this is to support architects, engineers and clients of building projects to choose and design the most suitable type of VGS in early project phases. Next, the alternative systems and the assessment criteria, grouped in themes, are established. The second phase is about collecting project-specific data that characterises the environmental conditions, location and project objectives. In consultation with the client, criteria are prioritised. The project-specific input is processed into an overall value per VGS alternative. This is the basis for the key result: a ranking of most suitable VGS types. This informs the users what VGS type is expected to perform best. More detailed results show how much specific criteria and themes contribute to this performance. Depending on the relevance and priority of criteria, design recommendations per criterion are provided, which can be useful for schematic design development after use of the framework.

7.2 Ready-to-use tool

Appendix 11.8 shows the Excel interface of the ready-to-use tool that implements the conceptual framework. The sheets in the Excel tool correspond to the phases of the framework: Introduction, Project-specific input, Processing, Results, Result per criterion, Design recommendations. The framework and tool are developed on the basis of the extensive literature study, complemented with insights from expert interviews. More specifically, chapter 3 (Decision context), 4 (Design alternatives), 5 (Criteria, parameters and performances) and 6 (Project-specific scoring) provide the elements of the framework and tool. The tool is meant to be self-explanatory for the intended users: architects/engineers, in consultation with the client. The next chapter explores the use and validation of the framework and tool.

7.3 Conclusion: guide to selection and design

The proposed multi-criteria framework can be regarded as one of the first guidelines that establishes a universal and integrated selection and design process for vertical greening systems. The framework captures benefits and burdens associated with VGS, delivers a project-specific scoring and ranking of VGS types and ensures a design that fulfills this potential. Moreover, the framework allows to select and design a VGS that is fit-for-purpose, because relevance (based on location) and priority (provided by client) of criteria is taken into account. This answers RQ6.

The ready-to-use Excel tool is a hands-on numerical application of the framework. It shows in what way the framework could be applied in building projects.

Chapter 8

Validation

This chapter reflects on the results of the framework/tool and analyzes to what extend these can be verified or validated. First, a sensitivity analysis discusses the effect of changes in input and weighting (section 8.1). Second, a case study on the Venlo city hall project is carried out (section 8.2). Third, the tool is tested on three more example projects (section 8.3).

8.1 Sensitivity analysis

How robust is the outcome of the tool to uncertainties in environmental input and priority weights? A sensitivity analysis answers this question [51]. A 'neutral' scenario is the starting point of the analysis [49] and reflects average Dutch circumstances. The urban morphology of Utrecht, a typical Dutch city, gives an aspect ratio of H/W = 24/20 = 1.2, comparable to Berlin [5]. For relevance weighting, average values of environmental input parameters are assumed (appendix 11.8). Priority weights are set at equal priority weighting (all 10).

8.1.1 Sensitivity for environmental input

When a single environmental input parameter changes, the highest-ranking system stays the same (LWSMB for this neutral scenario). This suggests that the alternative ranking is relatively stable to changes in the values describing the environment. However, the highest-ranking system could shift when multiple environmental parameters change.

On the contrary, the overall numerical performance is indeed affected by environmental changes. The sensitivity of overall performance scores is portrayed in figures 8.1 and 8.2, and follows the dependencies established in project-specific scoring and relevance weighting within the MCDM model (6.1).

The sensitivity to H, W, $C_{district}$ and urbanity follows the project-specific scoring:

- Whereas a larger average building height (H) increases overall performance, a larger average street width (W) results in a decrease (figure 8.1). This corresponds to the project-specific scoring for UHI mitigation and PM removal (chapter 6), which depend on the aspect ratio H/W [5, 89, 148].
- District facade vegetation coverage ($C_{district}$) hardly affects the overall performance (figure 8.1). This limited effect can be explained by the slight change in coverage (between 0.5 and 3.5%) compared to the maximum coverage of 100%. The positive relationship between $C_{district}$ and overall performance can be follows the project-specific scoring established in chapter 6 [148].
- The overall performance increases in peripheral urban areas (figure 8.2). This corresponds to the dependence of real estate value increase on the degree of urbanity (chapter 6), based on literature findings [221].

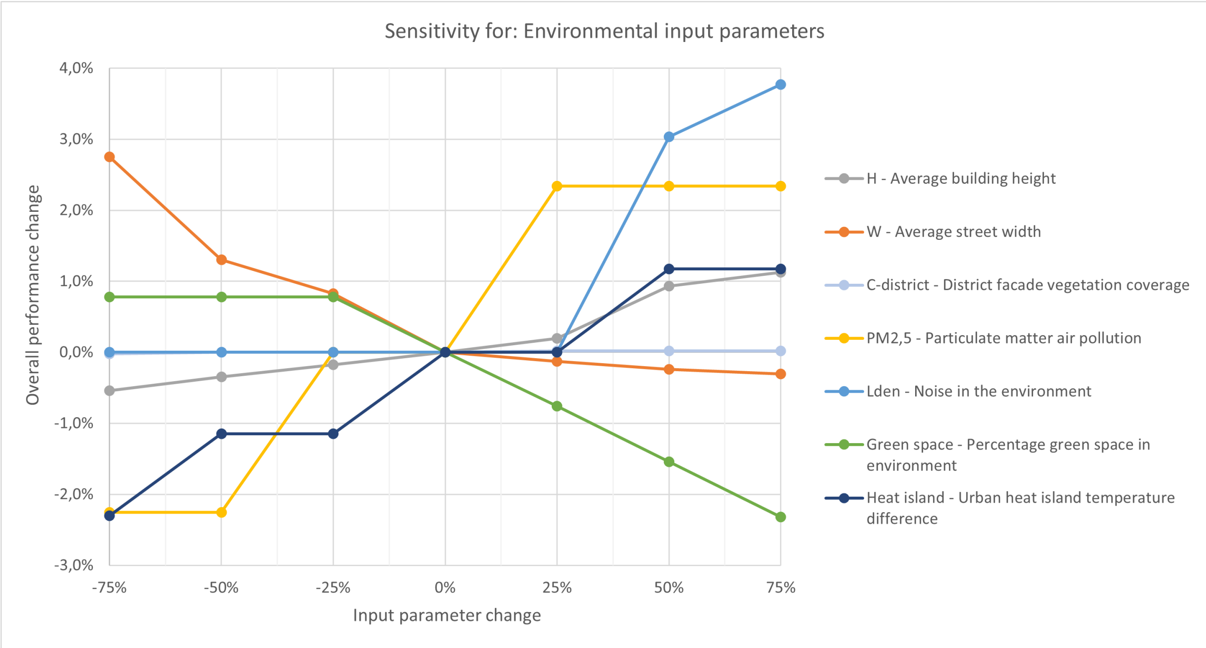


Figure 8.1: Sensitivity of maximum overall performance for environmental input parameters

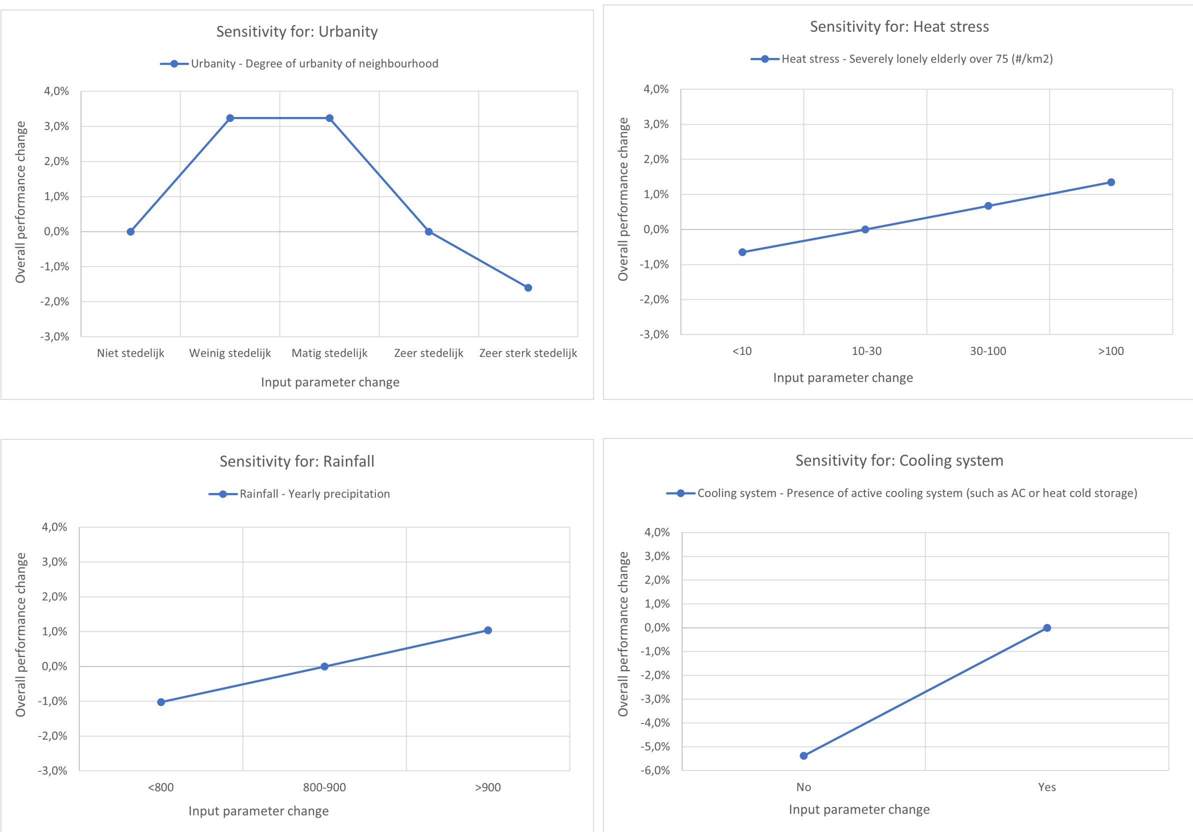


Figure 8.2: Sensitivity of maximum overall performance for urbanity, heat stress, rainfall and cooling system

The influence of $PM_{2,5}$, L_{den}, green space, heat island, heat stress, rainfall and cooling system on the overall performance is characterised by the 'relevance weighting' in the developed MCDM model:

- A higher concentration of particulate matter ($PM_{2,5}$) increases the relevance to remove PM, thus increasing the overall performance (figure 8.1).
- Noise in the environment (L_{den}) above nuisance levels (from +50%, i.e. +10 dB) makes traffic noise reduction relevant. This adds to the overall performance by up to 3.8% (figure 8.1).
- More green space in the environment of a building decreases the relevance of relaxation effects from VGS (figure 8.1).
- An amplified urban heat island effect enlarges the relevance of UHI mitigation, thus increasing the overall performance (figure 8.1).
- More occupants prone to heat stress increases the relevance of indoor heat stress reduction (figure 8.2).
- More rainfall makes rainfall runoff control more relevant (figure 8.2).
- The presence of a cooling system determines whether cooling energy savings are a relevant benefit (figure 8.2).

Overall, sensitivities for all environmental parameters align with the relationships set up within the MCDM model, based on literature findings. Although the project-specific scoring is founded on an extensive evidence base, the relevance weighting is more of an application of the philosophy (or assumption) that when a problem is present, its mitigation will automatically be more relevant. The stable highest-ranking system for changes in one environmental parameter fits this uncertainty, because a change in a single environmental condition is not able to shift the most suitable system.

Numerically, there is a positive effect of increases in most environmental parameters on overall performance. Some parameters (e.g. green space) negatively correlate with overall performance. The impact of changing one environmental parameter is limited to a 1-6% change in overall performance. The scoring categories (with a bandwidth) can explain the non-continuous, step-wise graphs in figures 8.1 and 8.2.

8.1.2 Sensitivity for priority weighting

The influence of priority weighting is considerable, since increasing the priority weight results in a different highest-ranking system for 7 of the 18 criteria (table 8.1). Priority weights can be changed without affecting the results up to a tipping point, where the most suitable system switches because of the more considerable contribution of the criterion to the overall scores. For aesthetic value and indoor heat stress, the most preferred system switches from LWSMB to LWSMT at a weight of 20. Costs prevail when given a weight of 40 or higher, resulting in DGF being the most suitable.

These tipping points coincide with a change in the slope of the curves in figure 8.3, which displays the effect of changing priority weights on the overall performance. A negative slope is exhibited when the 'best' system scores poorly on the prioritised criterion (in this case, e.g. noise reduction). After the tipping point, more emphasis increases the performance of the highest-ranking system. Figure 8.3 also shows varying sensitivities of the maximum overall performance for increased priority weights. This can be due to the relations assumed in the MCDM model or relevance differences in this specific neutral scenario. For example, prioritising a less relevant criterion (e.g. PM removal) results in lower maximum performance. Also, aesthetic value has a relevance of 1.0, which helps the large increase in maximum performance by up to 38%.

A different priority weight on certain criteria can change the most suitable system. This shows the influence of the client objectives on the outcome of the MCDM tool.

Table 8.1: Tipping points at which a higher criterion priority weight switches the most suitable system

Criterion	**Tipping point priority weight**	**Change in most suitable system**
AV - Aesthetic value	20	LWSMB >LWSMT
HS - Indoor heat stress	20	LWSMB >LWSMT
RE - Relaxation effects	60	LWSMB >DGF
EB - Environmental burdens	40	LWSMB >DGF
PC-I - Installation costs	40	LWSMB >DGF
PC-MO - Maintenance costs	40	LWSMB >DGF
PC-DC - Disposal costs	40	LWSMB >DGF

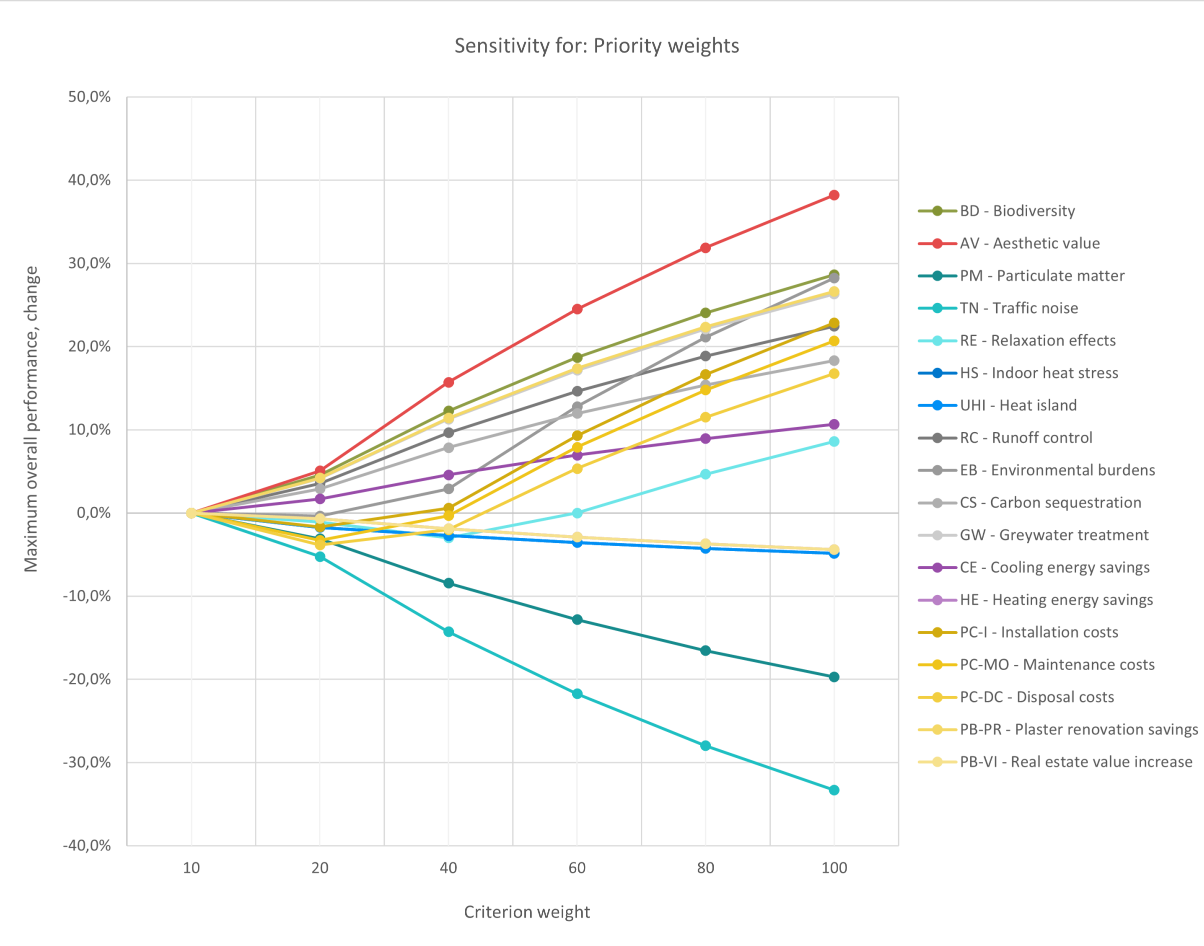


Figure 8.3: Sensitivity of maximum overall performance for priority weights

8.1.3 Conclusion: sensitivity analysis

Sensitivity analyses show the effect of changing input parameters on the results of the MCDM model. In this instance, they show that the numerical results (maximum performance) of the tool are particularly sensitive (up to 30%) to changes in priority weighting, and less so (up to 6%) to changes in environmental input. This can - at least partly - be explained by the larger changes in priority weighting (900% from weight 10 to 100) than in environmental input (75%). Whereas changing a single environmental parameter does not change the most suitable system, increasing one priority weight can switch the most suitable system. Although this suggests that client objectives have a larger influence on the results than environmental conditions, here too the larger bandwidth of priority weights might be the underlying reason.

It should be noted that the sensitivity analysis only changes one variable of the project-specific input, while in realistic cases more variables can change. The chosen neutral scenario also affects the results of the sensitivity analysis. Moreover, although the results align with the findings of the literature study, future research with expert judgement of the sensitivities would add to the accuracy of the framework/tool.

8.2 Case study

To validate the applicability of the framework and tool in building projects, a case study about a finished VGS project is conducted. This section analyses the project characteristics, allows the former project manager to test the tool (interview M), and compares the results with the actual design outcome. In addition, the added value and implications of using the tool are analyzed.

Figure 8.4: The city hall of Venlo, with a VGS on the north-east facade [74]

8.2.1 Context: city hall Venlo

Project

The new-built city hall of Venlo accommodates 650 municipal workers and the town's citizen's service centre. It is located on a busy junction on the outskirts of the city centre and is part of a large-scale redevelopment on the Meuse river banks [238]. The municipality Venlo drafted guiding principles in 2008, followed by the preliminary design (2010) and final design phases (2011). After 4 years of construction, the building was finished in 2016, with a total expenditure of 56 million euros [239].

The city hall design emphasizes both sustainable innovation and well-being. It follows sustainable 'cradle-to-cradle' principles, which focuses on the re-usability of building elements ([74]). Other priorities in the project are the minimal use of natural resources and providing an inspiring and healthy workplace ([239]).

An innovative design process was set up, with formulated cradle-to-cradle ambitions and early contractor and manufacturer (Mostert de Winter for VGS) involvement. A project manager (RHDHV) sat on a steering committee with the client (Municipality Venlo), and led the design team, which included the architect (Kraaijvanger Architects), building manager, installation advisor (RHDHV), construction advisor and cradle-to-cradle advisor [240].

The design relies on biophilic principles. Improving indoor and outdoor air quality, closing the water cycle, using renewable energy and applying reusable materials are the four principles of the preliminary design. Two solar chimneys naturally ventilate the building and a heat and cold storage system (thermal energy storage, i.e., TES) in combination with a heat pump provides heating and cooling. The greywater from the sinks and the cafeteria's kitchen as well as the rainwater from the roofs is purified naturally in a helophyte filter and then reused to either flush the toilets or to irrigate the green facades, or discharged to the Meuse [238]. Other design features are PV panels, demountable timber elements and an open office layout. Figure 8.5 visualizes the concept sketches.

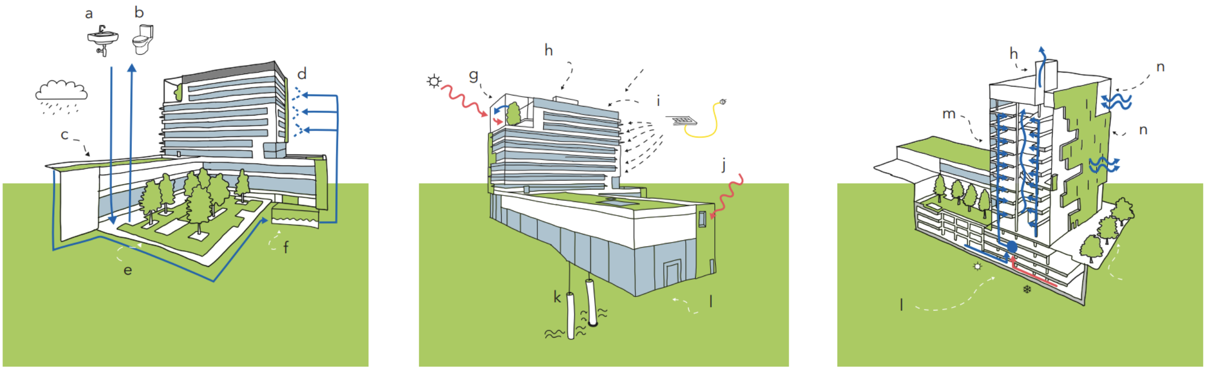
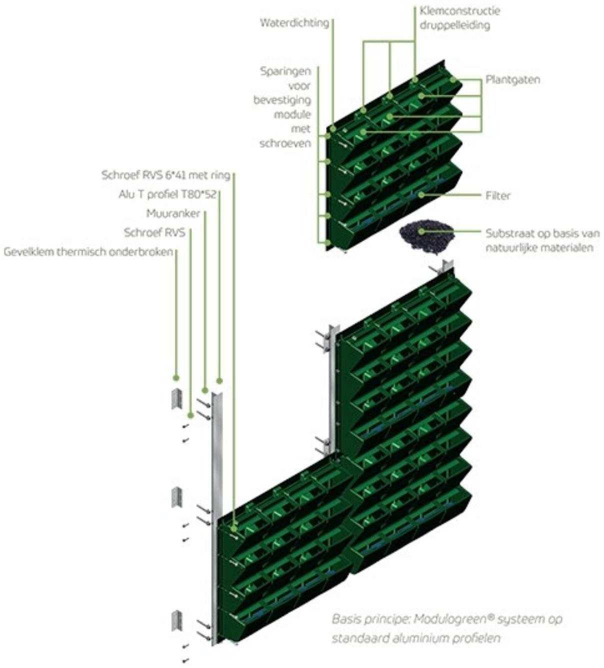


Figure 8.5: Concept sketches: Water circuit, energy and ventilation concepts (a = Wastewater from sinks; b = Grey water for toilet flushing; c = Wastewater from roofs; d = Grey water for facade irrigation; e = Helophyte filter, f = Grey water cistern; g = Greenhouse preheats the air; h = Solar chimney for exhaust ventilation; i = Brise-soleils with PV modules; j = Green facade insulates against heat stress; k = Groundwater wells; l = Air from car park as heat and cold source; m = Exhaust air rises through atrium; n = Greenhouse + green facade purify the air) [238]

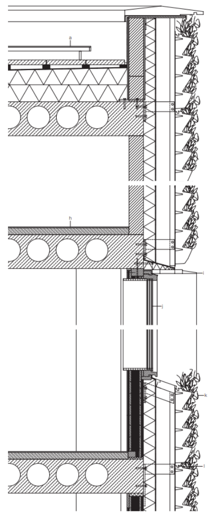
Vertical greening system

An exterior vertical greening system is applied on the northeast-facing facade (with minor extensions on the northwest and southeast facade). Plants grow in soil-filled plastic modules, classified as an LWSMT system (figure 8.7b). It covers over 2150 m2 and is pre-vegetated with 42.000 plants of more than 100 species [241]. In winter, air is blown out through the VGS, which purifies the outside air, while in summer it leaves through the solar chimney.

Figure 8.6: The LWSMT system [241]



(a) Standard system elements of LWSMT [242]



(b) Cross section of VGS facade (layers outside to inside: planting; soil in modular PVC planters; anodised square aluminium tube substructure; 200 mm rear ventilation separating membrane, open to diffusion; 120 mm flax fibre insulation; 170 mm cross-laminated timber, dowelled) [238]

Figure 8.7: System details

8.2.2 Application of tool

The tool is tested by an interview with the former project manager at RHDHV (referred to as Interview M; appendix 11.9), who fills in and uses the tool.

Project-specific input

The specific environmental conditions of Venlo (for parametric scoring and relevance weighting) can be found in appendix 11.10 . The presence of the seasonal energy storage system and heat pump indicate that there is an energy-consuming cooling system.

For priority weighting, input from the project manager was necessary. He was asked to simulate the VGS design priorities in early design phases as they had occurred. Table 8.2 presents the design considerations and the assigned priority weights. Since the building is close to a busy arterial road and railway, improving the outside air quality was the most important design criterion for the selection of a VGS (Interview M). Therefore, particulate matter removal (weight 100) and - to a lesser extent - carbon sequestration (weight 20) are assigned higher priority weights by the project manager. Also, greywater treatment was considered important (weight 40). Small priorities (weight 10) were given to private costs and benefits.

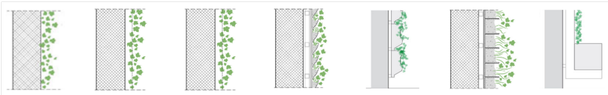
Other criteria were not explicitly taken into account at the start of the design process (interview M), but are still mentioned as a benefit in the preliminary design (PD). This shows the design team was aware of these benefits, and presumably believed these aspects are important to the design, so a weight of 20 was assigned to these criteria. They were considered 'nice to have', rather than the prioritised air purification as a 'need to have'. Benefits listed after the design was finished, such as noise insulation or biodiversity, are not considered in the priority weighting.

Table 8.2: Priority weights (PD = preliminary design; bold = assigned by project manager; N.A. = not prioritised or mentioned in PD)

Criterion	Design consideration in early design phases	Assigned priority weight
Biodiversity	'Place for animals and plants' (PD)	20
Aesthetic value	VGS has aesthetic benefit (PD)	20
Particulate matter removal	Improving outside air quality is most important principle (Int. M). 'Green facade purifies air' (PD) [238]	**100**
Traffic noise reduction	N.A.	10
Relaxation effects	N.A.	10
Indoor heat stress reduction	'Green facade insulates against heat stress' (PD) [238]	20
Rainfall runoff control	Rainwater from roof collected in reservoir and used for facade irrigation (PD)	20
Environmental burdens	Use of up-cycled or recyclable materials (PD)	20
Carbon sequestration	Improving outside air quality is most important principle (Int. M). Facade 'purifies' air and 'produces oxygen' (PD) [243]	**20**
Greywater treatment	Helophyte filter purifies greywater. Greywater partly used for facade irrigation. 'Reduction of wastewater to sewer' (PD)	**40**
Cooling energy savings	'Water in green facade provides cooling and reduces energy demand' (PD)	20
Heating energy savings	'Green facade isolates' (PD)	20
Private costs - Installation costs	N.A.	10
Private costs - Maintenance and operation costs	N.A.	10
Private costs - Disposal costs	N.A.	10
Private benefits - Plaster renovation saving	N.A.	10
Private benefits - Real estate value increase	N.A.	10

Results

The overall performance results in an LWSMT being the most suitable system for the city hall of Venlo (figure 8.8). This aligns with the actual chosen system. At first sight, therefore, the case study validates the resulting ranking of the tool.



VGS type	DGF	IGFC	IGFT	LWSC	LWSMT	LWSMB	LWSL
Overall performance	28,72	29,89	29,11	31,67	46,17	46,02	30,10
Ranking	7	5	6	3	1	2	4

Figure 8.8: Overall performance and ranking of VGS types, given project-specificity and priorities (green = most suitable, red = least suitable)

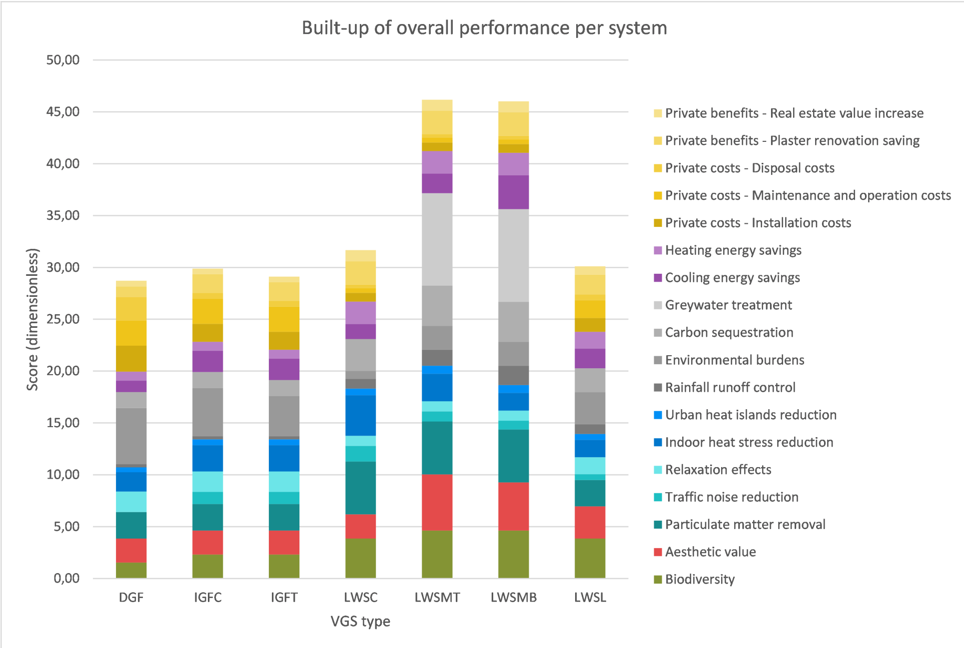


Figure 8.9: Built-up of overall performance for city hall Venlo

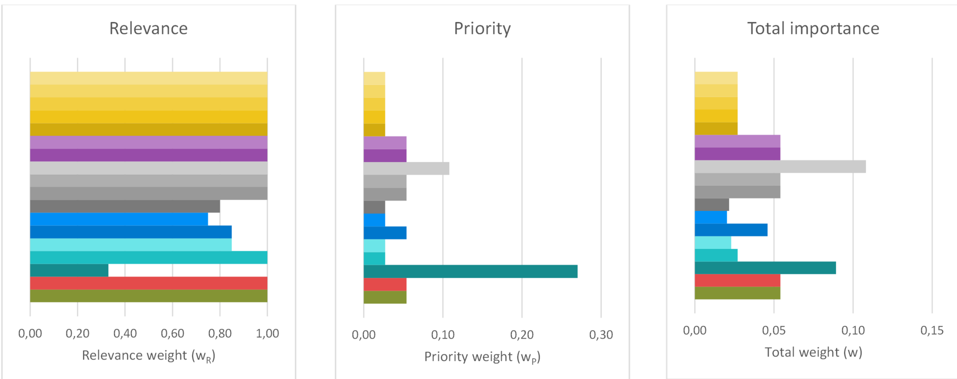


Figure 8.10: Weights for city hall Venlo

Reflection: the importance of criteria

The results of the tool allow to reflect on the importance of different criteria to the decision to use an LWSMT system. Figures 8.9 and 8.10 visualize the weights and contribution of criteria to the overall value per VGS system. More detailed results of the tool applied to this project can be found in appendix 11.10.

Particulate matter removal was the prime motivator to apply a VGS (Interview M). However, in the tool, the high priority on PM is counteracted by a low relevance weight ('somewhat relevant'; 0,33), dictated by the low PM pollution level (9 µg/m3). Figure 8.10 shows the combined total weight of PM. This shows that the tool can balance more subjective client objectives or wishes with more objective relevance aspects. In retrospect, thus, the tool brings nuance to the value PM mitigation by a VGS can deliver to the environment of this specific project.

It is interesting to note that two studies examined the actual performance of the city hall VGS. One of them measured that the VGS purifies air in a 500 m radius around the building, absorbing particulate matter (PM) from an estimated 3.000 m2 of roads [74, 238]. This strengthens the 500 m radius considered in the tool for estimating the street aspect ratio and district facade vegetation coverage, as input parameters for PM removal potential. However, the studies do not state the amount of PM mitigated. This aligns with the 'fair' PM removal performance (4 out of 7) in the tool, which is lower due to an unfavourable street aspect ratio and district vegetation coverage (parametric scoring).

In other words: the tool brings nuance to the relevance and potential of a VGS to mitigate PM in the Venlo city hall project, although it was the main motivator to apply a VGS. The built-up of the overall performance shows that the particulate matter removal and greywater treatment potential of LWSMT and LWSMB provide a distinctive contribution to their total score, helped by the relatively high priority weights (figure 8.9). Also, the low priority on costs makes the other, cheaper, systems less attractive.

Since measurements have confirmed that the LWSMT system mitigates PM, and PM removal was given a high priority (admittedly partly negated by a low relevance and potential), the 'most suitable' system was not accidentally chosen. Instead, the client's focus on PM removal and greywater treatment makes LWSMT the most suitable system.

Lessons: a multi-purpose perspective

Had the tool been used at the beginning of the project, then insight into some overlooked criteria/purposes could have changed the design considerations.

For example, traffic noise reduction could have played a larger role. This criterion has high relevance (1,00) because of high noise levels, but received low client priority (10 out of 100). Had the tool informed the users about the opportunity to reduce disturbing street noise levels, then the client might have given a higher priority. This would have resulted in a larger suitability of indirect GF or LWSL systems.

One of the studies about the Venlo city hall project conducted tests at the TU Eindhoven laboratory and has shown that this VGS system removes 30% of nitrogen and CO2 from the air [244]. This is in line with the assumed 'good' (5) performance of LWSMT on carbon sequestration. Had the client given more priority to carbon sequestration, then this would have resulted in a slightly larger suitability of GF systems.

Moreover, if the client had been aware of the biodiversity enhancement potential and biodiversity had been more of a priority from the start of the project (Interview M), then this would have strengthened the choice for a modular LWS, which scores high on biodiversity.

Application of the MCDM tool on the case study project, therefore, broadens the original focus on PM removal towards a multi-purpose perspective on VGS functionalities. In hindsight, the tool allows to include other relevant benefits, which could have helped to substantiate the application for a VGS type better in early project phases. Although it cannot be said with certainty whether the application of the tool on this project would have changed the choice of system, the client's indifference about costs and focus on air pollution removal would probably point towards the LWSMT system anyway.

Practical value: a conversation tool

Being asked about the usability of the tool and its results, the project manager indicates the tool it is easy and clear to fill in the environmental conditions and to consult with the client to fill in the priorities (Interview M). Also, the tool has added value to the design process, because it allows the user to show the client different VGS options with their respective value to the building or environment, as well as the contribution of criteria and themes to the overall value (Interview M).

Moreover, the tool allows to catalyse discussions in a design team about VGS in early design phases. The explicit display of benefits gives possible reasons to apply a VGS. The project manager appreciates the graphs of performances with(out) costs, that allow to compare systems on their cost-effectiveness in delivering benefits (Interview M).

Design recommendations

The design recommendations that are part of the tool are considered useful by the project manager. Table 8.3 shows the detailed design choices made, and the similarities with design recommendations provided in the tool. Especially recommendations for functionality and aesthetic value were applied during the project. The similarity between the recommendations and the actual design shows that (part of) the design recommendations are relevant and executable. At least for particulate matter removal, the detailed design choices have resulted in a measured reduction of PM in the environment.

Table 8.3: Similarities between actual design choices and design recommendations in the tool

Design field	**Detailed design choices**	**Design criterion/purpose with corresponding design recommendation(s)**
Vegetation: plant species selection	'The plants were specially chosen for their effect on the outdoor air' [241]	PM
	'Using plants that are wind- and frost-resistant' [241]	Functionality
	'Because of the extra high wind load at the corners of the building, the most wind-resistant species grow there' [241]	Functionality
	'The plants have been selected to take account of the different light incidence' [238]	Functionality
	'The facade is patterned with various plant species, giving it a beautiful colour every season' [241]	AV
Vegetation: pre-vegetation	Application of pre-vegetated planters [239]	HS/CE, HE UHI, PM, CS, TN, BD, RC
Supporting structure	Re-developed plastic of planter boxes to lower environmental burden and make it recyclable [241]	EB
Irrigation	'A computer-controlled irrigation system has been integrated in the planters to supply the vegetation with water and nutrients.' [238]	Functionality
Operation	'The town has signed a ten-year maintenance contractor with the manufacturer of the system to ensure long-term functionality' [238]	Functionality

8.2.3 Conclusion: case study

The most suitable system that follows from the results of the tool (LWSMT) was also applied in the city hall of Venlo. Also, design recommendations given in the tool align with the design choices made. This validates the results of the tool, for this specific case study.

The LWSMT system was not chosen by accident, because validation measurements indicated that this system could remove particulate matter from the air, which was the main motivator to apply a VGS in this project. Still, though, the client's focus on PM removal is tempered by the MCDM tool because of limited relevance and potential to remove PM. Nevertheless, the importance of PM removal and greywater treatment, in combination with non-prioritised costs, determines the high ranking of the LWSMT system.

The tool provides valuable lessons for the case study project, since it can broaden the original focus on PM removal towards a multi-purpose perspective on relevant VGS functionalities, such as traffic noise reduction or biodiversity enhancement.

The practical value of the tool lies in its purpose as a conversation tool that helps the design team to holistically and explicitly compare systems and to substantiate their choice.

8.3 Example projects

To illustrate its use for different project types and locations, the tool is tested with example projects. Based on desk research about designed or constructed buildings with a VGS, the project-specific input is retrieved or assumed (appendix 11.10). The different outcomes for the different projects show how the tool incorporates project-specific design considerations.

8.3.1 Education building

The first example project is the education building Echo on TU Delft campus, which includes education spaces, lecture halls, study spots and a restaurant. The environmental conditions as input for the tool can be found in appendix 11.10. For priority weighting, the design ambitions are taken into account. The university has ambitions for a fully sustainable campus by 2030, and much attention was paid to the circularity of materials and shadowing by possible VGS [245]. Thus, the environmental burdens (weight 80) as well as cooling and heating energy savings (weight 60) are prioritised. Since avoiding heat gain was important to the design team, indoor heat stress reduction was similarly prioritised (weight 60). The architect wanted to 'create an impressive green facade' [246], so aesthetic value is also given priority (weight 30). Installation and maintenance costs are given a weight of 30 too, because these generally play an important role in VGS type choice (Interview B). All other criteria are considered least important (weight 10).

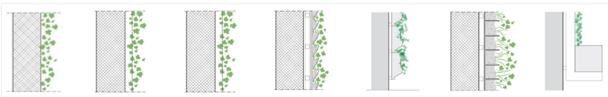
The resulting ranking of VGS systems is shown in figure 8.12. The most suitable system is DGF, followed by IGFC. Minimizing environmental burdens makes a large contribution to the total performance of these systems (figure 8.13). In reality, an IGFC system was adopted on the southwest, northwest and northeast facade (figure 8.11).

The relatively large distance between the steel cables and emphasis on a visual connection from inside to the surrounding public space and nature [245] suggest that the view outwards was an important design consideration as well. This makes DGF less suitable (since it can block views and requires a subsurface to grow on) and IGFC more suitable. This functional consideration about the transparency of the facade might - in hindsight - justify the choice of system, and could be included in future research and development of the MCDM framework.

Although the chosen IGFC system offers the opportunity for an outward view and has a slightly higher environmental burden than DGF, the low vegetation density limits thermal benefits, which were also prioritised. This makes the achievable thermal regulation potential for the IGFC in this location, as considered in the tool, not fully exploited. Eventually, the tool reveals trade-offs between

Figure 8.11: Echo education building [245]

different design criteria (environmental burden and thermal benefits). It shows that the decision-makers could have chosen a DGF system over an IGFC if the environmental burden or costs had been prioritised over thermal benefits or transparency (figure 8.13).



VGS type	DGF	IGFC	IGFT	LWSC	LWSMT	LWSMB	LWSL
Overall performance	46,12	45,45	42,97	32,21	42,80	43,96	40,06
Ranking	1	2	4	7	5	3	6

Figure 8.12: Ranking for Echo (green = most suitable, red = least suitable)

8.3.2 Data centre

The second example project is the data centre AMS11 near Schiphol airport (Amsterdam), which is in a well-advanced design phase [247, 248]. Cooling energy savings are assumed the most important criterion for priority weighting (weight 100), because of the large cooling load of data centres. Given the sustainability ambitions of the client [249], environmental burdens are prioritised (weight 60). In order to blend into the landscape (aesthetic value: weight 50) and to promote biodiversity (weight 40), these aspects are found to be important for distribution centres [45], and therefore presumably also for data centres. To a lesser extent, air quality control (PM reduction: weight 30) and stress reduction (relaxation effects: weight 20) are important for distribution (and data) centres [45]. Costs play an important role in VGS design considerations for data centres (Interview B). Especially maintenance costs are given priority in data centre projects (Interview B) [250]. Thus, the weight of maintenance costs is set at 70, and the other costs at priority 50.

Whereas the tool presents a ranking led by DGF, followed by a IGFC system (figure 8.15), the actual design adopts an IGFC system with stainless steel cables with a (relatively small) core-to-core distance of 250 mm. This creates a dense coverage in the visualisations (figure 8.14).

Mainly the prioritised costs and environmental burdens contribute to the top ranking of DGF in this project (figure 8.16). Yet, an IGFC system is more beneficial for cooling energy savings and aesthetic value. Possibly, the IGFC was favoured over the DGF because of these two latter benefits, for which facade coverage - and thus growing speed - is important. Another reason for the choice

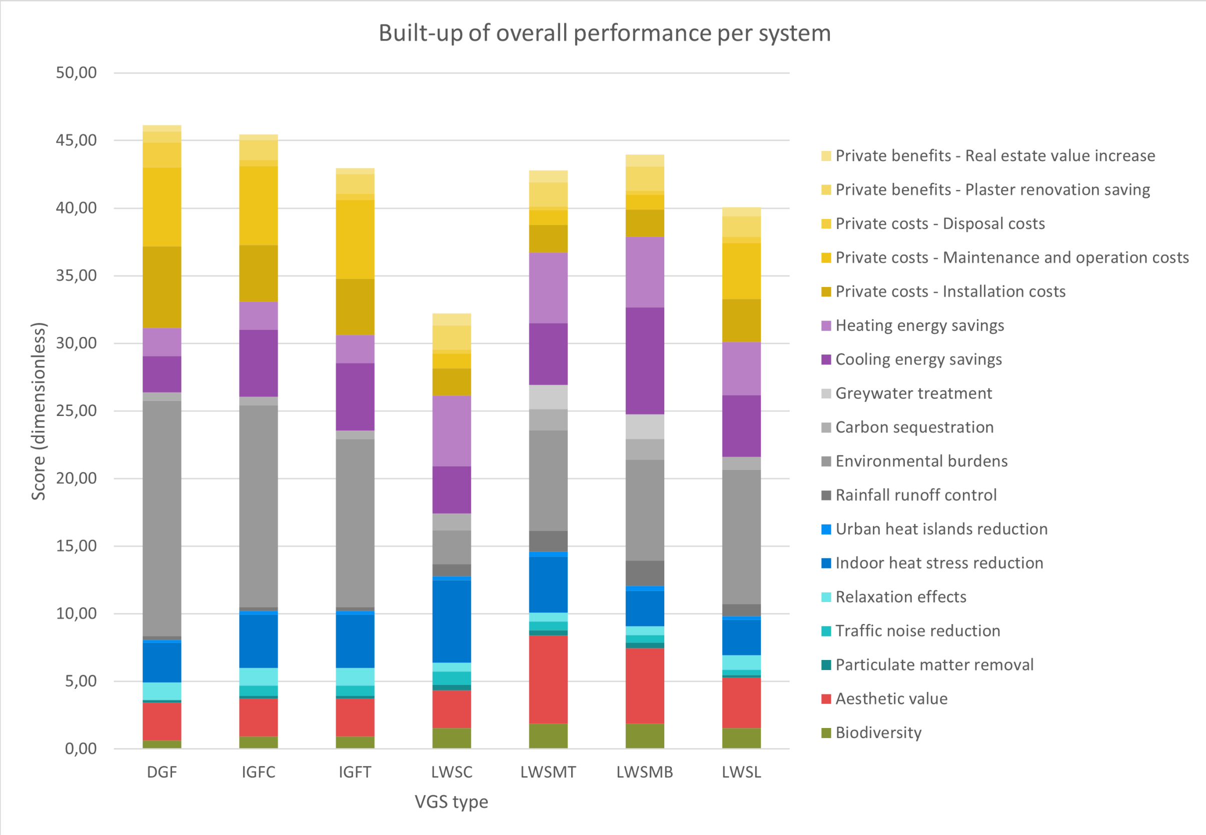
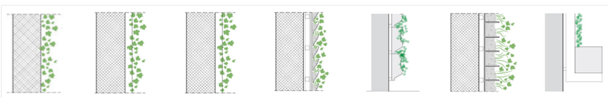


Figure 8.13: Contribution of criteria to overall value for Echo

(a) North-west elevation (b) South-west elevation

Figure 8.14: Design of AMS11 data centre [247]



VGS type	DGF	IGFC	IGFT	LWSC	LWSMT	LWSMB	LWSL
Overall performance	52,27	48,07	46,52	30,46	42,96	46,29	43,76
Ranking	1	2	3	7	6	4	5

Figure 8.15: Ranking for AMS11 (green = most suitable, red = least suitable)

of system might have been the challenging attachment of climbers in a DGF to the sandwich panel facade elements. So, if costs and environmental burden have prevailed over cooling energy savings and aesthetic value in the priorities of the client, then DGF would have been a more suitable system.

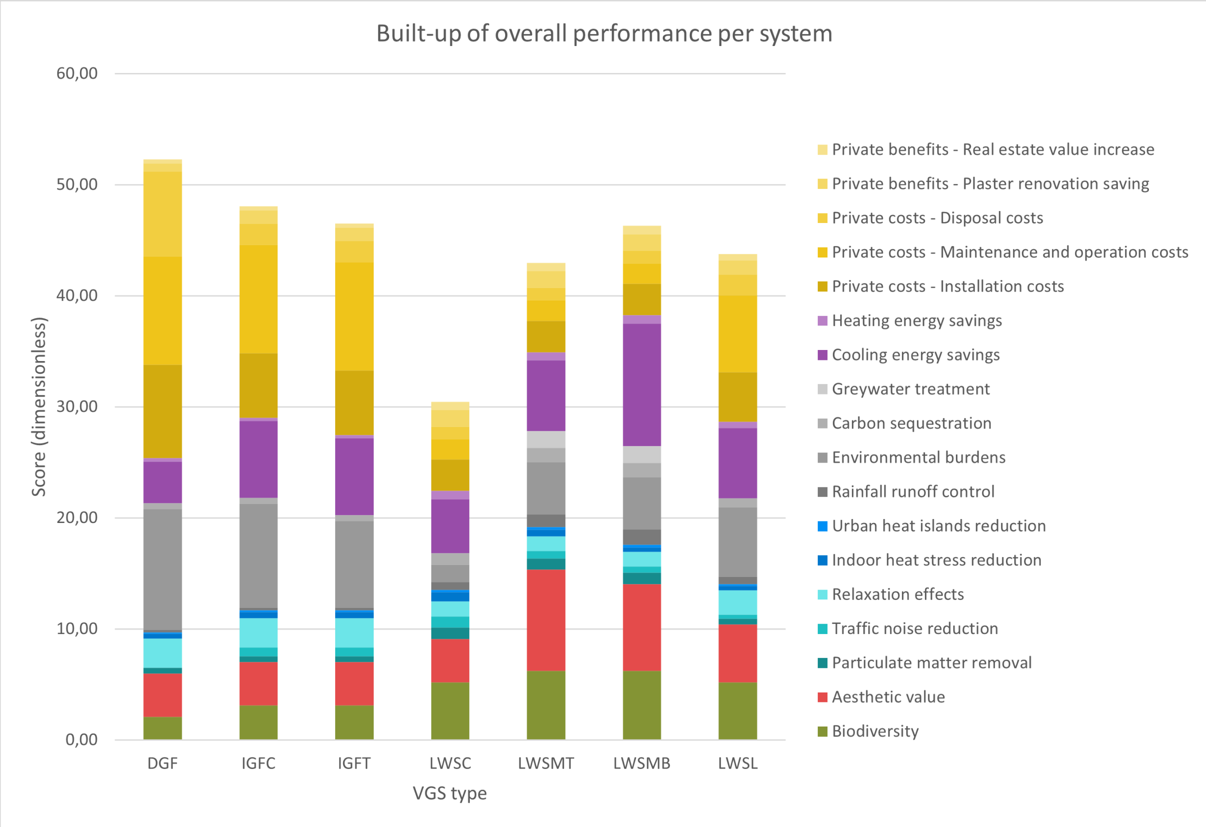


Figure 8.16: Contribution of criteria to overall value for AMS11

8.3.3 Residential building

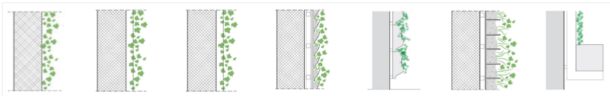
Third, the residential project Habitat Royale in Amsterdam is examined. The nature-inclusive design includes 94 high-end owner-occupied apartments, a kindergarten, an orangery and catering facilities [251]. Enhancing biodiversity by providing a habitat for flora and fauna is central to the project, reflected in the priority weighting (weight 100). Because the building mainly consists of housing, the real estate value increase is assumed quite important to the client (weight 60). For material choice, embodied carbon and circularity are given emphasis in the project [251] (environmental burden: weight 50). Since creating a healthy living environment for the residents is central to the project, a comparable weight is assigned to reducing indoor heat stress (weight 50). Energy production and use are given importance too (heating energy savings: weight 30). Because a 'quiet, healing place outside' is envisioned [252], traffic noise reduction (weight 30) and relaxation effects (weight 50) are given priority. Private costs are given a weight of 20, since they are considered more important than the remaining criteria.

The tool presents a ranking starting with LWSMT, LWSMB and LWSL systems (figure 8.18). In reality, the design adopts a perimeter planter-box system. This can be regarded as a variation of an LWSL, with planter boxes at each floor level along the full perimeter of the building, but without a climbing aid and with a wider range of plant species.

Especially biodiversity and aesthetic value contribute to the high scores of the top-2 modular LWS, whereas performance on relaxation effects advocates for an LWSL system (figure 8.19). Another reason this system was adopted could have been the larger opportunities for a free view of the outside environment from the apartments. The literature study assumed a lower biodiversity potential for LWSL due to limited variability in plant species. However, in this project a wider range of plants was used, enhancing the performance in terms of biodiversity and creating more value for LWSL than anticipated in the tool.

As such, this example project shows that the overall values and ranking of systems do not serve

Figure 8.17: Design of residential project 'Habitat Royale' in Amsterdam [251]



VGS type	DGF	IGFC	IGFT	LWSC	LWSMT	LWSMB	LWSL
Overall performance	39,34	40,54	39,19	38,01	50,02	47,38	42,37
Ranking	5	4	6	7	1	2	3

Figure 8.18: Ranking for Habitat Royale (green = most suitable, red = least suitable)

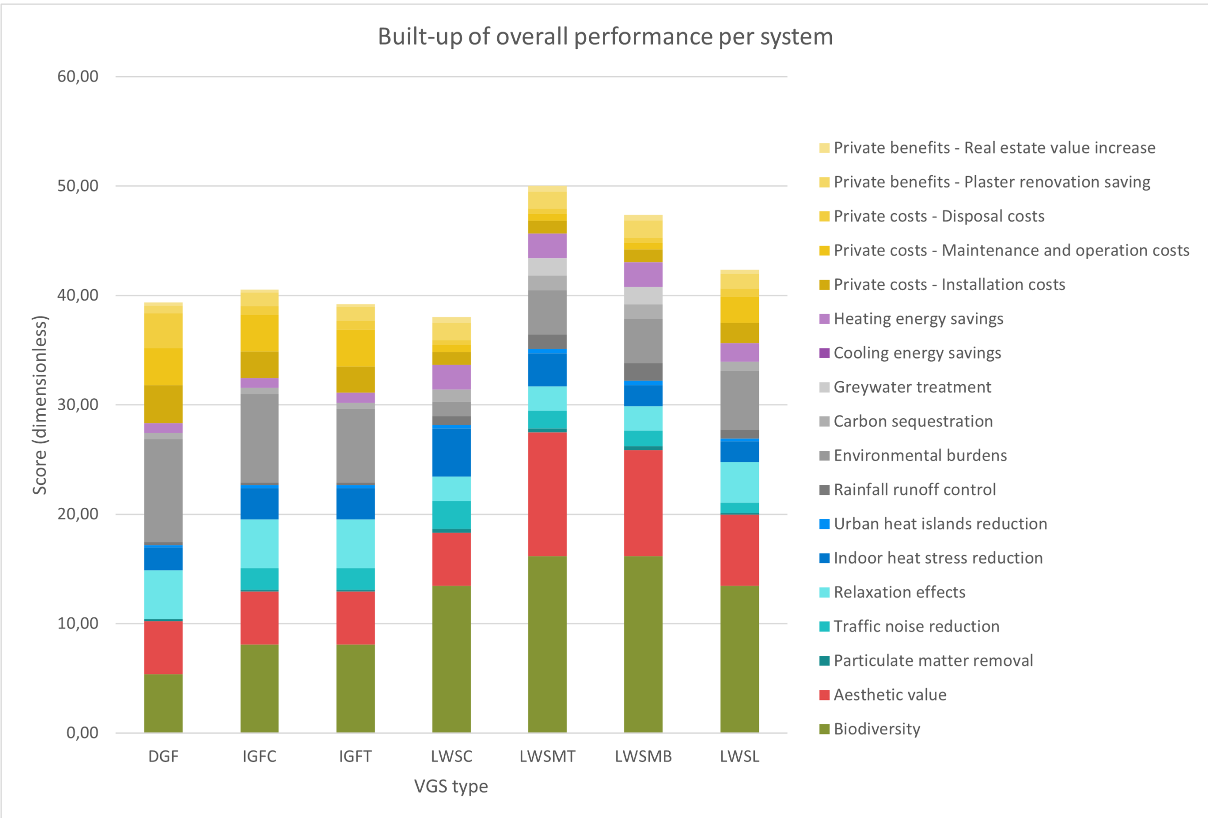


Figure 8.19: Contribution of criteria to overall value for Habitat Royale

as advice on blindly choosing the top-ranking system, but as an aid to defining, quantifying and comparing the value of different purposes per system. After careful consideration of these aspects, the decision-maker can then choose to apply one system over the other.

8.3.4 Conclusion: example projects

Overall, the example projects show how the outcome of the tool provides a project-specific potential overall performance per system type. This can serve as input for the ultimate design choice for a system.

Depending on project priorities and location, the rankings and maximum scores have different values (figure 8.20). This proves that the tool is applicable to building projects with different functions and locations and shows that the maximum value a VGS can deliver is higher in certain locations (due to a higher relevance). In this way, users of the tool can discover at which locations VGS have the most potential added value to the building and environment.

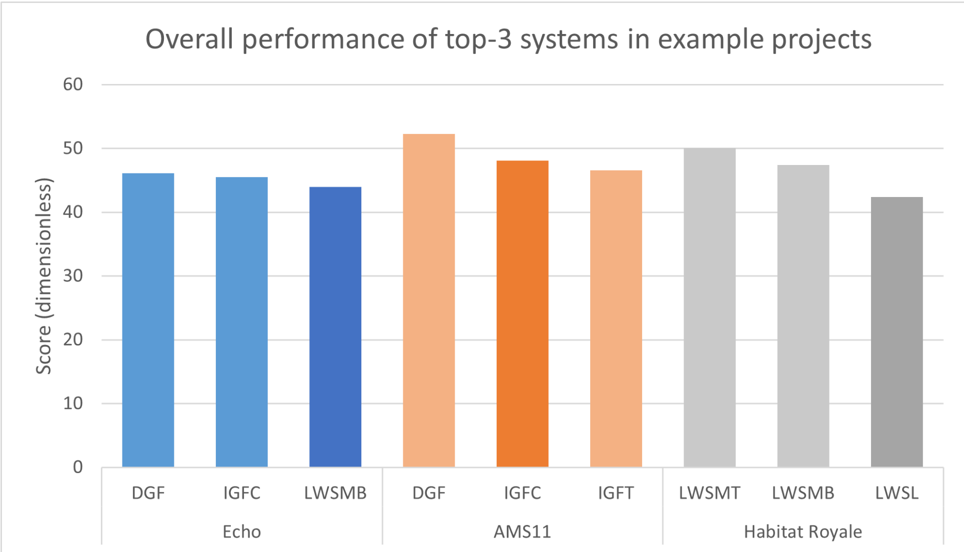


Figure 8.20: Top-3 scoring in example projects (darker colour = chosen system)

The actually chosen systems in the example projects are not the same as the most suitable system identified by the tool (figure 8.20). This can be attributed to an inaccuracy in assuming priorities, or to the importance of functional or technical considerations that can be decisive in the final choice.

All in all, although the example projects do not quantitatively validate the scores in the tool, they do verify the functioning of the tool as an aid to decision-making.

Part IV

Discussion and conclusions

Chapter 9

Discussion

This research has provided insights into multi-criteria decision-making for the selection of a VGS that is suitable for project-specific purposes. This chapter reflects on the value and contribution of the findings to research and practice, as well as the implications of the limitations of the research. The discussion concludes with recommended avenues for further research.

9.1 Contribution to research and practice

The resulting framework demonstrates a multi-criteria perspective on the decision problem of selecting a suitable and fit-for-purpose VGS for building facades.

9.1.1 Academic value

The results of the research, in the form of the framework and tool, can be regarded as one of the missing links in academic research focused on understanding and facilitating the selection and design of VGS.

It extends current perspectives on VGS evaluation, including those focused on ecosystem services or costs and benefits [46], by comparing VGS systems on all benefits and burdens of VGS for which evidence in literature exists. As such, the thesis integrates fragmented research insights into a holistic perspective on VGS functionalities. The multi-criteria approach proposes a structured and complete picture of evaluation criteria, since they are grouped into five sustainability themes and cover multiple purposes and impact levels (building and urban). Moreover, the themes provide a new way of looking at how VGS can address local sustainability challenges.

The findings about the influence of environmental and systems design parameters highlight the conflicting or complementing relations between different criteria. For example, increasing the moisture content of the substrate helps traffic noise reduction, but limits the rainfall retention capacity. These insights enrich the understanding of the effect of environment and design on VGS performance in previous research [45]. Therefore, the multi-criteria approach sheds light on the complex interactions of different criteria/purposes and makes trade-offs more explicit.

9.1.2 Practical value

The Excel tool translates research insights into a ready-to-use multi-criteria tool that supports architects, engineers and clients of building projects. In practice, the tool is an aid to decision-making, by catalyzing design team discussions about why and how to apply a VGS in the specific building project. The case study verifies that the tool helps to make more evidence-based, justified decisions because it shows to what extent different purposes contribute to the overall value of a system. Similarly, the example projects and case study verified the user value of applying a multi-criteria evaluation on VGS.

The framework/tool can also contribute to knowledge development at architecture and engineering firms involved in building projects. It can help avoid 'green-washing' when applying VGS products or cherry-picking in marketing since the framework substantiates which values are added (to what extent) to the building or environment. In that way, the study's results contribute to value-focused thinking in the early facade design process [253].

9.1.3 Enhancing VGS adoption: to green or not to green

The question that can be asked is: is this going to make cities green? The answer to this is multifaceted.

In one way, the framework can enhance VGS to be taken into account in the early facade design process and thus enhance VGS adoption. The use of the framework and tool by practitioners provides a way to select and design multi-purpose VGS that tackles building and urban sustainability challenges. Even more so, the tool enables a more targeted approach for applying VGS at the locations where VGS are most relevant, e.g. with much noise and air pollution. In this way, the tool can contribute to applying VGS where they make the most sense.

The framework can be the starting point for a common standard [21] that homogenizes and disseminates knowledge about VGS functions and ways to address technological challenges, such as maintenance strategies and water-proofing [250].

In other ways, implementation barriers other than the lack of guidance need acknowledgement. VGS are often met with fear of high installation and maintenance costs [30], but the framework takes this into account by integrating costs into the overall performance of a system. Also, it demonstrates economic and community value.

Still, though, costs are very often a discriminating factor over VGS benefits, so government incentives could be decisive to enhance VGS adoption, also because a large portion of the environmental improvements do not benefit the investor of the VGS. Given that more regulations and stipulations for facade greening are developing [21, 29], e.g. for data centres in Germany [254], the framework can help to choose the most suitable VGS when the application is obligatory, too.

For a successful implementation of VGS, the participation of citizens is necessary [57] (Interview A). This 'social' implementation barrier also needs to be addressed when trying to improve VGS adoption, for example through communication. Setting expectations, developing a good acceptance level, creating an understanding of the functions of a VGS and drafting operational strategies are all part of this [213].

Thus, the framework can contribute to more widespread implementation of VGS, together with policies and public involvement. As such, the results of this thesis can contribute to bringing about nature-inclusive construction that tackles pressing challenges in the built environment.

9.2 Limitations of research

9.2.1 Scope

Although the research covers a wide range of topics associated with VGS design and implementation, it has some limitations in scope. Some systems for green buildings have been excluded due to limited availability or limited evidence of performance (appendix 11.2). For example, perimeter pots can be categorised as LWSL, because they consist of planter boxes around the perimeter of the building [10]. Yet the inclusion of more plant species than climbers and the different sizes of boxes invite further research about the functionality and impacts of this specific VGS type.

Some ecosystem services were excluded, such as food production, due to a lack of thorough evidence (appendix 11.6). Since the completeness of the set of evaluation criteria was verified by the expert interviews, these excluded benefits are not expected to affect the results of the framework.

A multi-criteria analysis does not allow to include an explicit 'neutral' scenario or option of 'doing nothing' [50]. Therefore, a limitation of the outcome of the framework is that it does not clearly show if applying a bare wall instead of a VGS would result in a better score. Still, the global scaling for standardizing performances implicitly compares the performances of VGS to other facade measures. As a result, the performances per system type are relative to each other and other facade measures. Yet, the dimensionless overall performance gives an idea of the extent of the impact of each system, but not an absolute difference compared to applying a bare wall. The lack of a 'neutral' scenario in MCDM and the varying maximum achievable score per location are reasons why introducing a general threshold value for a 'sufficient' score to apply a VGS is not possible. Other evaluation approaches, such as social cost-benefit analysis (SCBA) are more suited for this, e.g. by using a positive net present value as an acceptance criterion [46].

Another limitation of the overall performance per system type is that it cannot show whether the alternative adds more to welfare than it detracts [50]. This is a result of the MCDM approach that accounts for a lower score, but not a negative one, for 'bad' performances regarding costs and environmental burdens. Instead, the results of the tool allow users to make trade-offs amongst criteria, such as some larger environmental benefits of LWS that are accompanied by higher costs and environmental burdens.

The proposed framework implies a full understanding of the selection and design process of VGS. The expert interviews and review of 5 qualities of a qualitative set of criteria (section 5.15.1), as well as example projects and case study, all confirmed that the key considerations in selecting and designing VGS are included in the framework and tool. Therefore, the research provides a verified full picture of the relevant aspects of this decision problem. Still though, the framework (and underlying MCDM model) could be even more in line with practice, e.g. in aligning with existing design practices, given that the content of the framework is mostly science-based.

Although the framework covers several input parameters, detailed building characteristics (such as area available for VGS, placement of windows, shadow on facade) could not quantitatively be taken into account. There are two reasons for this. First, detailed building characteristics are not known in early facade design phases, while the VGS does need consideration in those early phases to anticipate integration with the building design and maintenance planning [37]. Second, the literature study showed little research on the influence of building characteristics on VGS performance. Still though, the framework does take into account other parameters in terms of environmental conditions and the more general design parameters (e.g. plant choice).

Although the research started with a focus on VGS in urban areas, the resulting framework and tool are applicable on urban as well as rural areas. However, some issues that VGS solve are more prevalent in cities, such as UHI or noise hindrance. The tool takes this into account by assigning a higher relevance weight to these criteria, so that applying the tool in cities can result in a higher maximum score. The tool only functions for building projects in the Netherlands, but the conceptual steps of the framework remain applicable regardless of geographic location.

9.2.2 Reliability and accuracy of results

To arrive at a complete and functioning framework and tool, certain assumptions had to be made, based on the results of past research. In fact, a multi-criteria model (figure 6.1) was developed with established dependencies and quantification of performances.

Simplifications and assumptions

The framework represents a simplification of the complex reality. A multi-criteria approach simplifies decisions by breaking them into parts (criteria), but does not oversimplify decisions by neglecting the complexities of specific decisions ([49]). This also holds for this study's results, since the performance on criteria is given a project-specific dimension (parametric scoring and weighting). The evaluation criteria are assumed independent phenomena, although this might not fully be the case in reality. In fact, there might be dependencies between them, for example between indoor heat stress reduction and UHI mitigation, or real estate value increase and aesthetic value. Correlation between the different benefits of VGS is therefore an interesting avenue for further research.

Besides, the compensatory overall value [49] is a simplification. A 'bad' score on one criterion can be compensated by a higher score on another criterion. Therefore, the built-up of the score is part of the results. More specifically, simplifications were made to quantify performances. For example, the time value of money was not explicitly included in the economic benefits [20], but simplified to a relative increase in property value or a sum of plaster renovation savings after 50 years. Likewise, an average value was used to express costs, while the range of costs is only given in the 'detailed results' part of the tool. Although the framework is a simplification of reality and has its limitations, useful lessons can be drawn from the framework's functioning.

For most criteria, a deductive approach was used on quantitative scientific results. If available, quantitative system-specific performances based on modelling results validated by experimental research were used to inform the assumed scores per system type. However, for some criteria, little research or quantitative evidence for specific VGS systems is available. In that case, results were interpreted based on similarities with other green systems, such as green roofs, or on system characteristics, such as system thickness. The use of these argued estimates is substantiated in chapter 5. For criteria for which quantified performances are uncertain, a 7-point scale was adopted to reflect the qualitative nature of the score.

The effect of these assumptions on the reliability and accuracy of the results of the framework/tool is an important limitation. Whereas the MCDM methodology and purpose of the tool as an aid to decision-making are well-founded, the numerical performances per criterion need more validation.

The simplifications and assumptions did not have an impact on the appropriate application of the MCDM method on VGS. The example projects and case study have verified the holistic, project-specific and explicit functioning of the framework.

The results of the case study validate the ranking and design recommendations from the tool, indicating a certain reliability of the outcome, but do not necessarily prove the accuracy of the numerical scores per criterion. Sensitivity analyses showed that the ranking of VGS is sensitive to changes in (some) client priorities, and less so to changes in environmental conditions. This suggests that a change in a combination of multiple location and project conditions can change the preferred VGS. However, this still needs validation in future studies about the decisiveness of the environment and priorities in real-life design teams.

Although the database of performances per system type was composed based on a comprehensive literature study that acknowledges the research variables per study (such as distance from facade for outdoor temperature measurements), the tool cannot guarantee that the performance shown will be met when applying a VGS, because this study does not include a numerical validation of those performances. Considering this, no bold claims for performances are made in the framework/tool, but rather an 'achievable' or potential performance is provided in the detailed results section. Experimental validation of performances considered in the tool would be necessary to improve the accuracy of the numerical outcome.

The example projects have applied VGS that were second or third most suitable according to the tool, which indicates that the ranking of the tool is not completely validated. This also shows that the practical value of the tool lies in its purpose as a conversation tool that helps the design team to holistically compare VGS and to substantiate their choice. The results of the tool are not intended as a one-way advice to apply the best-scoring system, but to give insight into what objectives and effects play a role, what (dis)advantages are and what systems are the most promising in the project context. The framework and tool can start the selection and design process, and serve as a conversation tool between architect/engineer and client about the suitability of a VGS, rather than as a means to automatically generate the best VGS. This comes down to the purpose of an MCDM approach - of which the development was central to the main research question - as an aid to decision-making, rather than as a sole decision-maker.

Subjectivity

In addition, MCDM brings subjectivity to the analysis by consenting intangible benefits [20]. Especially for criteria expressed on a qualitative score, a judgement by the author or interviewees plays a role. On the other hand, a MCDM provides a degree of structure, analysis and openness, that would be preferred over an informal judgement in choosing a VGS without this study [50]. For the design recommendations, the author had to use some interpretation of the research results found. Therefore, this part also doesn't add up to the total numerical score but is rather qualitative, science-based advice.

The interviewees present a practitioner's view on the matter. Their experience and knowledge depend on personal background, past experience with VGS and their role, so might have affected the findings. Also, the semi-structured interviews leave some room for judgement and interpretations by the author [255]. Therefore, the results of the expert interviews were used to strengthen or nuance findings already found in the literature to prevent a biased outcome.

9.3 Recommendations for further research

Developing a multi-criteria analysis can provide useful hints for a wider understanding and diffusion of greening systems [52]. This section, therefore, makes recommendations for further optimization of the framework/tool and further academic research.

9.3.1 Optimizing the framework/tool

Recommendations for further development of the selection and design framework are:

- Including more green systems as design alternatives, e.g. other nature-based solutions such as street trees, green roofs or moss-based greening systems. Green roofs, for example, might have a lower aesthetic potential to passers-by [21]. When there is uncertainty about their performances, a confidence criterion in the value tree might be a solution, since it judges the probability that the design option will attain the value assessed on the other criteria [50].
- The current tool is only applicable on Dutch projects and projects in a Cfb climate. An improvement could be to include more climate types, with corresponding climate-specific performances.
- For some ecosystem services, such as food production, not enough evidence was found to integrate them into the framework. However, once sufficient evidence is found, integration of other ecosystem (dis)services [256] would be a valuable next step in creating an even more complete picture of VGS impacts.
- Refining the weight allocation method for priority weighting. As a more objective alternative to the direct allocation by the client, a weight allocation by experts that have experience in applying VGS in certain building project types could be useful.
- Extension of the design recommendations, e.g. making them system-specific and basing them on best practices from experts.

Recommended ways of developing a more detailed design process in later project phases are:

- More explicit problem definition. For example, a local (measured) determination of noise pollution or heat waves. Then applying scoring to the degree of solving that particular, localised problem.
- Include design considerations such as zoning of the facade, optimizing placement of windows, PV panels, a closed facade and a VGS, based on local conditions (e.g. shading) and functionalities in the building.

9.3.2 Academic research

In academic research, recommended avenues for further research are:

- Experimental research on VGS benefits, especially comparing measurements or qualitative results of different VGS systems in similar conditions. Purposes such as biodiversity potential and aesthetic value are well suited for this.

- Quantitative research on less-understood benefits, such as the increase in real estate value, because the determination of these effects could be a significant implementation booster. This can contribute to the numerical validation of the performances considered in the MCDM model [257].

- This study assumed the most common design characteristics per VGS type, such as common plant groups, to make sure enough performance data was available for every VGS option. Further research could explore the quantitative inhibiting or promoting effect of steering on systems design parameters, such as the type of substrate or plant choice (whereas this study was limited to qualitative recommendations). For example, the distance between steel cables in an IGFC can alter the vegetation density and therefore the extent of the benefits that depend on this - such as thermal benefits. Further research about the quantitative effect of design characteristics such as vegetation density and inclusion in the framework through numerical design requirements is therefore recommended. This way, a tailor-made design with quantitatively substantiated detailing for certain relevant or prioritised purposes can be developed.

- Comparing green strategies, or a combination of them. For example, the combination of green facades and green roofs.

- Further exploration of interdependencies between criteria, by testing the criteria interaction of the MCDM model and researching possible correlations between performances on different criteria. In this way, VGS could also be optimized.

- A district or public approach to enhancing VGS adoption. This research touches upon the effects at urban level, but it would be insightful to gain more understanding of the specific contribution of VGS to a mix of nature-based solutions that help restore nature and improve urban health and resilience. Also engaging the public in a 'public approach' could be part of this [213].

- Further research is necessary on how public incentives and involvement of citizens can enhance a wide diffusion of VGS, since a large part of VGS benefits affects the public rather than the private building occupants or owner.

- Exploring the total impact of VGS on sustainable and healthy buildings. Further research, and more numerical performances, might give insight in the total (quantified) sustainability impact and how application of VGS can contribute to achieving or further developing sustainability labels (e.g. Breeam or LEED). Similarly, the relation between outdoor and/or indoor VGS application and indoor health, e.g. the suggested effect on productivity [258], is an interesting research direction.

It should be noted that for GF, the potential performance considered assumes full coverage of the facade, while in reality the growth speed needs to be taken into account.

Chapter 10

Conclusions

This final chapter makes concluding remarks that answer the main and sub-research questions.

10.1 Conclusion main research question

The thesis answers the main research question: *How can a multi-criteria design framework on early design decision-making for multi-purpose urban vertical greening systems be developed?*

This study developed a multi-criteria decision-making (MCDM) approach to the decision problem of selecting the most suitable exterior VGS for a building project, based on an extensive literature study and expert interviews. The research integrates fragmented research insights into a multi-purpose and multi-level perspective on VGS. Moreover, it explores the relation between environmental conditions, VGS characteristics and performance.

The proposed framework (figure 10.1) establishes a universal and integrated guideline for the selection and design process of VGS. It can be adopted by architects and engineers during the early facade design process, and serve as input for the schematic design development. The framework captures benefits and burdens associated with VGS, and delivers a project-specific scoring and ranking of seven VGS types. Design recommendations ensure a design that fulfills its potential. Moreover,

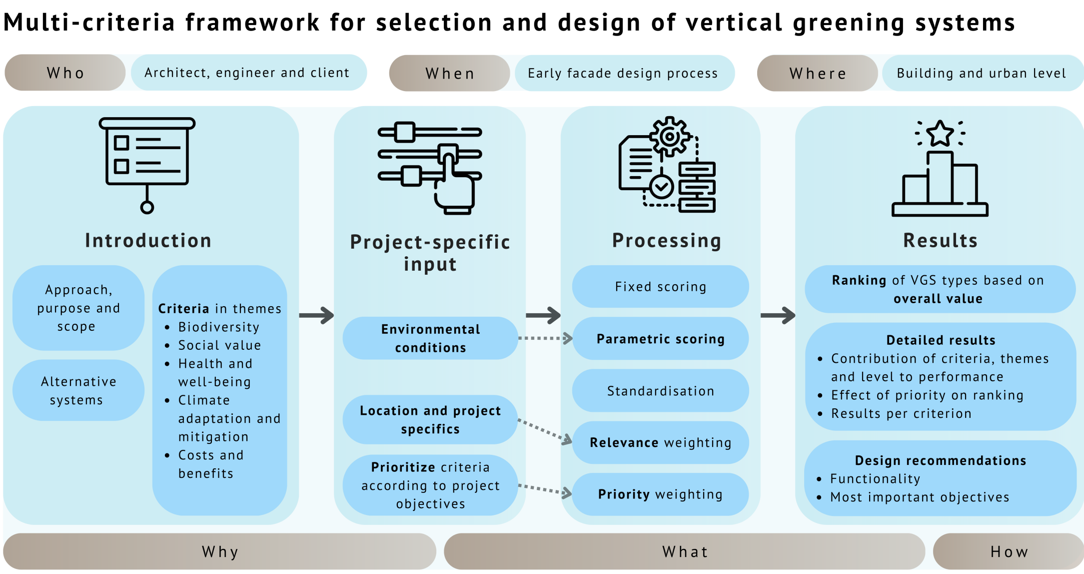


Figure 10.1: Multi-criteria framework

the framework allows to select and design a VGS that is fit-for-purpose, because relevance (based on location) and priority (provided by client) of criteria is taken into account.

The ready-to-use Excel tool is a hands-on numerical application of the framework that shows how the framework can be applied in Dutch building projects. Use of the framework and tool can enhance VGS adoption because it provides a way to select and design multi-purpose VGS that tackle building and urban sustainability challenges.

10.2 Conclusions sub-research questions

10.2.1 Alternatives (RQ1)

RQ1: What are the main design configurations for VGS?

This study identifies seven types of VGS as the main system typologies that are widely available and well-understood. In adopting a classification according to system components and construction characteristics, there is a split between two major system types: green facades, i.e. climber plant systems, and more intensive living wall systems. Direct green facades (DGF), indirect green facades with continuous guides (IGFC) or modular trellis (IGFT) consist of climber plants in ground soil without or with a climbing aid, respectively. The four other systems are continuous living wall systems with cloth or felt pockets (LWSC), modular living wall systems with trays (LWSMT) or framed boxes (LWSMB) and linear living wall systems with planter boxes at every floor level (LWSL). These seven systems serve as design alternatives in the MCDM approach.

10.2.2 Criteria (RQ2+3)

RQ2: What are the ecosystem services delivered by VGS?

RQ3: What are the environmental, economic and social impacts of VGS?

Previous approaches took an ecosystem services, sustainability, cost-benefit or limited multi-criteria perspective to evaluate VGS systems. This research adopts a holistic set of evaluation criteria that integrates the main benefits and burdens associated with VGS. The five themes 'biodiversity', 'social value', 'health & well-being', 'climate adaptation and mitigation' and 'costs and benefits' provide a structure for the effects of VGS at building and urban scale.

From an extensive literature study, 18 evaluation criteria are identified that either answer building and urban sustainability challenges, such as heat, air and noise pollution, or create value, such as economic benefits. For every criterion, a review of past research informs the (potential) performances per system type that are adopted in this study.

10.2.3 Parameters (RQ4)

RQ4: What are the key parameters to optimize the performance of VGS and how do they complement or conflict each other?

Environmental conditions and systems design affect the performance of VGS on the evaluation criteria. The climate type, street morphology and vegetated facades in the district are key environmental parameters, specifically affecting thermal comfort, energy savings, urban heat islands mitigation and particulate matter removal. The systems design parameters with a large effect on performance are orientation, building coverage, vegetation density, plant species, substrate and supporting structure. A large VGS is more costly, but provides more benefits, e.g. in enhancing biodiversity. Increasing the moisture content of the substrate helps traffic noise reduction, but limits the rainfall retention capacity.

10.2.4 Weights (RQ5)

RQ5: What are the project-specific characteristics that affect decision-making in early design phases of VGS?

No building project is the same. Project-specific characteristics that affect the selection and design of VGS are environmental conditions on the location of the project as well as the project objectives. Therefore, this study suggests three complementary ways to integrate project-specificity in a multi-criteria approach. First, parametric scoring can acknowledge the effect of environmental conditions (e.g. climate) on the potential performance. For example, a greater particulate matter removal is achievable in more narrow streets. Second, the relevance of the issue at hand can be reflected in relevance weighting of criteria. For example, traffic noise reduction is more relevant when street noise levels exceed noise pollution indicators. Third, client wishes and objectives can be expressed in priority weighting, to put emphasis on certain criteria.

10.2.5 Framework and tool (RQ6)

RQ6: How can design alternatives, criteria, parameters and weighting be integrated in a multi-criteria framework for the early design decisions of multi-purpose VGS?

This study proposes a multi-criteria framework, shown in figure 10.1. It can be regarded one of the first guidelines that establishes a universal and integrated selection and design process for vertical greening systems. The framework captures benefits and burdens associated with VGS, delivers a project-specific scoring and ranking of VGS types, and ensures a design that fulfills this potential. Moreover, the framework allows to select and design a VGS that is fit-for-purpose, because relevance (based on location) and priority (provided by client) of criteria is taken into account.

The ready-to-use Excel tool is a hands-on numerical application of the framework in Dutch projects. It shows in what way the framework could be applied in building projects.

10.2.6 Validation (RQ7)

RQ7: How can a multi-criteria design framework for the multi-purpose design of urban VGS be validated?

Sensitivity analyses show that a combination show that the ranking of VGS is sensitive to changes in client priorities, and less to changes in environmental conditions. This demonstrates how a combination of location and project conditions can alter the preferred VGS.

For a case study on the city hall project in Venlo, the most suitable system that follows from the results of the tool was applied. Also, design recommendations given in the tool align with design choices made. This validates the functioning and outcome of the tool for this specific case study. The use of the tool could have extended the initial focus of the project on air purification to multiple relevant VGS functions, such as the reduction of traffic noise.

Testing of the tool through example projects illustrates its use for different building typologies and locations, and shows its purpose as a conversation tool that helps decision-makers in holistically comparing VGS and substantiating their choice.

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Chapter 11

Appendices

11.1 Methodology RQ1: Details exploratory literature research

In order to identify the design options that are ready to be implemented, they were deducted from an exploratory literature research. First, the following search query was used on Scopus:
TITLE-ABS-KEY (("classification" OR "classify" OR "classifies") AND ("vertical green" OR "vertical greening" OR "living wall" OR "green facade"))

This resulted in the following articles (in chronological order):

- Pérez et al. [64]
- Pérez et al. [61]
- Manso and Castro-Gomes [35]
- Medl, Stangl, and Florineth [43]
- Bustami et al. [48]
- Fernández-Cañero, Urrestarazu, and Perini [62]
- Radić, Dodig, and Auer [15]
- Palermo and Turco [66]
- Ogut, Tzortzi, and Bertolin [36]

Afterwards, broader search queries (such as including "types") and further reading of cited literature (so-called "snowball effect") expanded the list of consulted articles:

- Dunnett and Kingsbury [32]
- Köhler [63]
- Perini et al. [71]
- Ottelé et al. [70]
- Perini et al. [67]
- Hunter et al. [68]
- Wood, Bahrami, and Safarik [58]
- Jim [65]
- Koc, Osmond, and Peters [59]
- Giordano et al. [39]
- Wang et al. [60]
- Ascione et al. [40]
- Perini [3]
- Hollands and Korjenic [37]

This results in 25 included documents.

11.2 Alternatives: Excluded systems

Apart from green facades and living wall systems, which have been developed in practice for years and researched the most thoroughly, other systems such as moss-based systems, indoor walls, tree facades, green terraces and naturally grown walls are available as well. These systems are excluded from this study down the line of the aim of this study to propose a widely applicable and evidence-based design framework.

Moss-based systems. A less established vertical green system are mosses that root on the facade and grow on building materials, i.e. wall vegetation, here referred to as moss-based systems (MBS). Such systems have potential to be fast-growing, low-cost and low-maintenance – as they have low substrate, water and nutrient requirements ([3]). The performance of MBS depend on the supporting material it grows on, such as bio-receptive concrete, as well as the water distribution capacity of that material ([3]). Future research should shed a light on the design of irrigation systems, adhesion of the moss mixture, environmental sustainability under different climate conditions and ways to quantify the ecosystem provided by moss-based systems ([3]; [36]).

Whereas green facades and LWS can be found off the shelf, the market implementation of the promising moss-based systems is ongoing but not finalised. For example, valorisation of moss-vegetated surfaces is happening during tests with vegetated noise screens ([**Innov2022**]). Also, the majority of the research on benefits, impacts and design approaches of VGS does not include MBS yet, resulting in a lack of thorough insight in performance compared to other systems.

Bio-facades. "Bio-facades" are algue-growing facades that are sometimes regarded as vertical greenery systems. However, as their purpose and functioning has large differences with other VGS, it is excluded from this study.

Indoor walls. The term active living walls is sometimes related to indoor green walls. Though it has potential to filter and cool indoor air ([62]), it is excluded from this study as it only provides a solution to indoor comfort and energy challenges, rather than the urban sustainability challenges laid out.

Vertical forests and green terraces. Bosco Verticale in Milan is a famous example of a tree façade, to be exact a vertical forest, with trees growing on cantilevered balconies ([60]). Vertical forests are not included in this study because vertical forest engineering is a relatively new field, which requires deeper understanding of root systems, tree stability and planting strategies before it can develop into a mature facade technology with according design guidelines ([60]). For the same reason, green terraces (plants growing on horizontal terraces along the facade) are excluded.

Naturally grown walls. Vertical green systems that grow in situ from seed are not taken into account, as they can grow coincidentally or on purpose, and their growing and performance is very unpredictable.

11.3 Methodology RQ2-5: Details systematic literature research

For RQ2 and RQ3, the ecosystem services and impacts that serve as design criteria were researched through a systematic literature research. Following steps laid out by Charles Sturt University [55], the research was conducted as follows:

1. Identify research question(s)

RQ2: What are the ecosystem services delivered by VGS?

RQ3: What are the environmental, economic and social impacts of VGS?

2. Develop protocol

The initial inclusion criteria adopted are:

- Resulting from search query, as defined in step 3
- Relevant to the included VGS
- Relevant to benefits (or ecosystem services) or environmental, economic or social impacts
- Year of publication (2017 - 2023)

- Quality metrics (FCWI (Field-Weighted Citation Impact) > 0.5, if available)
- Article type is a review

3. Conduct systematic searches

In order to make the review comprehensive, unbiased, clear and reproducible, the following systematic search queries are used on Scopus (on 17-1-2023):

TITLE-ABS-KEY (("vertical green" OR "vertical greening" OR "vertical greenery" OR "living wall" OR "green facade" OR "green wall") AND (("benefits" OR "ecosystem services" OR "performance") OR ("environmental" OR "sustainable" OR "sustainability") OR ("economic" OR "costs" OR "value") OR ("social" OR "societal" OR "human"))) AND (LIMIT-TO (PUBYEAR , 2023) OR LIMIT-TO (PUBYEAR , 2022) OR LIMIT-TO (PUBYEAR , 2021) OR LIMIT-TO (PUBYEAR , 2020) OR LIMIT-TO (PUBYEAR , 2019) OR LIMIT-TO (PUBYEAR , 2018) OR LIMIT-TO (PUBYEAR , 2017)) AND (LIMIT-TO (DOCTYPE , "re"))

This gives 73 document results.

4. Screening

First, the title and abstract are screened to remove obviously irrelevant studies. The following 32 studies were removed:

- Certini, G., Scalenghe, R. The crucial interactions between climate and soil (2023) Science of the Total Environment, .
- Ljubojević, M., Narandžić, T., Ostojić, J., Božanić Tanjga, B., Grubač, M., Kolarov, R., Greksa, A., Pušić, M. Rethinking Horticulture to Meet Sustainable Development Goals—The Case Study of Novi Sad, Serbia (2022) Horticulturae, .
- Bruckmann, L., Chotte, J.-L., Duponnois, R., Loireau, M., Sultan, B. Accelerate the Mobilization of African and International Scientific Expertise to Boost Interdisciplinary Research for the Success of the Sahelian Great Green Wall by 2030 (2022) Land, .
- Elaouzy, Y., El Fadar, A. Energy, economic and environmental benefits of integrating passive design strategies into buildings: A review (2022) Renewable and Sustainable Energy Reviews, .
- Sarr, M.S., Diallo, A.M., King-Okumu, C. A review of public versus private reforestation programs in the Senegalese Sahel: taking stock of realities and challenges (2022) Restoration Ecology, .
- Yan, F., Shen, J., Zhang, W., Ye, L., Lin, X. A review of the application of green walls in the acoustic field (2022) Building Acoustics, .
- Mahrous, R., Giancola, E., Osman, A., Asawa, T., Mahmoud, H. Review of key factors that affect the implementation of bio-receptive façades in a hot arid climate: Case study north Egypt (2022) Building and Environment.
- Rezazadeh, H., Salahshoor, Z., Ahmadi, F., Nasrollahi, F. Reduction of carbon dioxide by bio-façades for sustainable development of the environment (2022) Environmental Engineering Research, .
- Wróblewska, K., Jeong, B.R. Effectiveness of plants and green infrastructure utilization in ambient particulate matter removal (2021) Environmental Sciences Europe, .
- Adegun, O.B., Ikudayisi, A.E., Morakinyo, T.E., Olusoga, O.O. Urban green infrastructure in Nigeria: A review (2021) Scientific African, .
- Mahmoudi, A., Mousavi, S.A., Darvishi, P. Greywater as a sustainable source for development of green roofs: Characteristics, treatment technologies, reuse, case studies and future developments (2021) Journal of Environmental Management, .
- Mannan, M., Al-Ghamdi, S.G. Active Botanical Biofiltration in Built Environment to Maintain Indoor Air Quality (2021) Frontiers in Built Environment, .
- Halgamuge, M.N., Bojovschi, A., Fisher, P.M.J., Le, T.C., Adeloju, S., Murphy, S. Internet of Things and autonomous control for vertical cultivation walls towards smart food growing: A review (2021) Urban Forestry and Urban Greening, .
- Bandehali, S., Miri, T., Onyeaka, H., Kumar, P. Current state of indoor air phytoremediation using potted plants and green walls (2021) Atmosphere, .
- Zluwa, I., Pitha, U. The combination of building greenery and photovoltaic energy production—a discussion of challenges and opportunities in design (2021) Sustainability (Switzerland).
- Crosta, S. From ecological disasters to the pan-African dream of a Great Green Wall [Des désastres écologiques au rêve panafricain d'une Grande Muraille verte] (2020) International Journal of Francophone Studies, .
- Yenneti, K., Ding, L., Prasad, D., Ulpiani, G., Paolini, R., Haddad, S., Santamouris, M. Urban overheating and cooling potential in australia: An evidence-based review (2020) Climate, .
- Al-Kayiem, H.H., Koh, K., Riyadi, T.W.B., Effendy, M. A comparative review on greenery ecosystems and their impacts on sustainability of building environment (2020) Sustainability (Switzerland), .
- Yang, W., Jeon, J.Y. Design strategies and elements of building envelope for urban acoustic environment (2020) Building and Environment, .
- Gubb, C., Blanusa, T., Griffiths, A., Pfrang, C. Can plants be considered a building service? (2020) Building Services Engineering Research and Technology, .

- Talaei, M., Mahdavinejad, M., Azari, R. Thermal and energy performance of algae bioreactive façades: A review (2020) Journal of Building Engineering, .
- Moya, T.A., van den Dobbelsteen, A., Ottelé, M., Bluyssen, P.M. A review of green systems within the indoor environment (2019) Indoor and Built Environment, .
- Andrić, I., Koc, M., Al-Ghamdi, S.G. A review of climate change implications for built environment: Impacts, mitigation measures and associated challenges in developed and developing countries (2019) Journal of Cleaner Production, .
- Gunawardena, K., Steemers, K. Living walls in indoor environments (2019) Building and Environment, .
- Pettit, T., Irga, P.J., Torpy, F.R. Towards practical indoor air phytoremediation: A review (2018) Chemosphere.
- Irga, P.J., Pettit, T.J., Torpy, F.R. The phytoremediation of indoor air pollution: a review on the technology development from the potted plant through to functional green wall biofilters (2018) Reviews in Environmental Science and Biotechnology, .
- Liu, R., Wei, T., Zhao, Y., Wang, Y. Presentation and perspective of appealing green facilities for eco-cyclic water management (2018) Chemical Engineering Journal, .
- Latin, I.B., Vardić, Z.P., Buljan, I.H. Antunini in the placa: The Spatial Arrangement of Members of the Confraternity of St Anthony along Dubrovnik's Placa (15 th Century) [Antunini na placi: Prostorni razmještaj članova Bratovštine sv. Antuna duž dubrovačke Place u 15. Stoljeću] (2018) Povijesni Prilozi, .
- Santamouris, M., Ban-Weiss, G., Osmond, P., Paolini, R., Synnefa, A., Cartalis, C., Muscio, A., Zinzi, M., Morakinyo, T.E., Ng, E., Tan, Z., Takebayashi, H., Sailor, D., Crank, P., Taha, H., Pisello, A.L., Rossi, F., Zhang, J., Kolokotsa, D. Progress in urban greenery mitigation science – assessment methodologies advanced technologies and impact on cities (2018) Journal of Civil Engineering and Management, .
- Prihatmanti, R., Taib, N. The biofaçade as a vertical edible landscape in high-rise buildings: A review (2018) Arab World Geographer, .
- Imam, A.U.K., Banerjee, U.K. Review of Strategies for Thermal Efficiency in Landscape Planning of Cities for Conservation of Energy and Enhanced Climatic Resilience to Urban Warming (2017) Journal of The Institution of Engineers (India): Series A, .
- Yuksel, E., Turkeri, A.N. A litterature review of experimental setups monitoring thermal performance of vegetated facade systems (2017) Journal of Facade Design and Engineering, .

This gives 41 included documents.

Second, full texts are screened for compliance with the inclusion criteria.

Third, to maximise credibility of performance claims, the included literature is complemented with further reading of cited documents ("snowball effect"), disregarding year of publication.

5. Critical appraisal

The reliability, impact and importance of the findings, and applicability to the research questions, are analysed.

6. Data extraction and synthesis

Relevant data is extracted and summarized in tables, in same units of measurements, where possible. The synthesis includes a critical overview of key findings, considering methodological quality and other pertinent features. Depending on the outcomes of the data extraction, a descriptive method or meta-analysis is used.

For RQ4 and RQ5, the literature used for RQ2 and RQ3 serves as the basis for the systematic literature research. Through the snowball effect, complementary literature was found.

11.4 Expert interviews RQ2-5: methodology and transcriptions

The expert interviews are conducted in a semi-structured way, because this gives the interviews a clear theme while it also allows for flexibility ([255]). This suits the exploratory nature of the thesis. In practice, an interview guide with fixed questions is used. These questions are complemented with additional follow-up questions. Analysis of the interviews is done with a mostly deductive approach (confirming or complementing the preconceived themes from literature), and sometimes with a inductive approach (raising new themes). This appendix presents the interview guide and transcriptions of the three interviews conducted (referred to as A, B and C).

11.4.1 Interview guide

The interview guide provides the same structure for every ecosystem service or criterion (referred to as [ES]):

- What mechanisms determine the impact of an IGS on [ES]?
- What are appropriate indicators to quantify the impact of IGSs on [ES]?
- What is the relative performance of different types of VGS with respect to [ES]?
- Important system components are plants, substrate, support system and irrigation system. Which components are most important for [ES] and why?
- Which parameters are most important for [ES] and why?
- What are critical design aspects for a VGS that optimal [ES]?

In addition, questions about the design process of VGS in general were asked, such as:

- What are the key considerations when choosing a VGS type?
- To what extent are costs and benefits, both private and public/environmental/ecosystem services, currently considered in the design process?
- What are project-specific characteristics that influence early design choices?
- What aspects in a design framework could help architects and engineers in early design choices?

11.4.2 Interview A: Arnold Wielinga

Arnold Wielinga is a Leading Professional and Strategic Advisor Water and Climate Adaptation at RHDHV.

Introduction

- Speakers: Hugo van Reeuwijk (HvR) and Arnold Wielinga (AW).
- Date: 13-4-2023.
- HvR introduces thesis topic and aim of interview: to complement insights found in literature, specifically about climate adaptation and ecosystem services.
- HvR explains the semi-structured character of the interview as well as the neutral/open questions asked to prevent bias, and asks permission to record the interview.
- HvR shows a diagram with VGS typologies.

[00:00:02.160] - HvR Ja, en het zijn vrij, soms vrij open vragen, soms vrij specifiek. Maar als u ergens gewoon geen antwoord op heeft, dan is dat ook goed. Het is meer om het een beetje gestructureerd en onbevooroordeeld te laten zijn natuurlijk voor t wetenschappelijk onderzoek.

Urban heat island mitigation

HvR

Dus ik wil eerst vragen over stedelijke hitte eilanden. Ik heb dus wat literatuur gevonden waarin eigenlijk ze modelleren of meten welk effect groene gevels, of een hele straat met groene gevels, wat voor een invloed kan hebben op de luchttemperatuur en dan vooral is dat natuurlijk relevant als er sprake is van stedelijke hitte eilanden waarbij dan de hitte hoger is dan en ook blijft dan in de omgeving.

[00:00:48.930] - AW Mm hu.

[00:00:49.950] - HvR Nou vroeg ik me eigenlijk af. Welke mechanismen bepalen de impact van een groen systeem op die hitte eiland mitigatie? Dus op welke manier kan een groen systeem, of misschien groen in het algemeen, bijdragen aan hitte eiland-vermindering, dus aan het verlagen lagen van de luchttemperatuur?

[00:01:12.990] - AW Volgens mij zijn dat twee dingen, maar dat is een heel specialistische vraag. Aan de ene kant zorgt het groen op de gevel voor beschaduwing van die bewuste gevel. Ik ben wel eens met een warmtecamera in de gemeente Eindhoven naar buiten gegaan. Ik ben daar gedetacheerd als programmaleider water en klimaatadaptatie en ben ik met een collega met de warmtecamera afgelopen zomer gevels gaan fotograferen en dan zie je gewoon op die warmtecamera als mensen een klimplant langs die gevel hebben, dan is de muur achter die klimplant was geloof ik 29 graden, terwijl de muur een meter daarnaast, waar geen klimplant groeide, was in de veertig graden. Dus daar zat zo richting de vijftien graden verschil tussen op dat moment. Dus los van wat het doet in dat huis met de opwarming van dat bewuste huis is die muur dus ook aan weerkaatsen en daarmee ontstaat dat hitte eiland effect.

[00:02:25.510] - AW Dus hoe meer groene gevels je hebt, hoe minder die muren de hitte weerkaatsen in die bewuste straat. En daarnaast is hoe meer groen zorgt ook voor meer verdamping, wat ook weer voor verkoeling zorgt. Dus dat zijn volgens mij, maar daar ben ik geen expert in, maar dat zijn volgens mij de twee grootste mechanismen. En heb je nog bomen, dan zorgen ze natuurlijk ook nog voor schaduw, maar dat doet in het loopgedeelte. Dat doet natuurlijk gevel begroeiing veel minder. Maar op die manier.

[00:03:08.000] - HvR Inderdaad, dat is ook wat ik had gevonden. Maar dat is goed om dat te bevestigen. En mijn volgende vraag zou zijn: wat zijn geschikte indicatoren om de impact van een groene gevel op het stedelijk hitte eiland effect aan te geven? Want ik kan me voorstellen je hebt natuurlijk de buitentemperatuur van een muur, maar in welke mate geeft dat aan wat de gevoelstemperatuur op straat is?

[00:03:36.970] - AW O niet, denk ik. Tja, dit is een echte hittevraag, dan moet je eigenlijk een hitte specialist hebben. En ik ben zeker geen hitte specialist, dus ik vind het moeilijk beantwoorden.

[00:03:58.440] - HvR Ja. Wat is de relatieve prestatie van die groensystemen? Of kunt u een inschatting maken van die LWS en die groene gevels aan de andere kant?Heeft u een idee van de relatieve prestatie? Dus dus dat bijvoorbeeld het ene systeem beter de luchttemperatuur zou kunnen verminderen dan een ander systeem.

[00:04:28.940] - AW Nou, ik denk dat die living walls uiteindelijk meer doen. Zeker ook jaarrond. En daar zit een verschil tussen hè. Je zei het net zelf al, ze wegen ook vijftig kilo per vierkante meter. Dat betekent natuurlijk ook dat er nog een stuk aarde in zit en een stuk vocht wat je inbrengt, dus ongetwijfeld zullen die systemen meer doen en ook in alle jaargetijden. Natuurlijk kun je groene gevels ['green facades', ed.] doen met planten die jaarrond het blad houden. Maar uiteindelijk wortelen die [GF] toch ergens onderaan de gevel en groeien ze helemaal omhoog en zul je ze moeten snoeien en doen. Aan de andere kant, het grote voordeel is weer dat die [GF] in misschien wel 90% van de huizen bouwtechnisch toegepast kunnen worden. Of er ruimte is in de straat om het te doen is een tweede. Maar ik denk dat de toepasbaarheid van die maatregelen vele malen groter is en in die zin misschien uiteindelijk het effect ook nog groter omdat je het het volume veel groter kan maken.

[00:05:55.360] - HvR Dan heb ik in mijn onderzoek bepaalde parameters gevonden die invloed zouden kunnen hebben op hoe goed een groene gevel eigenlijk de luchttemperatuur kan verminderen.

Dat zijn zowel de systeem componenten, namelijk planten, substraat, maar ook het draagsysteem, het irrigatiesysteem. En daarnaast zijn nog wat ook wat andere parameters. Op stadsniveau is dat dan gebouw-dichtheid, hoogte-breedte ratio van straten en wind. En dan heb je op gebouw niveau ook hoeveelheid groene gevel, de verdampinggraad van planten en de dichtheid van het plantendek. Dat zijn eigenlijk allemaal parameters die ik heb gevonden die een invloed kunnen hebben op de hoeveelheid of de performance van groene gevels op de luchttemperatuur.

[00:07:04.960] - AW Ik kan me voorstellen dat de kleur van de muur, dat dat ook nog uitmaakt.

[00:07:19.060] - HvR Klopt. Ook ja, want het maakt uit hoe de straling achter het plantendek weerkaatst.

[00:07:25.450] - AW Precies ja.

[00:07:26.230] - HvR En ook volgens mij is het ook vooral de muren die dan niet groen zijn, welke kleur die hebben. Ja, eigenlijk beide, dus zowel in de omgeving als bij de groene gevels zelf.

[00:07:41.540] - AW Precies. Zowel achter de plant als daar waar de plant niet is als, als in de omgeving. Enwat volgens mij ook nog uitmaakt, maar dat je zei net al, bij die wind dus oriëntatie van straten ten opzichte van de reguliere windrichting maakt ook heel veel uit. Maar dat is iets wat je lokaal moet bekijken want je zou zeggen van de windrichting is zuidwest over t algemeen maar langs de Maas is dat net effe anders want de rivier heeft dan zoveel invloed daarop. En dat moet je dan ook weer bekijken met de momenten waarop het heel heet is.

[00:08:32.820] - AW Dus op het moment dat wij een en hittegolf hebben, hebben we dan ook zuidwestenwind? Of is er dan oostenwind? Ja dus hoe ga je dan die straten, ik weet in ieder geval wel, op het moment dat je dus een woonwijk hebt waarin het veel doorlucht, dan is er de wind die hitte kan verdrijven, dan scheelt dat enorm als het s avonds afkoelt en in het tempo waarin dat hitte eiland effect eigenlijk weer oplost. Of vermindert in ieder geval.

[00:09:08.370] - HvR Mijn vraag zou dan zijn: Wat zijn dan de belangrijkste parameters of welke hebben de grootste invloed of zijn altijd relevant? Maar daar begrijp ik dus sowieso de wind.

[00:09:29.220] - AW Ja en misschien ook wel natuurlijk de orientatie van de gevel waar je een plant neerzet.

[00:09:39.910] - AW Kijk tot tot 11.00u s ochtends staat de zon zo laag en is ie ook nog niet zo warm dat die opwarming maakt. Het gaat er natuurlijk om- dat je vooral die gevels groen maakt die tussen elf en 3.00 of 4.00u s middags in de zon zitten. Een percentage groene gevels hoeft niet altijd direct iets te zeggen. Als je op de één of andere manier altijd aan de tussen haakjes verkeerde kant neer kunt zetten, dan is het effect van een hoger percentage veel lager dan als je een lager percentage hebt die precies tussen elf en 3.00 of 4.00u s middags in de zon staat.

[00:10:24.510] - HvR Ja, duidelijk. En mijn laatste vraag over het urban heat effect zou dan zijn: wat zijn kritieke ontwerpaspecten voor een groen systeem dat gericht is op het verminderen van het hitte eiland? Uhm, dus eigenlijk: zijn er naast het meenemen van deze parameters nog andere aspecten die belangrijk zijn?

[00:10:53.900] - AW Bedoel je dan om dat hitte eiland effect te verminderen? In de praktijk en in mijn werk is het, wordt vaak een een wat meer opportunistische handelswijze gehanteerd van, het is leuk als we allemaal weten hoe het optimaal zou moeten. Maar uiteindelijk zijn die huizen van particulieren. Daar waar we het voor elkaar krijgen om te doen, geven we bijvoorbeeld subsidie, ook al is het een pand eigenlijk niet helemaal op de goeie plek ligt. Misschien triggert het ook wel weer anderen in de straat om het dan ook te doen hè. Dus wordt er veel meer vanuit een opportunistische benadering geacteerd. En dan is het vooral belangrijk dat we het zo aanleggen of de mensen zodanig advies geven dat die planten het ook gaan doen. Hoe zorg je nou dat die planten voldoende water krijgen? En vaak hebben ze maar, zeker als t huis aan direct aan het trottoir, dus aan de gemeentegrens ligt, dus aan de openbare ruimte, en mensen dus bijvoorbeeld ook geen voortuin hebben. Dan kun je d'r hooguit één tegel uit halen hè. Dus dan heb je dertig centimeter grond waar je het in moet doen. Maar vaak zit die grond ook weer, of kan die grond ook weer, in de regen-schaduw zitten van het huis zelf. Dus het kan wel eens een hele droge plek zijn waar die wortels zitten. Hoe zorg je er nou voor dat die wortels wel genoeg water krijgen, terwijl het ook een hele kritieke locatie is. Want vlak aan de andere kant van die gevels zit de kruipruimte. En water heeft ook gewoon de vervelende neiging om altijd de makkelijkste weg te zoeken. Dus op het moment dat je heel veel water dan vlak voor de gevel in de grond stopt, dan zul je zien dat als je het luik van de kruipruimte opentrekt dat je gewoon eigenlijk een zwembad aan het creëren bent onder je huis, wat ook niet goed is voor vocht, schade enzovoort. Dus het komt best wel nauw hoe je daarmee om gaat .

[00:13:12.300] - AW Ja dus. Het gaat ook vooral om communicatie en de bewoners, of de eigenaren, of gebruikers van die panden vertellen dat ze ook regelmatig water moeten geven bijvoorbeeld. Dat dan weer duurzaam door geen kraanwater. Dus niet die regenpijp in in de grond zetten maar een regenton plaatsen en regelmatig met een emmertje gewoon de planten water geven zodat ze het ook goed blijven doen en die bladeren groen blijven en ze blijven verdampen. Op de warme droge dagen. Wat ook gewoon goed helpt, maar dat kan ook lang niet overal, dat als je gevelgroen combineert, je ziet het in Zuid-Europa steeds meer gebeuren, is dat het groen bijvoorbeeld via lijnen over de straat gespannen wordt. Dus dat je ook een soort pergola achtig idee krijgt, waardoor je ook weer schaduwwerking krijgt en ook de straat zelf minder opwarm,t en je dus ook weer minderdroogte problematiek hebt. Want doordat er meer schaduw is verdampt ook het water, daar waar de wortels van die planten zitten weer minder.

[00:14:38.810] - HvR Ja, dus je geeft ook schaduw op de grond waar de plant zelf geworteld is?

[00:14:43.670] - AW Ja, dus los van dat het voor de mensen prettig is om dan in de schaduw te kunnen lopen. Daarbij wordt er ook minder water verdampt door de zon en blijft dus beschikbaar voor diezelfde plant.

[00:14:59.360] - HvR Interessant, ja. En ook wel goed om te weten inderdaad, dat een deel van het succes van een goede gevel gaat ook heel erg over de verwachtingen managen en goede instructies erbij geven.

[00:15:13.670] - AW Ja, en dat mensen daar serieus mij mee bezig zijn. Je kunt als gemeente bijvoorbeeld, er zit ook een groot verschil tussen particuliere huizen en woningbouw. In particuliere huizen hebben mensen bijvoorbeeld zelf die stellage tegen hun gevel aan geschroefd en die planten daarin gezet en die hebben daar dan eigenaarschap op. Die hebben dat gedaan vanuit een duurzaamheids idee of letterlijk vanuit hittestress of wat dan ook, misschien wel biodiversiteit en de ecologische meerwaarde. Maar op het moment dat het droog is gaan die zelf water geven. Die hoef je eigenlijk niet zo veel te stimuleren. Maar zit je in een complex van een woningbouwvereniging? Ja die mensen huren en in sommige wijken zijn ook gewoon mensen die wel wat anders aan hun hoofd hebben dan het water geven aan de planten, die zitten met hun dagelijkse struggle. Hoeft niet overal te zijn hè, dus ik generaliseer in die zin niet.

[00:16:18.710] - AW Maar de kans bestaat in ieder geval dat dat in die wijken misschien veel minder vanuit de bewoner zelf onderhoud aan het systeem wordt gepleegd. En dan moet je dus als woningbouwvereniging daar zelf misschien iets in doen of dat goed afspreken met die bewoners en zodat ze ook die meerwaarde begrijpen. Dat zij er ook eigenaarschap over krijgen. Maar dat geldt voor alle klimaatadaptatie maatregelen. Dat eigenaarschap en het begrijpen is heel belangrijk. Ga maar eens in een straat het erover hebben dat er vijf parkeerplaatsen weg moeten omdat je een boom gaat planten. Nou dan heb je in heel wat straten heb je ruzie met de bewoners. Hoe moet ik verder lopen en waar moet ik dan auto kwijt? Ja, terwijl als je ervan zegt van jongens het is heet in de zomer en zullen we samen een boom planten? Dan roept iedereen ja, maar als je dan zegt hoeveel parkeer plaatsen dat kost, dan zegt opeens nog maar een heel klein deel ja.

[00:17:21.240] - AW Dus verwachtingsmanagement is wel een belangrijke. En dat is dus los van alle technische achtergrond parameters die je kan opschrijven.

[00:17:35.970] - HvR Ja ja inderdaad, en natuurlijk, omdat dit kader bedoeld is om de toepassing of het gebruik van groene gevels aan te jagen. Dus dan is het goed om erbij te zetten van: er zijn meer implementatie barrières. Dus heuvels om overheen te komen voordat het echt een wijdverspreide maatregel kan zijn.

[00:18:06.890] - AW Precies.

[00:18:08.030] - HvR Dus daar geldt ook niet alleen de technische kant.

[00:18:09.830] - AW Ja nee en dat is wel één van de dingen die ik geleerd heb. Wat ik vooral geleerd heb na mijn studie is dat de maatschappij zelf eigenlijk bepaalt of iets wel of niet slaagt. We kunnen supergoed iets technisch uitwerken en natuurlijk zijn alle technische universiteiten hardstikke belangrijk. Alleen het besef dat dat je met de getalletjes en de technische randvoorwaarden alleen maar kunt uitrekenen of het überhaupt kan ja of nee. Versus voor gaat het ook gebeuren. Daar zit een hele sociale en maatschappelijke component achter en die is in de praktijk zeker net zo moeilijk als de technische. Ja, ik zou het leuk vinden als je in je verhaal daar een kadertje of iets dergelijks over opneemt. Ja, als dat belang aangeeft tussen de combinatie van de technische opleidingen en sociaal maatschappelijke opleidingen om daadwerkelijk tot gedragen oplossingen en gedragsverandering te komen. Gedragsverandering, want dat is in feite wat wat er moet gebeuren als je allemaal groene gevels kwijt wil. Dan moet gedragsverandering bij mensen plaatsvinden. Ja, wij als technische mensen kunnen zorgen voor randvoorwaarden van hoe het in theorie zou moeten. Maar we hebben de maatschappelijke studies en maatschappelijke mensen nodig om die gedragsverandering en samen moeten we dat doen. Dat is in de praktijk mijn werk.

[00:20:03.530] - HvR Ja. Ja, en ik kan me ook voorstellen, zelfs bij een gewone gebouw-eigenaar van een kantoor. Ja, daar is natuurlijk ook een verandering van mindset nodig om van een hele onderhoudsarme gevel naar een servicecontract te gaan, wat die moet aangaan voor dertig jaar om die groene gevel te onderhouden. Dat zou je ook kunnen zien als een gedragsverandering of een sociale verandering.

[00:20:28.960] - AW Zeker een gedragsverandering.

[00:20:30.370] - AW En dat vond ik wel het triggerde me aan het begin wat je zei: van ik maak een multi-criteria analyse en da's heel goed, want in eerste instantie maak je dus met die criteria analyse voor die eigenaar van dat bedrijvenpand inzichtelijk wat de voordelen zijn. Want uiteindelijk maakt die beste man toch een commerciële afweging. En dus moet hij een kosten-batenanalyse hebben. Het is helemaal terecht dat lang niet alle baten zijn in euro's uit te drukken. Maar stiekem als je dat toch probeert zijn er veel meer baten in euro's uit te drukken dan je denkt. En soms met een bandbreedte en ook dan kom je weer op het knelpunt van allerlei technische achtergronden, omdat men er niet achter staat omdat het niet 100% zeker is of accuraat genoeg is.

[00:21:37.990] - AW Maar ik push ze om dat toch te doen en waar ik achter kom: in Nederland heb je met klimaatadaptatie, heeft de gemeente de verplichting om een stresstest te doen. Met die stresstest maak je eigenlijk niks anders inzichtelijk dan: waar wordt het te heet, te nat, te droog en wat wat voor overstromingskans heb je daar bij? Daar krijg je allemaal kaarten uit met bijvoorbeeld hitte eiland effecten of water-op-straat situaties bij een bui die eens in de honderd jaar voorkomt en dan staat er een grote blauwe vlek op op de Stationsstraat, bijvoorbeeld in Utrecht. Ja dat zegt de waterman of vrouw van Utrecht heel veel, maar de ruimtelijk ordenaar al een stuk minder. En iemand die in het sociaal domein werkt helemaal niks. Ja, is dat erg als er één keer in de honderd jaar vijftien centimeter water staat? Maar wat kost het nou?

[00:22:37.030] - AW Nou dat, dat breng ik dus in beeld. Ik reken dat uit wat het kost of om hoeveel huizen gaat het? Komt het water op de parketvloer? Gaan de stroomvoorzieningen er gaan? Nou, al dat soort dingen kun je doorrekenen, al is het maar een orde grootte, waardoor je een inzicht krijgt in wat de kosten zijn als je niets doet. En vervolgens kun je dus zeggen oké maar wat kost t eigenlijk als we die waterdiepte van vijftien centimeter terug willen brengen naar vijf centimeter, want dan staat het netjes tussen stoepranden in en dan hebben we er eigenlijk geen last van. Dus dan moeten we tien centimeter waterberging keer die straat is zoveel kuub. Nou gaan we nadenken, dan wordt het weer opeens een technische vraag, dan laten we die kuub ergens kwijt en dan rekenen we uit wat het kost. En dan heb je opeens een kosten-baten verhaal. En dan snappen wethouders het opeens wel en afdelingshoofden en het hele ruimtelijke domein en zegt ze oké, maar ja, dan uh.

[00:23:37.750] - AW Tuurlijk gaan we dat doen, want met twee van die situaties hebben we de kosten er al uit. Zitten we alleen nog met het grote verschil, en dat is dus ook een hele interessante, tussen dat de kosten en de baten niet altijd bij diezelfde partij liggen. Dus als gemeente doe je dan bijvoorbeeld die kosten maken, terwijl de baten van het niet meer overstromen liggen bij de particulieren. Die natuurlijk via de rioolheffing ook belasting betalen, dus indirect dat ook weer betalen. Waarbij in het voorbeeld wat je net zei kan dat anders liggen. Je moet goed de kosten en de baten in beeld houden voor die bedrijfseigenaar van het pand. Maar op het moment dat bijvoorbeeld zijn pand minder opwarmt in de zomer. Dan is daar de temperatuur en misschien dat mensen zelfs met 10% beter werken. Dan kun je dat ook omrekenen naar geld. En wat die je bespaart aan energie.

[00:24:43.240] - AW Doordat ie geen airco's aan hoeft te zetten kun je ook op geld zetten. En wat je in de winter bespaart aan minder verwarming omdat het ook isolerend werkt kun je ook op geld zetten. Ik ben helemaal eens met de multi-criteria analyse, maar mijn ervaring is wel dat het simpele staatje met kosten en baten, is voor een ondernemer vaak makkelijker ja tegen te zeggen en ook uit te leggen aan de z'n board of aan directeuren. Dan: ja het is voor de omgeving toch wel beter dat er meer vlinders kunnen wonen en meer bijen komen. Ja gaan we daar vijf ton aan uitgeven is dan de vraag? Wij maken chips hè of wij maken weet ik veel wat autolampen, maar wij zijn niet van de bijen en de dingen.

[00:25:39.040] - HvR Ja dus eigenlijk om te overtuigen voor toepassing van een groene gevel moet je ook kijken naar die geldwaarde. En ook inderdaad, ik denk dat het heel interessant is om dan ook goed te kijken: wat is op gebouw niveau, wat op gebieds niveau, zoals dat stedelijke hitte-eiland effect. Heb je als gebouweigenaar die een groene gevel plaatst daar niet heel veel mee te winnen? Of in ieder geval niet direct. Heeft het eigenlijk vaak pas nut als het een gedeelte van een straat dan is bedekt? Dus meer op gebiedsniveau, dus onder andere voor gebouwgebruikers, maar vooral ook de mensen op straat hebben er natuurlijk profijt van, dus dan zou je ook kunnen denken, dat is dan ook voor een gemeente logisch om een subsidie daar op te geven. Of een regeling of stimuleringsmaatregel omdat het is op gebieds- of buurt schaal impact heeft.

[00:26:28.320] - AW Ja precies.

[00:26:28.950] - HvR Terwijl die energiebesparing inderdaad en bijvoorbeeld vastgoedwaarde die omhoog gaat, dat zijn meer echt geld-waardes voor de gebouw eigenaar.

[00:26:41.580] - AW Ja klopt. Dus er zijn veel gemeentes die daar subsidies voor geven. Je zou ook kunnen denken van okay, maar moet je het dan bij alle individuele eigenaren doen of moet je dat met de vereniging van het bedrijventerrein, want het gaat ook om als je medewerkers in de pauze naar buiten kunnen en een rondje kunnen lopen zijn ze veel gezonder dan dat ze na hun zittende werk ook nog eens zittend in de kantine binnen een vette hap gaan eten. En wat levert dat op als ze allemaal gemiddeld drie of vier keer in de week een rondje van een half uur over een groen bedrijventerrein lopen waar het niet te warm of tte heet is, waar ze groen zien, beestjes zien, als ze daar allemaal door een dag minder ziek zijn per jaar, al is maar één dag, dan is dat ook weer op geld te zetten.

[00:27:48.980] - AW Dus we moeten veel meer naar verdienmodellen. En dan is t inderdaad niet één gevel, maar dan zou je als gezamenlijke vereniging van bedrijven op een bedrijventerrein dat allemaal moeten doen.

[00:28:05.130] - HvR Ja inderdaad, ja een andere afstudeerder die heeft inderdaad echt gekeken naar dat monetariseren. Maar ik denk dat het goed is om erbij te zetten van wanneer je kan monetariseren is dat altijd goed eigenlijk om het in ieder geval inzichtelijk te maken wat ongeveer het effect is en hoeveel je er mee kan winnen.

[00:28:23.010] - AW Je kunt meer monetariseren dan je denkt en je moet er vaker over doordenken. Vaak is het secundaire effect is opeens wel te monetariseren en zover kijken vaak mensen niet. Maar maar vaak is het primaire effect misschien alleen kwalitatief, maar het secundaire effect is opeens wel weer op geld te zetten.

[00:28:48.810] - HvR Ja en daar liggen dan aannames onder. Maar ja, dat kan natuurlijk wel, beargumenteren waarom je dat doet of niet.

[00:28:54.020] - AW Ja en als je wil kan je alles onderuit schoppen. Dat is ook zo. Zo is het nou eenmaal. Ja. Maar dan is het ook trekken aan een dood paard he. Dus iemand die er zo in staat

die overtuig je toch niet, dat is dan mijn mening.
[00:29:10.940] - HvR Ja er moet wel ergens een wil zijn.
[00:29:12.800] - AW Ja precies.

Rainwater runoff control

[00:29:14.030] - HvR Ik wilde eigenlijk nog even kijken naar de stormwaterafvoer en eventueel grijswaterzuivering. Ja dus eigenlijk heb ik daarover vergelijkbare vragen als voor het hitte eiland. Ik heb gevonden dat op het gebied van stormwater, of eigenlijk regenwater, maar dan wanneer het veel is, kort gezegd, dat groene gevels daarin kunnen opslaan (in het substraat). Eigenlijk net als groene daken en daarmee dus ook het vertragen van de piek. Dat dat één aspect is wat mogelijk zou kunnen. En het andere aspect is dat het regenwater ook echt gebruikt wordt voor irrigatie. En dat het dan onder andere kan verdampen. Dus dat je daarmee de totale waterafvoer ook iets verminderd.

[00:30:03.200] - AW Ja.

[00:30:03.920] - HvR Klopt het dat die twee mechanismes een rol spelen bij groene gevels?

[00:30:10.090] - AW Nou ja, ze spelen een rol. Alleen als je het hebt over intensieve buien dus echt zomer-onweersbuien die voor water overlast zorgen. Dan valt er zoveel water in zo kort tijd, in 1 uur . Dat die groene gevels niet zo heel veel gaan doen, zeker niet groene gevels [GF], die met het substraat heb je tenminste nog iets wat kan vullen, maar het volume wat je daarin in zo'n korte tijd kwijt kunt, ten opzichte van wat er in dat uur valt, is zo weinig dat je wel superveel groene gevels moet hebben wil je daar effect van zien in waterberging. Als je echter kijkt naar jaarrond naar buien, dan werkt het hartstikke goed. Want negentien van de twintig buien die er vallen die hebben niet die intensiteit dat een substraat zou overlopen, dus dat kan je prima daarin kwijt.

[00:31:21.630] - AW Dus procentueel gezien: een groot deel van van de neerslag die valt kun je in zo'n substraat systeem [LWS] kwijt. In hele lange natte periodes houdt het op gegeven moment ook op hè, want dan zit ie gewoon vol. Dus wat we in de periode januari en zo hadden, ja dat waren dan misschien niet de piek buien, maar het regende zoveel elke dag. En de zon is er niet of nauwelijks, dus verdampt nauwelijks. Dus zodra je er een druppel in gooit loopt die er aan de andere kant er weer overheen, dus dan houdt het ook op. Maar gemiddeld genomen in normale situaties, net als bij groene daken, kun je vrij veel water dus gebruiken of daarin opslaan wat weer voor de verdamping zorgt en dus voor verkoeling. Dat was je ene vraag, dat ging om die piekbuien, en de andere vraag?

[00:32:24.900] - HvR Ja, dat ging eigenlijk over het vertragen van de piek en het andere gedeelte was het verminderen van de totale afvoer omdat het dan gedeeltelijk gebruikt wordt voor irrigatie.

[00:32:33.960] - AW Vermindering van de totale afvoer: ja. Vertragen van de piek: tot op zekere hoogte. Maar dan moeten we ons niet rijk rekenen .

[00:32:41.970] - HvR Ja precies ja. Dus dan gaat het eigenlijk meer om de gewone buien.

[00:32:45.390] - AW Ja.

[00:32:45.480] - HvR En daar gaat het dus niet zozeer om het overstromingsrisico neem ik aan, want dat is dan hoger bij echte intensieve buien. Maar dan gaat het misschien meer om überhaupt gewoon het totale debiet wat de regenwaterafvoer ingaat dat je dat iets vermindert, om de druk daarop te verminderen is sowieso goed lijkt me?

[00:33:07.080] - AW Ja. En wat veel mensen zich niet beseffen: als ze gaan ontharden en dus meer groen gaan aanleggen, dan hebben we geen wateroverlast meer als het heel hard regent. Nou als die echte zomer piek buien vallen van boven de zestig millimeter in 1.00u. Dan reageert daar onverhard oppervlak hetzelfde op als verhard oppervlak. Je moet wel een super zand ondergrond hebben wamt anders slaat die gewoon dicht en ja ik woon hier in Culemborg ja hier de klei is zomers keihard dus het is al bijna verhard oppervlak dus het stroomt gewoon over die klei weg alsof het gewoon asfalt is. Dus voor die echte piekbuien heb je gewoon waterbergingslocaties nodig.

[00:33:55.890] - HvR Ja. Ja duidelijk. Ik heb inderdaad gevonden dat de plant zelf een rol speelt, en ook het substraat voor een groot deel denk ik voor waterbergingscapaciteit.

[00:34:13.190] - AW Ja ja, je kunt wel wat doen met de bodemverbetering. En je kunt dus in het substraat van langs je gevel, maar ook in het stuk onderaan je gevel waar je plantjes neerzet, daar kun je wel het een en ander doen.

[00:34:37.160] - HvR Ja

Greywater treatment

[00:34:37.340] - AW Dan ben ik wel benieuwd wat je er over grijs water wil weten, want daar ben ik een beetje sceptisch over.

[00:34:42.380] - HvR Ik heb een paar studies gevonden over grijswaterzuivering en dan gaat het eigenlijk er om dat je dus de afvoer van bijvoorbeeld badkamer en keuken koppelt aan het irrigatiesysteem. Dus dat je die twee systemen eigenlijk enigszins combineert. En daarbij gaat het dan om vooral die living systems, dus met veel substraat. Als je het grijswater daardoorheen laat filteren, of laat stromen van boven naar beneden, dan hebben een paar studies gevonden dat je dan bepaalde verontreinigingen kan verminderen. Vooral organisch, even uit m'n hoofd. Maar mijn vraag daarbij is: ik neem aan dat het daarvoor nodig is om dan dat het grondsysteem ook heel goed daarop te ontwerpen? Dus om die verbinding te maken met dat systeem, maar ook heel specifiek te kijken wat is dan de verontreiniging? En natuurlijk ook waarvoor ga je dan gebruiken? Veel studies nemen dan aan dat je dan het gefilterde grijswater kan gebruiken om het toilet mee door te spoelen, waardoor dan de eisen voor de waterkwaliteit iets lager zouden zijn.

[00:35:55.770] - AW Dan zouden we dus een systeem moeten maken dat ergens een relatief schone waterstroom heeft. Nou dan gaat toch wel heel erg over gedrag van mensen. Want als jij allerlei wasmiddelen of bleekmiddel gebruikt om je keuken schoon te maken, over het algemeen genomen is, is water wat je door je gootsteen in je keuken spoelt natuurlijk prima her te gebruiken, het is eigenlijk zonde dat zo naar het riool gaat en dat je d'r dan niet nog iets mee doet voordat we het weer schoonmaken op de rioolwaterzuivering. Tot zover ga ik er in mee. Alleen om dan te zeggen van nou we gaan dat water gebruiken voor irrigatie van die systemen. Zou nog kunnen als je, zeker als je een gesloten systeem hebt gemaakt waarmee je zeker weten dat vervolgens niet onderaan het systeem dat dat irrigatie water gewoon in de sloot stroomt of in de grond eruit gaat. Ik denk in de praktijk dat er zo vaak troep in terecht komt dat die planten er misschien wel dood van gaan, omdat het gedrag van mensen gewoon niet zeker is. Dit zijn systemen die je op bijvoorbeeld een flatgebouw zou kunnen doen. In een flatgebouw heb je dat er heel veel inwoners, ook nog is misschien in veel talen, veel verschillende etniciteiten, wonen, dus het is echt wel lastig. Het is überhaupt al lastig om op een goede manier, en daar zijn echt best wel veel fouten in gemaakt, regenwater wat op het dak valt te gebruiken om het toilet door te spoelen. Met een goede aannemer klopt het allemaal bij oplevering, maar vervolgens gaan al die mensen zelf ook lopen klungelen want die ene die zegt van: ik wil van de douche een bad maken en de ander van een bad een douche, en dan wordt de badkamer weer omgedraaid en dan wordt de keuken op een andere plek gezet. Nou noem maar op. Dus er gaan gewoon in de loop der tijd heel veel leidingen door elkaar lopen.

[00:38:19.580] - AW Het is gewoon in het verleden gebeurd dat opeens de kraan aangesloten zit op de grijs waterleiding. Ja dan drink je dus toch regenwater wat op het dak gevallen is. Tja dat kan best een tijd goed gaan, maar als het een keer een warme zomer is en daar zitten bacterien in het water, dan word je doodziek van. Dus: we moeten zeker wat in Nederland met het duurzaamheidsvraagstuk. Dus ik ben het er zeker mee eens dat we veel te veel schoon drinkwater gebruiken voor [verkeerde] toepassingen. In feite dat je in de zomer in je tuin kunt sproeien met schoon drinkwater, dat is eigenlijk een beetje raar natuurlijk hè. Maar ja, dan moeten we dus met z'n allen als het regent het water wel ergens vast houden. Ik doe het zelf ook niet, want ik heb een regenton neergezet, maar ik kwam er heel snel achter dat je niet wil weten hoeveel muggen daarin terecht komen in zomer als je daar water in laat zitten.

[00:39:23.140] - AW Dus ik die regenton is er wel en het werkt als vertraging maar het kraantje aan de onderkant staat altijd open dus hij loopt altijd leeg uiteindelijk. Dus ik ben wel afgekoppeld, ik heb een vertraging met met de berging van een regenton. Is veel te klein voor een dak van een huis hoor. Dus er loopt bij echt een bui, loopt ie over van. Eigenlijk zou je dat water willen vasthouden voor als het twee weken later dertig graden is en mooi weer is, om dan je tuin daarmee sproeien.

[00:39:57.150] - HvR Ja precies. Of dan dat groene systeem. Ja.

[00:39:59.910] - AW Ja. Nou dus. Dus er moet echt wel wat gebeuren. Maar er grijswatersystemen, daar ben ik zelf behoorlijk sceptisch over. Dus ik zie veel meer in, als dit zo'n groene gevel langs een flatgebouw doet, dus dat je ook een groen/blauw dak maakt. Dus dat je al het water wat op de dak valt eigenlijk op dat dak kunt bergen en er ook vrij weinig mensen last van hebben, kan misschien ook wel voor heel veel verkoeling zorgen en dat je dat druppelsgewijs door het [VGS] systeem laat lopen en eventueel op basis van schone energie als er aan de onderkant dus water uitkomt dat je dat gewoon weer terug naar het dak brengt. In plaats van, dan in het riool af te voeren naar de rioolwaterzuivering.

[00:40:55.370] - HvR Dus als ik het goed begrijp niet zozeer die grijswater-kringloop, maar meer dat de hoeveelheid irrigatiewater die je gebruikt voor zo'n groen dak en die groene gevel, dat je daar eigenlijk als bron niet alleen schoon drinkwater maar juist ook dat regenwater, dat dat een meer haalbare verbetering is.

[00:41:16.630] - AW Ja. En dat is best een opgave, want die jaarrond hebben wij in Nederland echt prima genoeg water. Alleen wat te doen als het grootste deel van het water, zoals afgelopen jaar bijvoorbeeld, hebben best kans dat het straks en in mei of juni, dat er al berichten in de krant komen dat we droogte hebben. En dat er misschien geen boeren meer mogen irrigeren of dat er een water-inname-stop komt. Terwijl eigenlijk vanaf november tot nu is het echt super nat geweest en we hebben echt in die zin 'slecht' weer gehad. Alleen hoe zorgen we er nou voor dat, als we dat in ons landelijk gebied al niet voor elkaar krijgen, om dat water vast te houden? Kunnen we dat wel op het niveau van een gebouw? Dat is eigenlijk de vraag. En dat is wel leuk, want dat dat is meteen de technische vraag. Daar kan een volgende student zich in verdiepen.

[00:42:15.940] - HvR Ja, inderdaad.

[00:42:16.870] - AW Ja, hoe zorg je nou, zonder dat je overlast krijgt, dat je water wat in de periode van oktober tot april valt, dat je dat tot in augustus kunt gebruiken. En dan in de zomer diezelfde berging weer kunt vullen met die piekbuien. Het tweede wat dat systeem zou moeten kunnen. Ergens in juni, juli, augustus komen een aantal van die grote piekbuien langs. Dus dan zou dat systeem zodanig moeten zijn dat je dus die enorme piek van zestig millimeter in 1 uur of zeventig millimeter in 1 uur, wat je niet gewoon op het dak kunt kunt vasthouden. Om eigenlijk met één zo'n bui weer twee weken vooruit te kunnen, aan irrigatiewater. In plaats van dat ie twee dagen later al het water alweer weg is en je gevel weer staat te verdrogen .

[00:43:15.570] - HvR Ja.

[00:43:16.920] - AW Want dat is wel een aandachtspunt als we gaan vergroenen. Dat moet er niet toe leiden dat we een veel grotere drinkwater vraag kan krijgen, want die is niet beschikbaar in Nederland.

[00:43:33.500] - HvR Dus tegelijk met het vergroenen moet je ook goed kijken naar de water toevoer. En waar je dat vandaan haalt.

[00:43:40.020] - AW Dus los van het type planten die daar dus misschien ook wel tegen moeten kunnen dat ze een tijdje een relatief droge periode hebben. Ja er is van alles te ontwikkelen. Maar goed dan dan hebben we het weer over nieuwbouw en en een flatgebouw is dan weer makkelijker dan de rijtjeshuizen. Voor bestaande bouw is dat natuurlijk alweer al heel wat lastiger ja. Dus dat is ook wel goed om in je onderzoek continu onderscheid te maken tussen nieuwbouw en bestaande bouw. Toen we net na de tweede wereldoorlog Nederland gingen opbouwen, toen was alles nieuw. Nu hebben ook een enorme woningbouwopgave, dus ook een enorme kans om het het die woningen goed te doen. Maar daar staat tegenover dat we gewoon ook heel veel bestaande huizen hebben. Ja en dat areaal is nog veel groter. Dus als we echt richting de gezonde stad willen gaan en echt verbetering willen maken, dan gaat het er ook vooral om van: hoe gaan we nou die bestaande stad verbeteren en wat voor systemen zou je nou kunnen bedenken om die groene gevels die je eventueel bij bestaande gebouwen kunt neerzetten, om die van water te voorzien zonder dat we dat uit kraanwater moeten halen?

[00:45:00.520] - AW Want de gemeente zit altijd met het punt dat een waterberging binnen 48 uur weer leeg moet zijn omdat hij dan weer beschikbaar moet zijn voor de volgende piekbui. Dus je zit heel erg met een soort early warning systems van: Okay, je houdt het water in die waterberging vast totdat er onweersbuien voorspeld worden, dan laat je dat die dingen leeglopen 48 uur van tevoren. Zodat ze beschikbaar zijn voor die onweersbui. Ja dan heb je natuurlijk pech als die onweersbui niet pech valt. Dan heb je wel het water weg laten lopen, maar je hebt geen aanvulling gekregen. Nou dan moet je misschien een keer wel aan drinkwater gaan. Er is van alles voor te verzinnen.

[00:45:59.470] - HvR Ja. Water is een heel onderwerp op zich in de groene gevel business. Maar wel heel goed om dat goed te onderscheiden. En ik had eerst een focus op die grijswaterzuivering. Maar ik denk nu eigenlijk dat irrigatiewater en hoe je dat organiseert dat dat eigenlijk nog een grotere haalbaarheid of kans van slagen heeft. Het is wel goed om even die realistische blik te hebben ten opzichte van de theoretische ontwikkelingen die er in het onderzoek zijn. Maar hoe haalbaar is dat en wat is de kans dat het op grote schaal wordt toegepast? Dat is natuurlijk altijd goed om mee te nemen.

Design process [00:46:44.400] - HvR Ik had ook nog wat vragen over het ontwerpproces voor groene gevels, maar ik denk dat we dat al wel zo'n beetje hebben behandeld. Ging eigenlijk vooral over: in hoeverre worden kosten-baten, of juist dus ook de bredere baten, dus die ecosysteemdiensten op gebiedsniveau, in hoeverre wordt dat al meegenomen in het ontwerpproces? Maar ik denk dat dat wel gaat over die kosten-baten analyse waar we het net over hadden. Dus dat je als ontwerper wel kan aangeven van: dit zijn de voordelen, maar dat het uiteindelijk voor de beslissing ja of nee voor een groene gevel, dat daar gemotoriseerde waarden wel van belang zijn.

[00:47:27.940] - AW Ja en wat dit een beetje lastig maakt is dat klimaat adaptatie een hot item is de laatste vijf jaar, misschien tien.. Daarvoor deden we ook wel wat, maar dan was het eigenlijk over het waterbeheer voor intensieve neerslaggebeurtenissen.

[00:47:49.330] - HvR Ja.

[00:47:50.320] - AW Wat je nu ziet is dat de overheid, dus de openbare ruimte, nu langzaam wel meer stuurt. Als er projecten of herinrichtingen zijn, dat die klimaat robuust moeten worden. Of in ieder geval dat er een afweging wordt gemaakt: gaan we hier een klimaatrobuuste situatie realiseren of is de functie, zoals busbaan, belangrijker? Op particulier terrein begint dat nu eigenlijk. En groene gevels is iets wat pal tegen gebouwen staat. Dan heb je het dus over woningbouwcorporaties of inderdaad een hele hoop ondernemers die een eigen pand hebben. Of individuele woningen. Nou individuele woningen staat nog helemaal in de kinderschoenen. We krijgen wel steeds meer subsidie-aanvragen voor groene daken, dus daar probeert men wel. Dat is al een stuk bekender. Ik denk dat daarmee daar wel een inhaalslag kan plaatsvinden, dat het niet zo lang hoeft te duren als het bij groene daken duurde.

[00:49:03.870] - AW Als ze eenmaal groene daken hebben, ja waarom dan niet ook een groene gevel? Maar in ieder geval heb je met heel veel partijen te maken, want dat zijn allemaal individuele partijen. Dus dat is een verschil met als je met een gemeente te maken hebt in de openbare ruimte. Ja en het is de benadering, maar dan zitten we weer op de maatschappelijke kant en de gedragsverandering. De benadering is anders dan dat je de openbare ruimte moet benaderen. En dat maakt dus ook uit met dat monetariseren, dat op geld zetten van die kosten baten. Bij een overheid kom je makkelijker weg met die kwalitatieve analyses. Omdat die daar intrinsiek in gemotiveerd zijn. Die zitten minder op de business case van het verhaal. Bij particuliere partijen zit je toch meer op de business case.

[00:50:12.330] - AW Dus die multi-criteria analyse werkt beter, in mijn beleving, voor de openbare ruimte dan voor particuliere ruimte. Of in ieder geval, hij werkt wel goed, alleen zullen ze in de praktijk vaak een doorvertaling vragen naar een kosten-baten analyse dus.

[00:50:34.740] - AW Ik moet naar een volgend overleg. Ik hoop dat je er wat aan gehad hebt en dat je er iets mee kunt.

[00:50:40.170] - HvR Ja heel erg, even een goede nieuwe blik dus ik ga er mee aan de slag. Bedankt in ieder geval.

[00:50:49.590] - AW Hardstikke mooi en succes.

11.4.3 Interview B: Maria Alexiou

Maria Alexiou is a Project Facade and Building Engineer at RHDHV, with experience in VGS design, for example in data centre projects.

Introduction

- Speakers: Hugo van Reeuwijk (HvR) and Maria Alexiou (MA)
- Date: 12-4-2023
- HvR introduces thesis topic and aim of interview: to complement insights found in literature, specifically about designing for functionality and the design process.
- HvR explains the semi-structured character of the interview as well as the neutral/open questions asked to prevent bias, and asks permission to record the interview.
- HvR shows a diagram with VGS typologies.

Design criteria

[00:00:09.800] - HvR [Shows preliminary version of value tree] Of course, if you have thoughts about this framework or other things that are important, let me know.

[00:00:20.040] - MA Yeah. Look, in terms of environmental issues, maybe something you can add that I don't see here is that the fact that with the green facade systems, you can achieve reduction of heat islands. Actually, this is very good in terms of the environment.

[00:00:39.460] - HvR Yeah.

[00:00:41.600] - MA Except if you have it somewhere else. And if you don't have it, put it a bit more specific. The heat island reduction is a very good aspect, environmental aspect. So there I would add this out. But for the CO2, because it is important actually for the CO2, because it's a way to absorb, let's say, the carbon dioxide through the plants.

[00:01:15.200] - HvR Yeah.

[00:01:16.100] - MA This is good. What is the PM? Can you explain to me a bit? What is the PM there?

[00:01:24.730] - HvR That's the particle matter. So that's the fine dust. And then you have the PM 10 or PM 2.5 or PM 1. Different leaves have different capacity to collect it from the air. So it's mainly from traffic, that's the source, and then it can reduce that concentration in the air. And it's mostly in street canyons, so where it's very high buildings with narrow streets. There they can take up the most PM basically, particle matter.

[00:02:04.190] - MA For the noise reduction, you say ambient and emergent. So, in which cases it is emergent? Ambient, I can understand. It's like what we call actually in building physics, I don't know if you spoke with any specialist, it's what we call R A traffic. It's this value, the R A traffic value. So when it's a lot of traffic around and you have the green facade, you are able to absorb some of the noise. It works in the terms of noise absorption. But what about the emergent in this case?

[00:02:45.990] - HvR Yeah. So with it, I meant, for example, a motorcycle that comes along at night. I'm not totally sure, but it's more about the noise that is not constant, but peak. And I found one study where it's a bit a different performance for ambient noise and for emergent noise. So that's why I divided it in that way. But I still need to look into that theme a bit more. So I'm not sure if I will keep that division there.

[00:03:22.570] - MA Because, Hugo, I think the green systems, okay, they can provide some noise reduction.

[00:03:29.770] - HvR Yeah, yeah.

[00:03:31.190] - MA But for emergency, okay, of course, if it provides for ambulance, it provides for emergency. So I don't know if it makes very much sense to make this division, but okay, whatever you prefer. I mean, just think when you make divisions, will it help you to draw different conclusion out of each division or not?

[00:03:54.160] - MA Or is one a bit more specific than the other, but the conclusions are almost the same. So maybe before you do such divisions, think, okay, what is the conclusion out of each category? It's a subcategory. It may be a general conclusion you need to take into account for noise reduction and not to be super specific. Think of it. I don't say it's wrong, it's not wrong. It's how you want to drive this research on. How specific you want to be. Okay, the other is. I want us to go through everything just to have a full idea and then I can speak a bit more for functionality. The other is what is it? Mitigation?

[00:04:37.460] - HvR That is the urban heat island you were talking about. So included that here.

[00:04:43.990] - MA Because you had it like this, I wasn't sure what it could be. Actually, Hugo, maybe when you want to use such... How to say this?

[00:04:56.470] - HvR That you don't want to use the abbreviations.

[00:04:59.420] - MA Maybe put a legend, Hugo, to explain what is it. And then I will not have this comment because then I understand exactly what is it. Yeah, I think a legend would be very helpful in this case for someone who first time sees this.

[00:05:20.820] - MA And what do you want? You have these three categories. For example, you have categories for each one of them. What do you want to do with these categories? You want to refer to each one of them separately?

[00:05:33.880] - HvR You mean the environmental, social, economic?

[00:05:37.870] - MA I mean the subcategories for the noise reduction, for example. Ambient and emergent. What do you want to do with these two categories?

[00:05:45.450] - HvR I wanted to get performances for every subcriterium per type of system, basically. So for example, for particulate matter, I can assume that it's always with a climber. And then when I find in the research, okay, climbers have better performance than plants that are very often used on living wall systems. I give these green facades a higher score. And then, for example, for some things, I will use a 7 point scale. So then it's 1 is very poor and 7 is excellent and then in between, so that you have actually a relative performance.

[00:06:26.930] - MA For the noise reduction, I can give you a hint. When you use systems like the continuous felt system, this continuous felt system can provide very good sound absorption because they have this felt that it's a sound absorption material, but it's also very good. When you have different modular systems, then you have sound leaks when you have different panels. Every time that you have the seam in between panels, you have a sound leak. So in terms of sound reduction, a continuous system is better for sound absorption, let's say. I can give you this as a hint. And another hint is if it's a system which is also, you remember in my presentation that I was saying about systems that they have as a substrate, like a stone wool based material. These systems also provide better sound insulation than soil based systems. Because in general, when you use, even in the interior, but also in the exterior, when you use mineral wool based or stone wool based materials, they provide very good sound insulation.

[00:07:46.110] - HvR Yeah.

[00:07:47.390] - MA So for sound insulation, this type of systems are better than the soil based systems. Yeah. This I can give it to you as a hint to know how to categorise it.

[00:07:59.720] - MA Then for the heat island, let's think. Or you have already categorised everything?

[00:08:06.500] - HvR Well, I found all the information and now I just still need to write, what performance do I assume? What exact value? So I don't know out of my mind what performances I gave to what system. For urban heat island effect, there were a lot of other parameters that influence the performance , so climate and then how wide the street is, for example.

[00:08:37.620] - MA But okay, have this in mind also. So for the noise reduction, the materialization of the system, the materials that the system consists of are very important.

[00:08:47.810] - HvR Yeah.

[00:08:48.190] - MA It is not only all the surroundings and how wide is the road or how far is the facade from the road and all this. Okay, these are very general aspects that are important, but also the materialization of each system is also important for the noise reduction.

[00:09:07.880] - MA For the other category that you have about the urban heat island mitigation, the most important part, I think, has to do with the vegetation. Because when you have really dense vegetation, this provides a better passive cooling strategy in general. So normally, more dense systems, they're better. So I wouldn't choose for this category, for example, a climber plant system. I don't remember exactly the categories you used, the modular trellis or in general, the climber plant systems, they can help only when they are fully grown plants there because it takes time for the plants to grow. But there are systems that already the plants are there and they are already pre planted. And again, they have even this type of insulation material as a substrate. And in this case, they can already provide better control of the ambient temperature. So have this in mind. However, the climber plants, because they have a very good...

[00:10:26.320] - MA Most of the plants that climb there, they can really grow very much. In its full potential, it can work very well. In its full, I don't know, but in its full potential when it's fully grown up this plant. So this is also a consideration, I think, for the urban heat island mitigation, I would say that their vegetation is the most important aspect.

[00:10:49.520] - HvR Yeah, vegetation.

[00:10:52.130] - MA What else can it affect the urban heat island? What have you put in your research? Do you want to discuss a bit more about this, or you have the information you need?

[00:11:03.630] - HvR Yeah, well, I already found a lot about it, I think I already have enough information on that, basically. But it's good that you say, like, vegetation is the most important system component there because, of course, you have also the substrate a little bit, maybe that it matters just, maybe some evapotranspiration from the soil. But I guess it would be mostly the vegetation.

[00:11:38.490] - MA And also if you have a green facade that this it's properly also watered, irrigated, because of the irrigation itself, you drop the ambient temperature also because there is... Because of the moisture on the plant, the air temperature also drops. So also, if you have a good irrigation of the system, this can also help. So if the plant stay very dry, of course, this doesn't help at all with the reduction of the urban heat island. This is always a consideration maybe you can take into account.

[00:12:19.780] - HvR Yeah. Because of course, more water use would be worse for the... Well, the total water demand, basically. And then there's a bit of a balance, or a trade off there, basically.

[00:12:32.550] - MA Now for the water management, GW is the gray water or something else?

[00:12:41.750] - HvR Yes. That's gray water.

[00:12:45.070] - MA And the QL?

[00:12:47.340] - HvR That's qualitative, but that's just my own indication for that I will use a score that is qualitative because there are only two studies where they really put a percentage on the amount of run-off that they reduced, and other studies were more qualitative. That's why basically there's not enough evidence to say: a certain green facade will reduce it with that peak with so much

[00:13:42.080] - MA I understand. And the gray water treatment, do you want, for example, to store the rainwater which is left over and use it for irrigation again? How do you think of it, of the gray water?

[00:13:55.030] - HvR Yeah. So the gray water will then come... Basically, I divided this theme in then rainwater for the run off and then gray water. So that would be the water from everything.

[00:14:06.910] - MA From the toilets?

[00:14:08.210] - HvR Everything except the toilets. Including toilet flush would be wastewater. That's a bit too polluted. But most research was on gray water, so from the bathroom or kitchen.

And then you would need a separate system to bring that gray water to the top of a living wall system and then let it percolate through. And then when there's a lot of substrate, basically, that can filter out certain nutrients or pollutants, and then that water is cleaned as much that it can be used again for toilets, for example, because then you don't, of course... So that's basically the idea. And there are some studies where they measure all the concentrations of the pollutants, and basically they concluded, I think, that the substrate is basically the critical factor. So when there's more volume of substrate, it will be better in reducing the pollutants than, for example, in a felt system that has less substrate, less volume, so also less pollutant reduction.

[00:15:25.160] - MA Okay, I understand. Okay, nice. And then for the water management, though, Hugo, I don't know if it is on the system itself that you choose on the green facade system or it is also the irrigation system? You understand what I mean? Because every green facade system, every subcontractor can provide its own irrigation system and provide also such solutions, say, for water retention or for using of rainwater for irrigation and all these things. And even all green systems can provide such solutions. Which system is better? I don't know, but.

[00:16:10.460] - HvR Yeah.

[00:16:11.320] - MA They provide almost the same type of solutions most of the time. With the water storage tank. So I don't know. Think of it. But what you said now for the felt, you are right in terms of the pollutants. But think of it if it's really the water management has to do with the green facade system itself or the irrigation system used.

[00:16:40.270] - HvR It's more that I use it here as an... It's more like an extra benefit that you can implement with a green system. And irrigation is more, of course, necessary to keep it alive. So that's why I use these aspects here for the water management. But it's true that irrigation is, of course, basically a functionality need, you could say.

[00:17:08.730] - MA Because, for example, you can choose for a system that uses indeed the gray water to irrigate your green facade or uses the stored rainwater. So use both of these two strategies you have set up here.

[00:17:28.570] - MA To irrigate your green facade system.

[00:17:34.310] - HvR Yeah. So combining the gray water with the rainwater storage. Yeah, okay.

[00:17:38.660] - MA Just as a consideration.

[00:17:40.230] - MA Then for biodiversity, this is a very big discussion within engineers, you saw in the meeting, because sometimes you really don't want a lot of insects and smaller animals. You don't want a lot of insects on the facade or mice or anything like this. So you really want to prevent it in a way. But this really depends on the type of the building, of course. And on the other hand, most of the times the green facade systems we apply are fully closed facades, most of the times we apply it in combination with sandwich panel system. So it's a fully closed facade and then it really doesn't matter. It really doesn't matter if there are insects or not. And you can really say, okay, I really like to use it to improve the biodiversity. So when we speak about biodiversity, we need to make sure the function of the building.

[00:18:45.180] - MA And also the type of the facade, which is the underlayment of the green facade system. So if it is a fully closed-off facade, that can work completely on its own and provide itself water tightness and be completely a layer which protects the building from the outside conditions, which is, for example, a metal sandwich panel facade, then it really doesn't play a role at all if there are insects there or not. Because I saw the guys from MEP were very actually very keen on not having it, avoiding all these issues. But actually, it's not an issue if you choose for the right underlayment system. This is also consideration you can think of it. What is the other element system of your facade?

[00:19:47.660] - MA Then for social, you can say more about this. I will not go more in depth on the social aspect because you know a lot on this.

[00:19:58.650] - MA You don't need a specialist to let you know about the social aspects.

[00:20:02.360] - MA For economic now, for economic, indeed, installation, maintenance, and disposal, this is very important.

[00:20:10.540] - MA Something else, I don't know, Hugo, were you in the suppliers meeting, the [name of supplier company] meeting? One of the questions that I did to them, which is important to take into account, is that if it's a modular system, for example, can it fulfill multiple life cyles the system? For example, can I reuse it in another building? Is it reusable? Is it recyclable? Because some systems are recyclable actually. This can reduce the life cycle costs, which is also important. It's a part of the cost analysis. You really make sure that the system, it's a robust system that can last for longer and you can reuse it. This is also good.

[00:21:05.360] - HvR Do you already know if there are systems that are, or parts of systems, that are reusable or that they say that is reusable, at least?

[00:21:14.290] - MA Most of the times, Hugo, when you have these modular systems that there is aluminium or steel substructure behind, you can definitely use it.

[00:21:25.010] - HvR Yeah, exactly. Because it's so strong.

[00:21:26.490] - MA Aluminium and steel is really recyclable and you can really reuse it. It can be both recyclable and reusable. It is not very good in terms of sustainability because you use metal substructure. But on the other hand, you can reuse it. It can be more circular, you understand? This is a good point. But for example, the felt system, Hugo, some of the felt systems, I don't know in which specific one you speak about, they just really fix directly the felt onto the underlayment, just with fixings without any substructure. In this case [LWSC]. This system [LWSC]... There are not parts you can reuse, actually. It stays on this building and then you cannot reuse it somewhere else, I think. For the felt, the cloth system.

[00:22:36.870] - MA Also the climber plant system [GF], all these steel rows and all these steel brackets and all these parts, you can really reuse it for another system. It's a good system if you think about the end of life, what you say there is disposal. What happens with the end of life of the system?

[00:22:57.210] - MA What is the next step? Can you reuse it or not? Can you recycle some of the materials or not?

[00:23:04.460] - MA Maintenance is of course very important, but this is not up to very much to the engineering aspect. We discussed it also in the meeting. It's up to really the client to sign up a maintenance contract and make sure that the facade is properly maintained.

[00:23:22.680] - MA And installation costs, something important to take into account, the cost can have to do also with the transport itself. So if you choose for local suppliers, you can put even transport on this categories, I would say, because if you choose for local suppliers, then you directly reduce the transport cost. Because you choose for more local suppliers. If you choose for prefabricated systems, because everything more prefabricated, modular systems, I would say, that they are very easy to be installed, you save a lot of time in terms of installation. So also the installation cost can be reduced. For example, in a climber wall system [GF], because everything has to be fixed on site, the installation cost can be higher actually than a modular system that you just have a few fixings to do and it's done.

[00:24:30.880] - MA Because the installation time is longer, then installation cost is also larger.

[00:24:36.410] - HvR So the labour is a bigger part?

[00:24:38.520] - MA The labour is more intensive in a climber wall system, let's say. Then this directly increases a lot the installation. But then for the maintenance, you know already, I mean, maintenance is quite a cost in these systems.

[00:24:58.860] - HvR Yeah, true.

[00:25:00.010] - MA Long maintenance, they say it's the climber wall system. But on the other hand, even in these systems, you saw that it really depends. We have to take into account in which climate we apply such systems. If it's a really dry climate or with really warm and dry winters, for example, this system would not be a really good choice because then you will really need to irrigate it. Then you will have increased maintenance costs. So maintenance cost is not only a category on its own, that you think only about maintenance, purely. But it also has to do also with the location itself. When you choose a system, choose also according to the climate itself. Some of the systems are actually more independent in terms of the climate. So maybe in this case, it will be a better option. It is a more safe option.

[00:26:06.060] - HvR And then living more systems would maybe be more independent, because they need watering anyway.

[00:26:19.260] - MA Exactly. Just consider this aspect. And for the cost include also transport, I would say it's quite important.

[00:26:24.430] - HvR It's part of the installation, exactly. But then I can say, because now I assumed one study where they had to drive 300 kilometres from a city to the other city. But then I can, of course, see, okay, what if you lowered it and what if you make it higher and give like... Basically, of course, I cannot put everything in this framework or in one score, but then I wanted to give a score and then also give some recommendations. So for example, then it would be good to include: how can you lower the installation cost: by choosing local suppliers. Because then the transportation cost can be lowered and I can say, oh, that's so much percent of the total installation cost.

[00:27:08.000] - MA Yes exactly.

[00:27:10.040] - MA Okay. Then for the facade benefits. Yes, indeed. How do you define the facade longevity? How do you define this?

[00:27:30.450] - HvR Well, so they... Some studies, mostly LCA or economic studies, they assumed that the facade underneath a living wall system or a very covering system basically, would need less painting or maintenance when it's plaster. So for a plaster facade. Basically, that's the only real evidence I found for facade longevity. But of course, there's less wind and rain. In theory, you could say it's less prone to weather, so you need less maintenance. Or you can... Basically, the period before you need maintenance for the facade underneath is longer. So then they, for example, they use not 30 years, but 45 years before maintenance would be necessary. But I think I will make the point that it's very theoretical and not very proven yet.

[00:28:27.430] - MA Please do it because there are systems. I will refer again to sandwich panel system. They have a lifespan of 60 years. They are one of the most robust systems.

[00:28:45.640] - MA So there are systems already without using any green facades that they have a longer life than a green facade system.

[00:28:55.070] - MA So I really think the real estate value is a very important aspect of the benefits.

[00:28:59.590] - HvR Uhu.

[00:29:00.880] - MA Energy savings also, but do you have any studies to prove this? Because most of the times we say, okay, it's a good means of passive cooling, or it can provide also an extra insulation layer. But do you have any studies to prove this?

[00:29:17.520] - HvR Well, there are a lot of studies that use the temperature on the outside of the building walls, so underneath the green system on the outer surface of the building wall, basically. There are a lot of studies about that. They also have different scores per climate and between heating and cooling. Then there are a few studies about energy savings in percentages, basically. Then they look at, for a case study, for example, they look at the total kilowatt hours for a year needed for cooling, and then how much less was used with a green system. I think I will use those data for the performance because then it's in a percentage of the total heating load or cooling loads, basically.

[00:30:10.700] - MA Do you know what? Because I know that there are not many other RHDHV projects that they did such calculations to prove it. They use green facade systems a lot, but actually we don't have proof with numbers and calculations that, how much is the impact. There is an impact, but how much is the impact? We don't do as a company, calculations.

[00:30:35.620] - HvR Yeah.

[00:30:36.240] - MA Don't know if you spoke with [name colleague] already about this, but I don't think... Maybe he has done his calculations, but from what I know, from my knowledge, they haven't done any. Normally, they don't do calculations on it. The impact of using the green facade on cooling, for example, or on heating.

[00:30:56.160] - HvR No, exactly. It's also very difficult to model it because you need to assume certain insulation values for the vegetation, but you don't know how fast it will grow or how dense it will exactly be. So that's very difficult. And also with the winds and the orientation and the climate, those are all impacting. So it will be more of an assumption here, I think, the score that I will give. So it's more the potential there is basically.

[00:31:28.340] - MA Yeah I understand.

[00:31:35.240] - MA Now we go to the important part of functionality. Structural suitability. Okay, look, most of the systems, there is a wide range of systems. But in general, if you have a steel structure or a concrete structure behind it, they can really handle a very big weight. So it cannot be very much a limiting factor. It can happen when you have systems like silty based systems or wooden based systems and you want to apply green facades. But Hugo, I don't know many examples actually of such combinations.

[00:32:18.540] - HvR Yeah, okay.

[00:32:20.500] - MA Yes, it's good that we check. It's important that we check on the weight before we choose the system. And if the primary structure can handle these loads. But most of the times, if it is steel based structure or concrete based, they can really handle a lot. So I wouldn't foresee any problems on this.

[00:32:51.620] - HvR No, it's more about the mounting, for example, that you need to think about that.

[00:32:57.140] - MA For the mounting, another thing you need to think about will go is fire safety. Because if you want to mount in a very safe way, you don't mount directly on the... Most of the times we have a metal sandwich panel facade on the back. You don't mount directly on the metal sandwich panel facade. You have to penetrate through the panels and mount on the primary structure behind, which will be concrete or it will be steel. And this penetration really has to be handled in such a way as to create a barrier, fire barrier. You really have to make it fireproof, this penetration. And the reason why they do this, they penetrate and they actually fix directly on the primary structure.

[00:33:54.960] - MA Another thing for you to know is for the what we call AE. So to maintain the structural integrity of the facade when the fire catches, so as not to collapse directly. Because a metal sandwich panel is quite flammable material, so it will start collapsing much easier than the steel structure behind. But if you fix your system and your steel structure of the green system directly on the primary structure, it will stay intact for much longer. So you can ensure the structural integrity, what we call AE in fire safety. This is important and most of the buildings, especially data centres, they have very high fire requirements or distribution centres, the mounting process, what I explained to you now, is quite important. Because fire safety is a very big part to take into account.

[00:35:01.410] - MA This is quite important. Then what else you can think about? Considerations on functionality. Then what else? When you penetrate fully, it's also maybe water tightness to take into account. But with the right detailing, you can, of course, mitigate these issues.

[00:35:26.000] - HvR With a layer?

[00:35:30.250] - MA It can be like an NPDM membrane or...These are the things that you can take into account. I hope I was a bit helpful. I don't know.

[00:35:45.320] - HvR Yeah, you were. A lot. I was just wondering that if you could say... Well, are there other building characteristics that you need to take into account to design for functionality. Besides that load bearing capacity or mounting or water tightness?

[00:36:11.600] - MA Fire safety I said, very important. Let me think. I think this is the most important, Hugo, actually. You have covered, I think, most of the stuff in this framework. And in terms of sustainability now, because you have put environmental reasons, but are you planning to put also sustainability as one of the categories or not?

[00:36:56.320] - HvR Yeah. I wanted to, but then the LCA score, for example, has already... Sometimes it includes, for example, the water demands, or it includes some of the environmental benefits for noise reduction, but it doesn't include other benefits. I think I won't use the total LCA value, but more the part of it, for example, for materials that still has a higher CO2 burden than the others. So I will try to give some scores on parts of the environmental score, but not really the total one because it is a lot of overlap with the benefits that I'm using. And then there's double counting would be included. So I'm still seeing how I can integrate that. But of course, I think it would be good to include some sustainability score.

[00:37:59.070] - MA Because for example, when you say that the building can... For example, sustainability, you know, it doesn't have to do only with biodiversity or only with the climate change, energy efficiency and all this. It has to do also with the well-being. So the social aspect that you analysed before is part of the sustainability, the wellbeing and the social aspect have also to do with the sustainability. I try to explain to you because some people will have it completely on their mind that sustainability is only biodiversity, improving the biodiversity, energy efficiency, material transition, energy generation, and net zero carbon buildings, net zero energy buildings. It's not only this. So even the social aspect that you... Maybe you can have a general conclusion in the end because you already tackled all these different aspects, but some of these aspects, they are really related to sustainability. So you can really say that in all our systems actually you will use, it can improve the sustainability. It can really facilitate sustainability goals in a project when you apply green system.

[00:39:29.630] - MA And it's more of course, it has to do more with sustainability things like climate change or biodiversity or also well-being. But in general, yeah, you can give it as a final conclusion. I think you should put it somewhere in your research. I wouldn't advise you to do a full analysis because it's very complex issue. And then you should have started your, let's say, your thesis completely on focus on this, let's say, and do it with this way. You have to start it in a different way if you want to do this.

[00:40:12.950] - MA Yeah, then I should have focused on that.

[00:40:14.180] - MA Just the general conclusion, I don't know. Maybe it would be nice.

[00:40:20.120] - MA Because I wanted to share something with you because actually I'm very focused a lot as an engineer on sustainability aspects. And we worked previously this previous year with my colleague on a sustainability framework. I want to show you what a green system can improve on this. Let me show you a bit. I will share a bit the framework with you to show you how it works. I don't know if you can use it directly, but just a food for thought, let's say. Let's close off with this.

[00:41:06.530] – MA Okay, this is the framework we created. So this is to help the company to set up sustainability goals, to set up objectives in order to facilitate the goals. It shows what strategies you can use to achieve the goals of sustainability and in which part of the building they are applicable. If it's in the green facades, it will be on the skin, for example, let's say. So these are the three different sustainability themes you will have from the RHDHV company, from our company.

[00:41:51.940] - MA The one has to do with climate change and adaption. The other has to do with the resources and circularity. The other with biodiversity and natural systems. And you can choose yourself. You see, I just click on it. Some of the objectives can be, for example, to reduce urban heat island effect or maximize energy or design for adaptability. And if I choose on this, you see that the green facade is actually there.

[00:42:15.950] - MA But I have put a couple of strategies here. Then if I go back again on the biodiversity and natural systems, you can conserve existing biodiversity, but you can also maximize. Again, green roof and green facade comes here again.

[00:42:37.740] - MA Reduction of embodied carbon. You see, there are many different ways to do it. And this can help you also when you use, for example, prefabrication, you can reduce CO2 emissions during construction, or modularity, modular systems, or easily demountable building products. So maybe this you can use your research and you choose for green facade systems that are easily demountable and they are, for example, modular. With this way, you can reduce CO2 emissions during construction. So it leads to reduction of embodied carbon of the building. In case of such a system.

[00:43:18.490] - MA Choice of local suppliers. I come back to what I tell you before and I can share the link with you because this is open to all our colleagues. I really think it has to do generally with sustainability, but maybe it can help you set up and I don't know, help you a bit with the way of thinking, maybe. Yeah. Sourcing of local suppliers or sourcing of local materials, again, leads to reduction of embodied carbon.

[00:43:48.240] - MA And what I told you before about the end of life stage, if you use demountable products, you can easily also reuse it in another building. Then you can facilitate multiple life cycles. You see all these things. The reason I tell you all this, I have done a lot of research on this, on the sustainability aspect.

[00:44:10.540] - MA I would really like to share this link with you. I have shared with a couple of colleagues already. We try to make a check if this works and helps us out in projects. So check it out a bit and see, maybe you can use some of this material on your research.

[00:44:24.920] - HvR Yeah, for sure.

[00:44:28.100] - MA I will send you that.

[00:44:28.310] - HvR It's good to see the parts of the sustainability, basically, and the difference in aspects.

[00:44:34.370] - MA Just check it out. Maybe for conclusions, if you navigate a bit, it can help you out to write some conclusions.

[00:44:40.940] - HvR Yeah, exactly. Very nice.

[00:44:45.370] - HvR I also wrote down some questions, but I think we covered most of them already. For the functionality, I think I have a good idea already now. And then I was still wondering on maybe in general, when choosing a type of green system, what are the main considerations that play a role, or is it a lot?

[00:45:13.350] - MA Actually, I really think you already covered this.

[00:45:16.680] - HvR Yeah, exactly.

[00:45:17.680] - MA Okay. First is the cost. Sorry for saying this, but cost is very important. Second, I think the weight of the system and what you said before, if it is lightweight or not lightweight, actually the weight of the system can affect even the cost. And I will tell you why. If you choose, it's already in the plan of the architect in the preliminary stages before we start constructing that we define the structure, that we use a specific system like the... What system can I say? Like the climber plant system, which is quite a lightweight system.

[00:46:03.250] - MA Then already with the first choice that you do, the preliminary design phase choices, you can already define that, okay, I don't need really serious structure, or I don't need a very heavy structure for the green facade. So this is actually it is quite important. The choice of the system itself can even come while you are in the preliminary phases.

[00:46:28.150] - HvR Yeah, exactly. That's also what my main goal with this framework is, to not delay the choice of system to a later stage, but do it in the beginning and then already take it into account with all the things that are connected to it.

[00:46:53.790] - MA And then you said also, I think you have covered the aspects yourself, installation is very important, maintenance also. But the cost, you described yourself also the different types of cost you can have. I really think these are the most important. So cost, the weight of the system itself, installation and maintenance, these four aspects, I would say these are the most important.

[00:47:24.230] - HvR Yeah. And the environmental benefits, for example, heat island mitigation, is that already taken into account in the choice of system at the moment or not really?

[00:47:38.340] - MA I don't know, Hugo. It really depends because it really depends if it can play a role. But it's not really critical, I would say, Hugo, to be honest. It's not very critical. But most of the times, the green facades, I don't know what actually [name colleague] told you. The green facades can offer some passive cooling and passive heating. But the green systems that they make even bigger impact, quite big impact, are the green roofs. Green roofs have much bigger impact than green facades. So they can provide some mitigation of the heat island, but the impact is not so big to speak about very big differences. There are differences, I explained to you before, but not such big differences as to say, okay, because of the heat island reduction in the system, I chose for this system. I would say. But I don't know if it comes with the answer, but okay. I think for this, it's wise to ask even a building physicist.

[00:48:54.280] - HvR Yeah, for the details on the energy. Yeah, exactly. And then I had this question written down, what are the project specific characteristics that can affect the early design tools for a certain system? But I think we already covered some of that. So it's the type of building and the type of facades and climate.

[00:49:17.090] - MA Also the sustainability goals. If you set up sustainability goals, like that you need to improve the biodiversity, this is very important. And many of the projects, especially data centres, have really big requirements, improving the biodiversity of the environment and all this.

[00:49:34.660] - HvR Do they also need to show how they do it? So how the green facade will add to biodiversity, or is it enough then to just say, okay, we will use a green facade and we assume that it will improve the biodiversity?

[00:49:51.000] - MA Normally they ask for the product you will use. But they want to achieve that, for example, in many projects, it was, for example, a requirement to use 6

[00:50:15.940] - MA So it was not so much. Unfortunately, sometimes... And also, something else that they give you into account, in a couple of clients, they even ask you to install local plants. And this is quite important, Hugo, because according to this, each system has its own limitations in terms of the vegetation. So if there is a requirement for local plants, you should really consider if the system you choose can provide this, I don't know, this option of the plans that you need to install.

[00:50:52.140] - HvR And is there a general performance or are certain systems often more suitable for local plants than others, or does it depends on what the local plants are?

[00:51:03.820] - MA It really depends on the requirement of the client. It depends on the area where the project is placed because there are different requirements.

[00:51:19.660] - MA But many times you can find a couple... In many climber systems, there are a lot of options for local plants, I would say. There is a very big variety in climber systems for the choice of local plans. When it's a hydroponic system, so it's the system that is based also with the insulation based substrates, then there are more limited options because there should be really specific plans that they can grow through this substrate medium. So it really depends.

[00:51:56.410] - HvR Yeah, exactly. I also read that they use more exotic plants then often.

[00:52:01.500] - MA Exactly. So then it's... Then okay, so have this in mind. If they ask for local vegetation and improve of biodiversity, the best practice is to use local plants.

[00:52:18.210] - HvR Yeah, exactly.

[00:52:20.220] - MA And then you have to check for systems, which systems can supply the biggest variety for local plants or has more potential, let's say. This is also quite important actually, because many clients request for this to use local plants and improve biodiversity.

[00:52:38.830] - HvR Okay.

[00:52:39.790] - MA Yeah. I think this is it, Hugo. I think you have enough info already. You have worked a lot on it.

[00:52:46.820] - MA I will send you also the sustainability framework just for you to help you out a bit to see for you. Maybe you want to use it a bit, this content, maybe not. Just check it out.

[00:52:59.900] - HvR I will definitely look for sure. Thank you so much. I think it really helped because I knew these topics would be important, but just to hear it from you, it's good to confirm it and how it works in practice as well. I think that's good. And then I hope that eventually the tool I will make can be really used and not a theoretical thing only.

[00:53:33.830] - MA I think it's a very nice research and I wish you good luck with this. If you need any more feedback, anyway, you can always call.

[00:53:40.760] - HvR Yes, thank you so much. Thank you for your time and all the efforts.

[00:53:45.550] - MA Nice to see you.

[00:53:47.190] - HvR Bye. See you.

11.4.4 Interview C: Arend de Wilde

Arend de Wilde is a Senior Consultant Ecology at RHDHV.

Introduction

- Speakers: Hugo van Reeuwijk (HvR) and Arend de Wilde (AdW).
- Date: 17-4-2023
- HvR introduces thesis topic and aim of interview: to complement insights found in literature, specifically about biodiversity and plant choices
- HvR explains the semi-structured character of the interview as well as the neutral/open questions asked to prevent bias, and asks permission to record the interview.
- HvR shows a diagram with VGS typologies.

VGS typologies

[00:00:15.340] - HvR Ja, ik wilde u eigenlijk even mijn soorten groene gevel laten zien die ik heb als systeem typologie. Dus eigenlijk maak ik een onderscheid. En ook in heel veel onderzoeken doen ze dat, tussen die groene regels en echt living wall systems, waarbij dan groene gevels direct op de gevel kunnen worden geplaatst. Dat is eigenlijk een klimplant tegen de buitenmuur aan, of iets van de muur af met een stalen grid of die stalen lijnen van boven naar beneden, als groeihulp. Dus dat zijn deze twee. Of met continuiys guides of met met een wat dichter gaas.

[00:01:09.840] - AdW Ja gaas of, van alles. Ook houten kan hè?

[00:01:13.570] - HvR Ja ja . Ja en aan de andere kant ook dan.

[00:01:17.350] - AdW Het is een logische typering ja, en living wall systems.

[00:01:20.110] - HvR Eigenlijk zoek ik dan ook naar scores of dat probeer ik dan uit de literatuur af te leiden voor deze verschillende systemen dan. Natuurlijk vooral heb ik veel grote verschillen gevonden tussen groene gevels en living wall systems, maar t maakt toch ook nog wel uit. Is dat dan van dun vilt zoals hier? Of zijn het dan meer bakken of echt horizontale plantenbakken? Dus ja dat heeft natuurlijk invloed op elkaar.

Biodiversity

00:01:48.820] - HvR Even kijken, pak ik even mijn vragen erbij over biodiversiteit. Ja, ik ben eigenlijk benieuwd en ik stel vrij open vragen denk ik. Maar dat is juist bedoeld om te kijken van waar u aan moet denken en dan kan ik daaraan natuurlijk toevoegen wat ik al zelf had gevonden. Eigenlijk is mijn eerste vraag: welke mechanismen of wat bepaalt de impact van een groene gevel op biodiversiteit? Dus in hoeverre kan een groene gevel biodiversiteit toevoegen, of daaraan bijdragen?

[00:02:20.220] - AdW Ja dat t begint eigenlijk al met je definitie van biodiversiteit. Maak je gewoon een lijstje van alles wat je kan vinden of kijk je naar wat van nature op een bepaalde plek thuishoort?

[00:02:34.920] - HvR Ja.

[00:02:35.580] - AdW Dus maar ja in de praktijk. Uhm sommigen zijn heel erg van ja het moet inheems zijn anders doet werkt dat niet, maar al onze steden zijn volledig cultuurlijk in veel aspecten. Dus je kan ook zeggen in hoeverre past het? D'r is ook zo een hele discussie gaande over in hoeverre soorten die hier al wat langer zijn en die passen binnen het ecosysteem. In hoeverre die ondertussen al onderdeel zijn van biodiversiteit? En dat maakt de discussie een stuk lastiger al, want waar ga je van uit? Dus je zult, het is waarschijnlijk handig dat je iets opneemt over het type biodiversiteit.

Je hebt dus zuiver inheemse soorten, daar kun je wat aan hebben en je hebt een wat bredere van soorten. Gewoon een diversiteit die in de stad leeft.

[00:03:28.340] - HvR Ja.

[00:03:29.450] - AdW Da's al een verschil natuurlijk. Om even terug te komen op die waar ik zei van: ik ben zelf gaan kijken van, wat gebeurt van nature op een rotswand. Ja, van nature heb je geen rotswanden in Nederland.

[00:03:45.080] - HvR Ja, ja.

[00:03:45.860] - AdW Dus eigenlijk heb je in Nederland geen natuurlijke referenties voor vegetatie die op rotsen groeien. Je moet er al over de grens kijken wil je iets vinden.

[00:03:55.850] - HvR Ja.

[00:03:57.150] - AdW En dat geldt dan als je dus, want je had een indeling van planten, maar je planten die direct tegen de muur opgroeien. Daar heb je eigenlijk alleen maar planten die in de volle grond wortelen. Je hebt geen planten die op de muur groeien, die zijn er ook. In Nederland heb je een paar soorten mosjes en muur-varentjes die gewoon rechtstreeks op de muur groeien. Dus als je heel volledig wil zijn kan je die er nog bij doen. En dat zijn dus zo'n beetje de enige die je kan zeggen van, die zijn op onnatuurlijke habitats die wij gemaakt hebben zijn ze toch natuurlijk terecht terechtgekomen.

[00:04:37.540] - HvR Ja precies.

[00:04:38.200] - AdW Die heb je wel. Dus in eerste instantie is het natuurlijk voor biodiversiteit gewoon... Het is een groeiplaats voor die plant zelf.

[00:04:46.690] - HvR Ja precies ja.

[00:04:48.070] - AdW En die muurvarentjes, die waren op een gegeven moment zo zeldzaam geworden omdat wij een ander type kalk waren gaan gebruiken voor cement en zo. Dus vroeger konden ze in dat zachte kalk wat minder minder alkalisch was best wel goed groeien. En in die moderne Portland cement is gewoon te hard en te alkalisch. Daar dat doet niks t meer. Dus die werden prima zwaar beschermd, in veel binnensteden hechten ze erg aan hun varentjes op de muren.

[00:05:17.650] - HvR Ja.

[00:05:20.190] - AdW Dus dat is heel iets wat al heel lang speelt hè, dat is een vegetatie die op muren groeit. En dan heb je die klimplanten die daar tegenop klauteren. Die wortelen dus gewoon in de volle grond en die kan je naar de muur toe leiden. Ik vind het zelf geweldig goeie handige dingen, want ze zijn veel beter stuurbaar dan bomen en zo. Dus je kan vaak goed onderhoud plegen. Dat zijn ook gewoon inheemse soorten. Vaak hè. Gewoon klimop en een wingerd en kamperfoelie en dat soort typen. Sommige die kunnen heel goed zelf klimmen, die klauteren gewoon tegen een muur op, als die niet al te glad is. En als het maar een beetje ruw is en ze kunnen zich vasthechten dan klauwen ze d'r tegen op.

[00:06:07.680] - AdW En andere hebben wat hulp nodig. Maar dat zijn gewoon inheemse planten die al an sich een eigen waarde hebben, want ze voegen wat toe.

[00:06:17.420] - AdW Daarnaast is het gewoon vaak voedsel en een schuilplaats voor allerlei andere dieren. En dan heb je dus over allerlei insecten en andere ongewervelden. Uhm, vaak wordt daar niet zo hoog van opgegeven. Spinnen en dat soort beestjes. Want ja, die zijn niet zo zeldzaam en zo. Maar ja, wil je als je één insecten-etende vogel in leven wil houden zul je hem toch honderden insecten per dag moeten voeren en die moeten ergens groeien. Dus het hoeft helemaal niet heel bijzonder te zijn om om van belang te zijn voor biodiversiteit. Gewoon elke vierkante meter aan vegetatie waar maar insecten en ander klein spul kan leven draagt bij aan een grotere biomassa van soorten die we wel aaibaar vinden.

[00:07:03.770] - HvR Ja, dat je eigenlijk de hele keten bedient.

[00:07:06.380] - AdW Het is een voedselpiramide en alles wat je op een muur plakt draagt bij om de basis van die voedselpiramide breder te maken. Want ja, want uiteindelijk ik zeg altijd voor biodiversiteit. Het aller, aller, aller-belangrijkste is ruimte. Want je kan wel een geweldig prachtig iets maken van een vierkante meter, maar daar heb je gewoon geen reet aan, want er kan gewoon niks van leven. En dan? Je hebt gewoon volume nodig. Massa. En dan maakt het denk ik. Ik vind het ook helemaal niet erg dat ze langs zo'n parkeergarage gazen en stalen dingen langs de zijkant en drie soorten klimplanten. Laat maar doen. Dat is prima, want dat levert gewoon heel veel biomassa op en uiteindelijk draagt het bij aan voedsel voor soorten die er omheen vliegen. Dus het hoeft helemaal niet zo moeilijk te zijn. De biodiversiteitswaarde van de gebruikte planten hoeft helemaal niet bijzonder te zijn.

[00:08:05.800] - AdW Ik zeg ga altijd voor iets makkelijks, iets wat het doet. Want je kan wel iets heel moeilijks op gaan hangen, wat vervolgens heel veel onderhoud vergt of doodgaat. Daar heb je weinig aan. Dus gewoon robuuste spullen is prima. Nou dat is dus het voer-deel.

[00:08:21.560] - AdW Dan heb je ook nog beschutting, want tussen die planten gaat van alles en nog wat zitten. Ja d'r gaan vogeltjes die zelf een nestje bouwen, er gaan allerlei vlinders overwinteren. Er gaat van alles en nog wat tussen zitten. Uhm en dat heeft ook gewoon heel veel waarde want schuilplaatsen zijn vaak beperkt. Dus. En daarmee heb je wat mij betreft al de allerbelangrijkste dingen gehad.

[00:08:47.800] - HvR Ja dus eigenlijk die planten zelf. Het vegetatie dek als voedplaats voor dieren en dan dus die beschutting of die schuilplaats waar ze kunnen nestelen of schuilen.

[00:09:01.770] - AdW Ja, dus je vergroot de voedselpiramide en je geeft schuilplekken. Ja, en dat, dat vind ik eigenlijk al. En dan kan je dan allemaal specifiek gaan maken. Je kan zeggen van ja klimop, die bloeit in de winter dus die levert nectar op voor de winter-actieve insecten. Ja, prima. En zo zijn er ook nog andere dingen, die kan je allemaal specifiek maken. En dan heb je een gebouw wat meer in de schaduw staat, kan je misschien andere planten tegen opzetten. En ja, dat gaat allemaal prima. Ja, en als je als je living wall systemen gaat doen. Wat je in feite doet is je hangt bodem aan de muur.

[00:09:42.540] - HvR Ja.

[00:09:45.600] - AdW Het is een vorm van een gestapelde plantenbak en hoe je dat technisch uitvoert. Euh, ik ben er geen voorstander van dat je dat met een plastic systeem doet, want uiteindelijk gaat dat plastic na een paar jaar gewoon stuk en gaat het in je keten en draagt het bij aan een hoop plastic vervuiling. En je kan wel bioplastic gebruiken voor alles en nog wat. Uiteindelijk stelt het niet veel voor. Je hebt gigantisch veel plastic per vierkante meter nodig wil je daar iets van van maken. En er zijn allerlei hele leuke technische systemen verzonnen. Net als trouwens groendaken he. Dat is allemaal modulaire. Dat is allemaal gewoon vanuit hetzelfde consumptie-idiotisme bedacht om zoveel mogelijk troep te verkopen aan mensen. In de bredere context van het ecosysteem-probleem draagt het heel weinig bij natuurlijk. De planten die daar opgroeien gaat prima, maar ze zijn bijzonder onderhoudsgevoelig en gaan helemaal niet zo lang mee. Al die systemen, zeker als je dat van vilt en zo, dat is binnen de korste keren kapot. Plus en dat levert alleen maar om een ontzettende berg troep op. Heel veel werk. Planten ingezet die uit één of ander tuincentrum komen die er heel leuk uitzien. Esthetisch zeker. Er worden ook vaak wel inheemse planten gebruikt of planten die leuk bloeien, dus die bijdrage aan nectar of voorziening, dat is allemaal prima. Alleen het systeem zelf is zo vervuilend en het kost zo veel energie. En het is bovendien zeer kwetsbaar doordat je water moet geven. Bijna altijd. Juist die systemen, die drogen allemaal uit dus. Dus je moet er iets doen met een watergeefsysteem en dat is bijna altijd heel kwetsbaar. Dus je kan het doen als esthetisch iets, maar in de bredere biodiversiteit context ben ik er geen voorstander van.

[00:11:43.590] - HvR Ja, want er wordt wel gezegd dat die LWS dan aan meer verschillende plantsoorten ruimte kunnen bieden en dat het daardoor dan...

[00:11:53.400] - AdW Ja, absoluut.

[00:11:53.910] - HvR ... wel een grote bijdrage kan leveren aan die biodiversiteit.

[00:11:57.280] - AdW Ja nee, ik vind een living wall een prima idee, maar dan moet je het met je betonnen bakken doen. Dan moet je een living wall maken hè. Dus ik heb wel eens meegewerkt aan een project en dan hadden we dus in plaats van een horizontale muur, hadden we een beetje schuine muur en daar zat allemaal. Je had dus beton en daarbovenop had je gewoon schotten en daartussen zat weer grond. Ja, die gewoon voldoende vocht vast konden houden waarbij je eigenlijk een beetje schuin systeem hebt. En je kan dat natuurlijk nog een beetje slimmer doen door wat water in te vangen, maar het moet... Het moet robuust zijn.

[00:12:37.490] - HvR Ja.

[00:12:38.960] - AdW En dan kan je. Daar hoef je niet eens in te planten, want er waait gewoon vanzelf om van alles en nog wat in. Dus ja dat kan. Als je dus iets esthetisch wil dan kan je dus ook nog wel degelijk dingen aanplanten natuurlijk hè. Want d'r zijn best wel veel planten die... Als je een grondlaag hebt van pak m beet dertig centimeter ofzo met onderin een beetje vocht vast houdend iets. Nou, dan zijn er al heel wat dingen die t kunnen doen. En da's best aardig. En dat kan dus gewoon echt de hele bakken zijn die je d'r uitkragendend aan je gebouw hebt. Of je kan een steile helling maken van je muur. Dat soort dingen. Het kan. Maar helemaal verticaal... en dan grond op te tillen, zeg maar, met van die plastic bakjes en zo. Ik vind het. Het is alleen maar esthetisch en mode... Over vijftig jaar zie je dat echt niet meer. Kan me dat niet voorstellen. Het is gewoon wegwerp troep.

[00:13:42.820] - HvR Ja, ja.

[00:13:45.320] - AdW En ik zie ze ook heel vaak dood hè, na een paar jaar zijn ze gewoon vaak dood.

[00:13:50.590] - HvR Nee, want dat is ook een vraag, maar die kan misschien nu wel stellen: welke ontwerp aspecten zijn nou belangrijk voor functionaliteit, dus eigenlijk voor het in leven houden van planten? Dat is dus water. Maar zijn er ook nog andere ontwerpaspecten waar goed moet op worden gelet, maar wil je wel een goed systeem ontwerpen dat in leven blijft?

[00:14:16.670] - AdW Ja in de praktijk is onderhoudsgevoeligheid natuurlijk een ontzettend groot knelpunt. Want in de praktijk... Je hoeft maar één keer een crisis te hebben dat je dus,en het systeem functioneert een maand niet met water geven en de hele boel is dood.

[00:14:40.010] - HvR Ja.

[00:14:41.090] - AdW Dus het moet robuust zijn. Het moet zelfvoorzienend zijn. En dat kan ook doordat je bijvoorbeeld gewoon water op je dak opvangt en dan een doorsijpel-systeem whatever. Je kan er best wel robuuste dingen van maken, maar doe het alsjeblieft op zo'n manier dat je groene muur je living wall systeem net zo lang meegaat als je muur en je gebouw.

[00:15:06.750] - HvR Ja dus dat je die vijftig jaar haalt?

[00:15:09.240] - AdW Ja, minstens. Ik bedoel als ik ergens stad ga bekijken dan zijn de meeste gebouwen die ik ga bekijken veel ouder. Ja dus daar is heel goed over nagedacht, over materiaalkeuze en zo. Ja en volgens mij is zo'n zo'n groene wal, groene living wall, dat is ook een mooie isolerende factor volgens mij.

[00:15:29.760] - HvR Ja klopt.

[00:15:32.220] - AdW Ja het liefste zou ik zien... En d'r was op een gegeven moment was er een groepje studenten. Die waren aan t kijken of je beton kon coaten met een laagje.

[00:15:47.880] - HvR Ja die ken ik ja.

[00:15:50.190] - AdW Maar daar was t hetzelfde probleem. Hoe hou je dat vochtig? Want dat is op zich niet zo'n probleem. Je hebt zelfs. Je hebt zelfs systemen waarbij je zaden en organisch materiaal en een plakmiddel op grond spuit hè. Gewoon als je bijvoorbeeld een weg aangelegd hebt op een gebied en je wil heel snel je bermen vergroenen. Ja, in Nederland is dat niet zo hard nodig, want dat gaat vanzelf. Maar in andere gebieden daar heb je gewoon een sproei installatie die de weg eventjes sproeien met zaden en plaksel en wat organisch materiaal zodat je snel een organische laag krijgt. Dat kan je op alle gebouwen doen. Je kan elk gebouw helemaal groen maken. Alleen na een tijdje is het eten op en je moet zorgen dat er de hele tijd water is, dus dat is meer...T is ook meer de categorie gadget. Het kan. Het is leuk om te doen. Ik vind t ook helemaal niet erg als mensen dat soort dingen doen. Ik heb eens een keer een gebouw gezien wat helemaal bedekt was met gras.

[00:16:44.390] - HvR Ja.

[00:16:45.100] - AdW Ja, dat is gewoon grappig. Het draagt niet serieus bij aan biodiversiteit.

[00:16:49.450] - HvR Ja precies, want om daar nog even naar terug te gaan. Ik heb wat studies gevonden die dan kijken naar de diversiteit van het aantal soorten wat er dan op die groene gevel zit, en ook hoe de hoeveelheid, dus bijvoorbeeld hoeveel vogels er zijn geteld op een bepaald groen systeem. Nou wordt er ook wel eens gezegd dat groene gevels kunnen bijdragen aan ecologische netwerken, dus dat je een soort stepping stone als groene gevel bent tussen parken, bijvoorbeeld voor vogels. Ja, wat is eigenlijk de waarde van een groene gevel als onderdeel van zo'n ecologische corridor? Is die er of is dat meer iets wat wordt aangenomen?

[00:17:32.290] - AdW Ja, tuurlijk. Maar ik denk... Vogels hebben over t algemeen, die kunnen zich over het algemeen, zich erg goed verspreiden hè. Die vliegen prima en ik zou niet. Ja maar, vlinders misschien, dat die daar gauwer geneigd zijn om langs te gaan. Dus groene gevels voor een ecologische verbindingszone, ja, dat draagt natuurlijk bij gewoon alleen al vanuit het biomassa-idee.

[00:17:59.460] - HvR Ja.

[00:18:00.360] - AdW Maar het vervangt niet wat je op maaiveld moet doen. En dat is vaak het punt hè. Maaiveld is beperkt, dus ze zoeken gewoon andere ruimtes van kan ik niet een functie die nu op maaiveld plaatsvindt, kan ik die niet verplaatsen naar de muur? En dat gaat. Ja, dat kan. Je kan het wel. Met zo'n living wall kan je dat in zekere zin kan je daar wel iets mee doen natuurlijk.

[00:18:24.000] - HvR Uhu.

[00:18:24.820] - AdW Maar het vervangt hem niet helemaal. En ik denk dat groendaken, hebben daarvoor veel meer potentie en zijn ook veel goedkoper en beter om in te richten. Dus ik vind gewoon, dat elk dak moet of groen of zonnepanelen hebben.

[00:18:42.060] - HvR Of beide.

[00:18:43.620] - AdW Ja beide kan ook hoor, want ook onder een zonnepaneel.

[00:18:47.280] - HvR Ja precies ja.

[00:18:48.190] - AdW ...Kan gewoon de schaduw minnende vegetatie en dan kan je een wateropslag in de grond en weet ik veel, je kan hele mooie combinaties maken.

[00:18:55.950] - HvR Ja.

[00:18:57.220] - AdW En dat is denk ik voor vliegende soorten is dat heel handig. Kijk, voor de kruipende soorten is een muur niet relevant over t algemeen, want die kruipen over de grond. Dus een muur is alleen voor vliegende soorten van belang en dan werkt een dak vaak al beter. Maar het is gewoon een verbreding van je voedselpiramide, dus je draagt wel iets bij. Ja dus absoluut wel.

[00:19:25.080] - HvR Maar het is geen vervanging van, of daken of dus maaiveld. En met maaiveld, even voor mijn verbeelding, dat zijn dan bomen of grassen of een een begroeiing op straatniveau?

[00:19:34.340] - AdW Ja, in de echte grond hè. Nou maar je kan natuurlijk wel integreren he, want heel vaak heb je dus weinig ruimte op maaiveld en door die groene wanden waarin allerlei dieren beschutting kunnen vinden, heb je wel degelijk een optie natuurlijk.

[00:19:58.670] - AdW En de auto kost nu veel te veel ruimte in vooral stedelijk gebied. Dus als je auto's in gebouwen gaat parkeren, dat doe je dan vaak in de onderste verdiepingen. Dus die verdiepingen... Die zou je prima kunnen voorzien van een enigszins schuine wand en die kan als een soort dijk-vegetatie begroeid worden, want daar heb je toch geen ramen. Dus onderste verdiepingen van gebouwen, daar kan je prima auto's in opslaan, zolang we tenminste door blijven draaien met particuliere auto's hoor, want ik denk dat over een tijdje heb je gewoon je auto en dan komt er een aan. Maar tot die tijd mensen willen misschien toch wel dat soort dingen hebben en ook gewoon om functies die geen geen daglicht nodig hebben. Weet ik veel opslag. Warmtepompen, allerlei dingen kan je bij wijze van spreken daar kwijt en die kan je dan met met een soort dijkjes hè. Dat lijkt me op zich prachtig en dan is het schuin genoeg en blijft het contact met het gewone maaiveld. En dan denk ik aan soorten als muizen, mollen, slakken, vossen die kunnen allemaal wel gebruik maken van dat soort hellingen.

[00:21:14.330] - HvR Ik heb ook gevonden dat het landschap waar een groene gevel in staat zou eigenlijk moeten worden meegenomen om te kijken hoe een groen gevelsysteem kan bijdragen aan de biodiversiteit. Nou hoor ik ook van u, de totale oppervlakte, eigenlijk... hoe meer, hoe beter. En ook diversiteit en dichtheid van planten, dat had ik dan zelf nog gevonden. tja, eigenlijk heel kort gezegd. Hoe meer plant, hoe beter natuurlijk. Dat noem ik dan parameters die het potentieel van biodiversiteit beïnvloeden. Welke zijn het belangrijkst? Of waarbij denkt u, dat is echt belangrijker dan de rest? Of valt dat niet zo simpel te zeggen?

[00:22:04.300] - AdW Nee, het is én én. Ja, wat is nou belangrijk? Ja, ik denk dat, je moet in ieder geval een substraat hebben waar iets kan groeien en dat kan dus inderdaad vlak zijn of onder een helling. En je hebt licht en water dat zijn gewoon de basics. En ja, dat substraat de oppervlakte daarvan, dat is heel bepalend. En dat is het voordeel van als je bijvoorbeeld zo'n schuin talud daar tegen de onderste verdiepingen van een gebouw aan laat lopen, dan is de oppervlakte van je groen is groter dan als je het plat op maaiveld hebt. En je zit natuurlijk ook met je waterhuishouding en zo. In Nederland is dus heel vaak dat onder-in, je moet ergens ook je water kwijt. Dus ja dat is het laagste punt en dat is dan een of permanent nat, met een slootje, of het is een wadi achtig iets waarbij je je water tijdelijk kwijt kan en dan is het heel belangrijk dat er ook delen zijn die hoger en droger zijn.

[00:23:11.380] - AdW En dan kan dus die overgang van maaiveld naar gebouw... Als je dat schuin inricht of ook met klimplanten hoor. Dat kan wel een heel grote functie hebben.

[00:23:25.270] - HvR Ja. En ik las ook in sommige studies dat ze dan of vocht-minnende soorten meer onderin het systeem doen. En dan ja, planten die beter tegen droogte kunnen, of waar dan ook meer zon op komt, op andere plekken toepassen.

[00:23:37.420] - AdW Het zullen heel groot verschillen zijn en vooral noord hellingen. De noordkant van een gebouw is gewoon finaal anders dan de zuidkant. En met ons veranderende klimaat is echt een zuidhelling zo verschillend. Je hoeft maar te kijken bij een gemiddelde dijk in Nederland die oost-west loopt. Dan zie je dat de zuidkant zo andere vegetatie heeft dan de noordkant. Tenminste, tenzij ze de hele boel plat maaien, maar d'r zitten echt andere soorten. De bloei is eerder en echt dat is heel verschillend. En dat is dan nog terwijl er nog gewoon licht op valt. Maar bij gebouwen heb je die schaduwwerking.

[00:24:11.170] - HvR Ja.

[00:24:12.010] - AdW Bij gebouwen. Wat ook heel belangrijk is voor vegetatie is: het waait. En dat heeft een paar consequenties. Ten eerste, alles wat je aan het gebouw vastplakt, dat kan er veel makkelijker af waaien. Ik heb zelf een daktuin en als er een keer gewaaid heeft dan liggen er gewoon stukken naast in de tuin.

[00:24:34.070] - HvR Ja.

[00:24:35.900] - AdW Dat wil je niet hebben in alle gevallen. Dat is ons ook één van de redenen dat in Nederland daktuinen met echt, met bomen en zo. Best wel een dingetje is. Want ten eerste, het waait daar gewoon harder. Maar ook. Je belasting van je structuur van je gebouwen wordt anders omdat een boom die een beetje mee staat te wapperen. Dat geeft gewoon natuurlijk gigantische krachten op je gebouw.

[00:25:04.210] - HvR Ja dat geeft enorme krachten.

[00:25:07.190] - AdW Ja, dat weet je. Constructeurs weten dat, het is niet zo simpel.

[00:25:15.450] - HvR En soms heb je ook van die torens, bijvoorbeeld in Milaan met van die balkons met bomen op. Maar om die bomen dan vast te houden heb je zoveel staal nodig dat je eigenlijk de hele milieu impact van die hele boom te niet doet.

[00:25:30.750] - AdW Het ziet er leuk uit. Ja, wat ik heel vaak zeg is van: hoe duur is jouw groene gevel? O zo veel. Nou daarvoor kan je dus zoveel hectare van één of ander een mais akker opkopen om daar iets beters van te maken. Dus kijk, in Nederland hebben we helemaal geen gebrek aan ruimte voor natuurontwikkeling, g alleen we gebruiken dat verkeerd hè. Gelukkig gaan we nu in het agrarisch gebied een transitie doen, maar we zijn op een idiote manier met ons landschap bezig. Door enorm intensieve veehouderijen en en volledige biodiversiteitsloze groene woestijnen te creëren. En het is zoveel goedkoper om dáár een biodiversiteitstoevoeging te doen dan al dat gepreuts met gebouwen. Dus dat doen we vooral voor het lokale, voor onze eigen leefkwaliteit.

[00:26:24.300] - AdW En het is natuurlijk ook een bijzonder habitat hè, voor sommige dingen.

[00:26:32.980] - AdW Biodiversiteit in de stad, maar het heeft dan wel kosten als je het alleen maar vanuit biodiversiteit winst doet. Zet daar gewoon betonblokken neer in de stad en doe natuur buiten de stad. Dat is veel goedkoper.

[00:26:44.050] - HvR Ja ja.In het grote plaatje is dat dan de overweging. En ik kan me voorstellen dat het dan misschien in hele grote dichtbebouwde steden, dat het daar dan inderdaad meer betekenis kan hebben. Maar dan heeft het minder biodiversiteit-waarde, maar misschien meer leefklimaat of...

[00:26:57.160] - AdW Ja daarom dus. Maar dat ligt er ook aan hoe je naar die biodiversiteit gaat kijken. Ga je t alleen boekhoudkundig doen of wil je ook mensen bereiken? Want ik denk dat als mensen niet veel in contact komen met met natuurlijk leven en biodiversiteit dat ze d'r ook minder aan hechten en dat uiteindelijk de bescherming daarvan ondermijnd wordt. Want mij baart dat heel veel zorgen dat er nu heel veel mensen opgroeien in steden die echt geen idee hebben hoe de natuur werkt.

[00:27:23.490] - HvR Ja. Dus om begrip van natuur te kweken.

[00:27:29.070] - AdW Ja, draagvlak is een heel belangrijke component voor het beschermen van natuur.

[00:27:34.260] - HvR Ja.

[00:27:34.950] - AdW En dan helpt het dus heel erg als je van alles en nog wat naar de stad brengt. Maar dan moet je wel zorgen dat het robuust is. Want als mensen dus inderdaad een heel duur systeem aan de muur gaan hangen en vervolgens gaat het dood, psychologisch werkt dat gewoon niet.

[00:27:50.030] - HvR Nee, klopt en dat is ook. Er zijn best wat studies over hoe mensen groene gevels ervaren en wat ze ervan vinden. En dan aan het begin of als ze al een tijdje hebben gezien. En daarin komt ook heel erg naar voor dat als het dood gaat of als het er dood uitziet, dus bijvoorbeeld...

[00:28:05.660] - AdW In de winter. Nederlandse vegetatie. Ik was een tijdje terug in Manilla en dat is echt een vreselijke stad, helemaal dichtgebouwd enzo. Maar ze zijn daar sinds een tijdje bezig met echt felgroene dingen. En daar hebben ze ook van die groene gevels vol moduletjes aan. Echt in een tunnelbak er aan gehangen. Daar hoeven ze ook niks aan te doen want het regent daar elke dag. Dus daar groeit echt alles. Daar is de situatie volledig anders, daar hoef je maar ergens een litertje grond neer te gooien en dat gaat groeien. Of je hangt het op of je hebt mensen die hebben daar van die frisdrank flessen weet je wel. Dan snijden ze s de bovenkant eraf, maken ze d'r een haakje van, hups aan de muur. Ja een beetje grond erin.. Bam en daar groeit zo'n boom uit.

[00:28:53.820] - HvR Ja.

[00:28:54.450] - AdW Dat kan bij dat klimaat, is het altijd groen en het bloeit en het groeit allemaal heel makkelijk. Maar in ons klimaat is het er een groot deel van de tijd niet zo fijn. En dan ziet het er ook niet zo mooi uit. Iets als een wintergroene klimplant... Ik ben zelf enorme fan van klimop, gewoon omdat dat onverwoestbaar zooi is, die best wel veel toevoegt voor heel weinig kosten.

Plant species and their effect on ecosystem services

[00:29:26.880] - HvR Ik kijk voor die systemen niet alleen naar de diversiteit, maar ook naar andere ecosysteemdiensten. Bijvoorbeeld CO2 reductie of thermische isolatie van de gevel of geluidsdemping op straat. Eigenlijk is mijn vraag: wat is dan de invloed van die planten daarop? Of misschien anders gezegd: welke plant eigenschappen kunnen daaraan bijdragen?

[00:29:53.150] - AdW Ja, als je CO2 wilt vastleggen moet je gewoon via biodiversiteit vastleggen. Dus dat betekent dat je of moet zorgen dat je ondergronds organisch materiaal brengt. Dat doen dus wortels van bomen. Als je die boom afzaagt, je laat hun wortels zitten, dan heb je daar nog wat zitten. En die boom, die slaat natuurlijk zelf wel CO2 op. Een andere vorm die nog te veel onderbelicht is, is veenvorming. Veen is gewoon een groot organisch pakket en dat wordt opgebouwd uit CO2, dus veen is geweldig. Allerlei veen- en moerasvorming is prachtig. Dat gaat jou niet lukken op je muur.

[00:30:29.840] - HvR Nee, dat denk ik ook.

[00:30:30.920] - AdW En da's ook vrij zinloos. Sterker nog, aan je muur wil je niet te grote volumes hebben, want dat is onderhoudsgevoelig. Je moet ook als je planten hebt die heel hard groeien, dan ben je alleen maar aan snoeien en dat gaat frustreren, op een gegeven moment ben je hem kwijt. Klimop is er al zo eentje, maar bijvoorbeeld ook druiven en zo, ja die dingen die groeien meters per jaar. Dus je moet er ook wel bij kunnen voor onderhoud en hoe meer hoe meer biomassa je produceert, hoe meer onderhoudsgevoelig het is. Want je gebouw groeit niet. Dus als je vegetatie groeit en je gebouw niet, dan overgroeit je gebouw en dan heb je ramen die gaan volgroeien en dat soort dingen, wil je allemaal niet hebben. Dus CO2 opslag is er niet. Je haalt er af en toe een beetje snoeisel af en dat kan je inderdaad als biomassa gebruiken om te verbranden. Maar het is niet veel, dat stelt niet veel voor.

[00:31:22.340] - AdW Voor het klimaat koelen. Tuurlijk. Alleszins, het zorgt voor schaduw. Het zorgt voor verdamping. En allebei draagt gewoon geweldig bij. Een hete droge muur of een muur met een beetje robuuste klimplant ervoor, dat maakt gigantisch uit. Dus klimaatadaptatie helemaal top.

[00:31:40.910] - AdW Geluidsdemping, dat weet ik eigenlijk niet zo. Ik heb al studies gezien die zeggen ja vegetatie doet niet veel en andere zeggen nou toch wel wat. Ik denk dat het ook voor een weerkaatsing wel wat zal doen en... Maar goed ook al scheelt het maar twee decibel, dat is al heel wat. Dus ik denk zeker dat het werkt.

[00:32:02.740] - HvR Zeker, de som der delen van verschillende groene gevels of andere materialen op een andere gevel, want dat is natuurlijk...

[00:32:08.890] - AdW Dan hebben we fijnstof. Fijnstof is heel simpel. Hoe groter je oppervlak, hoe meer fijnstof daarop neerslaat. Dus veel bladeren is fijn. Dat haalt gewoon fijnstof uit de lucht. Daar slaat het op neer en als het regent spoelt het eraf. Dus fijnstof gewoon prima. En dan is het hoe meer blad, hoe beter. En een voordeel is van groenblijvende klimplanten bijvoorbeeld is aan je muur, is dat ie dat ook in de winter het doen he. Want een hele hoop laanbomen in een straat, die verliezen in de winter hun blad, dus dan hebben ze die functie niet. Dan hou je nog iets over tenminste.

[00:32:52.090] - AdW En was er nog, had je nog een functie? Eetbaar kan ook hé.

[00:32:59.050] - HvR Eetbare planten?

[00:33:01.210] - AdW Ja, je kan eetbare planten toepassen. Want er zijn verschillende bramen soorten die je kan laten klauteren, maar ook Japanse wijnbes, kiwi, druiven natuurlijk. Dus er zijn verschillende planten die dus meerdere functies kunnen vervullen.

[00:33:18.760] - HvR Ja. En verder had ik ook tegengaan van stadshitte, het tegengaan van het urban heat island. Dat het eigenlijk thermisch niet alleen thermische isolatie geeft, maar eigenlijk ook de lucht afkoelt.

[00:33:34.570] - AdW Maar dat ken ik ook. Instraling. En het wordt gewoon door de verdamping van het blad van de planten verdampen en dat koelt. Dat koelt echt flink hoor.

[00:33:43.570] - HvR Ja. Er zijn daar veel studies naar gedaan, naar die thermische kant, dus van binnen, maar ook van op straatniveau. En ook over de invloed van de stads-dichtheid. Bij hele hoge gebouwen blijft natuurlijk de lucht meer hangen, dus daar zou het meer verschil maken dan in een Nederlandse wat meer laagbouw stad met wat bredere straten.

[00:34:10.530] - AdW Nou is het wel zo heb ik begrepen dat in sommige gevallen, dat is dan met bomen. Dus als je een hoge stad hebt met grote bomen dan kan de warmte d'r ook onder blijven hangen. Dus dat t s avonds langer duurt, maar dat heb je dus minder als je gevel begroeiing hebt want dan heb je weer kan het makkelijker, de warmte omhoog.

[00:34:28.500] - HvR Dat het gewoon erlangs kan.

[00:34:34.000] - AdW Verder, gevelbegroeiing zorgt voor een iets hogere ruwheid van je gevel, waardoor het effect van wind ook wat, iets afneemt. Maar ik weet niet hoe groot dat is. Dat ligt aan natuurlijk allemaal hoe de omstandigheden zijn.

[00:34:51.360] - HvR Ja. En dat is dan uiteindelijk goed voor thermische isolatie of waarvoor is dat dan goed?

[00:34:56.030] - AdW Ja dan heb je minder last van wind, bij hoge gebouwen kan het wel de moeite zijn. Maar ik vind dat je bij hele hoge gebouwen is t bijna niet te doen om gevel begroeiing te hebben.

[00:35:06.750] - HvR Nee?

[00:35:08.160] - AdW Je kan er niet bij. En als er stukken af waaien, dan wie weet waar ze terechtkomen, kan het verkeerd terechtkomen. Mensen schrikken, je kan schade aanrichten dus.

[00:35:17.190] - AdW Je moet eigenlijk gevelbegroeiing alleen maar de onderste 10-15 meter, moet toch in ieder geval wel onderhoudbaar zijn, vind ik.

[00:35:27.760] - HvR Ja, terwijl veel toepassingen is zijn natuurlijk wel op torens, zoals in Utrecht is er nieuwbouw. Daar gaan ze het dan wel toepassen. Juist denk ik, omdat ze dan daar meer geld ervoor hebben.

[00:35:43.900] - AdW Ja, voor het beeld. Ik heb zelf ook eens een ontwerp gemaakt en ik vind dan dat je bijvoorbeeld echt met gazen kooien moet gaan werken waar die vegetatie in groeit, want anders is dat vind ik dat niet verantwoord.

[00:35:59.480] - HvR Dat is eigenlijk een gebouw-eigenschap die belangrijk is voor of het wel of niet gaat functioneren. Of dat het haalbaar is.

[00:36:08.810] - AdW En ja, weet je op zo'n grote hoogte. Zal d'r ook heel weinig dieren nog gebruik van kunnen maken. Want de meeste vogeltjes die in struiken broeden zijn struweel vogels, die vliegen niet hoger dan een paar meter.

[00:36:23.000] - HvR Ja.

[00:36:27.190] - AdW Vleermuizen. Die zullen misschien nog wel makkelijk tot twintig meter hoog gaan worden hoor. Maar ja, de insecten die er af komen en ja die gaan toch overal naartoe. Dus daar hoeft het niet per sé voor. Ik vind t ook bij daktuinen op hoge gebouwen moet echt gewoon laag zijn. Moet echt gras en kruiden vegetatie. Niet hoger. Kan eventueel lage struikjes zijn. En dan heb je veel parallellen met wat je in de duinen hebt en zo, echt soorten die goed tegen veel instraling en harde wind kunnen, duindoorn bijvoorbeeld. Maar je kan je afvragen of daar nog op die hoogte nog dieren op af komen.

[00:37:07.990] - HvR Ja, op zo'n hoogte...

[00:37:09.120] - AdW Ik heb een daktuin gemaakt van 1200 vierkante meter op 13e verdieping een keer ontworpen. En daar wil ik toch nog eens een keer kijken wat er nou eigenlijk aan beestjes terecht is gekomen. Ja, het is nog best wel hoog.

[00:37:26.430] - HvR Ja inderdaad. Als dat de goeie manier is ontworpen, dan wie weet.

[00:37:33.510] - AdW Ja ja, maar ze moeten daar kunnen komen. Want in een normaal weide systeem heb je allerlei dieren die komen aan kruipen en lopen, maar op de dertiende verdieping. Daar komen ze niet, dus daar komt alleen vliegend spul. Ja en dan heb je dus ook maar een incompleet ecosysteem. Ja, ze hebben wel. Vanaf het begin hebben, we wel gewoon grond meegenomen vanaf de grond, dus daar zitten wel wormen, springstaarten. En dat soort beestjes zijn er wel terecht gekomen.

[00:38:00.420] - HvR Ja.

[00:38:00.690] - AdW Maar het blijft... Maar goed, het blijft kunstmatig. Dat weten we.

[00:38:09.410] - HvR Ja, en over dat kunstmatige gesproken, er zijn verschillende studies die... De ene zegt, je moet voor een lokale plant gaan die van nature op die plek voorkomen. Andere studies zeggen, je kan exotische planten gebruiken omdat bijvoorbeeld living walls system ook geen natuurlijk systeem zijn, dat is al artificieel.

[00:38:37.330] - AdW Nee, dat klopt. Maar dan... Dan moet je je doelstelling helder formuleren. Als je biodiversiteit wil, moet je geen exoten gebruiken.

[00:38:43.800] - HvR Ja.

[00:38:44.220] - AdW Maar gewoon inheemse of ingeburgerde planten. Want ingeburgerd kan ook, want ik vind ook dat heel veel soorten die bijvoorbeeld in Frankrijk wel voorkomen. Die kunnen we hier rustig aan gaan planten, want ons stedelijk milieu is gewoon veel warmer dan Nederland van oorsprong. En een stedelijk milieu is niet meer oorspronkelijk. De omstandigheden zijn veranderd. Maar ik zou wel soorten doen die een beetje passen. Je kan heel veel... Zeker voor en begroeiing van gebouwen kan je ook zeker kijken, vind ik, naar Europese berggebieden. Want ja, daar zitten vooral planten die heel goed tegen een veel instraling, tegen wind, tegen droogte kunnen. En ja, die zouden hier van nature terecht kunnen komen. Als hier een berg lag.

[00:39:40.050] - HvR Ja.

[00:39:40.650] - AdW Ja, en een gebouw is in feite een soort berg.

[00:39:43.110] - HvR Ja. Qua weersomstandigheden.

[00:39:49.730] - HvR Ik ben ook wel benieuwd... Ik kan me natuurlijk voorstellen, ik kan niet in mijn kader, denk ik, een advies geven: gebruik deze specifieke plant. Daarvoor heb je veel meer informatie nodig van een bepaald project en van het klimaat. Maar zijn er ook manieren om planten in te delen in functionele groepen? Dus bijvoorbeeld groepen die veel dichtheid geven of bepaalde groepen die goed tegen de droogte kunnen?

[00:40:23.270] - AdW Ja hoor, er zijn hele grote planten-lijsten. Vaak is dat bij bij groen-opleidingen en dan geven ze gewoon aan van: is het een schaduw plant, kan die in de volle zon, is het inheems of ingeburgerd, geeft ie nectar, is die eetbaar voor bepaalde rupsen? Daar is wel veel informatie over. En er zijn gespecialiseerde hoveniers, ook voor dit soort projecten hè. Bijvoorbeeld, ik heb wel eens met [naam hovenier] samengewerkt. Da's een vrij grote hovenier en die doet graag dit soort wat complexere projecten. Ja, die hebben daar gewoon ook praktische ervaring mee, hoe je dit soort dingen doet. Ja, het blijft natuurlijk... Een hele hoop bedrijven willen omzet maken. Dus als je een groendak doet dan proberen ze dat met zoveel mogelijk laagjes en dure dingen te doen, in plaats van gewoon een bak grond erop storten.

[00:41:36.410] - AdW Want je hebt wel... Bijvoorbeeld je kan een licht substraat maken hè, met met vulkanische korrels en een plastic profiel eronder. Dat kan allemaal wel. Maar je kan ook zeggen: ik maak gewoon een constructie van m'n dak, een beetje sterker zodat er 500 kilo per vierkante meter bij kan. En dan pak je gewoon de grond die oorspronkelijk in dat gebied lag. Leg je er boven op. Daar hoef je daar helemaal niet moeilijk over te doen.

[00:42:01.860] - HvR Ja. Ja, behalve dan wat voeding er in laten komen?

[00:42:10.320] - AdW Nee, het is circulair. En bovendien er komt zoveel stikstof uit de lucht en in een natuurgebied gaat ook niemand de voeding toevoegen. Helemaal niet nodig.

[00:42:19.970] - HvR Nee klopt, maar dat staat wel meer in verbinding. Dus vandaar.

[00:42:26.230] - AdW Nee hoor, en over t algemeen heeft de Nederlandse bodem eerder te veel dan te weinig voeding. Dus het grootste deel van onze planten zijn juist specialist in het omgaan met weinig voedsel. Want van nature is voedsel schaars, behalve nu wij dus ontzettende hoeveelheden aan de ene kant kunstmest en mest, en aan de andere kant stikstof via de lucht aan toevoegen zijn, slaat de boel helemaal door. Maar nee, voeding is schaars. Dus daar zijn ze juist goed in. En dan krijg je juist allerlei plantjes die heel diep wortelen op zoek naar het laatste beetje eten. Als je nu bijvoorbeeld kijkt bij zo'n opgespoten terrein, een industrieterrein wat al een tijdje ligt, zie je allemaal van die kleine rozet plantjes, van die kleine geraniumtjes. Die doen het juist prima onder dat soort droge omstandigheden met veel licht, tegen zo'n gebouw aan. Dus voeding is geen probleem.

[00:43:29.370] - HvR Ja, dus als je die soorten toepast in een groene gevel, dat dan de plant zelf is wel belangrijk is, en het licht dat invalt en dat je daar naar kijkt, maar het substraat, als in de voeding of de grond, dat dat een minder grote rol speelt?

[00:43:43.050] - AdW Met een living wall, wat ze doen is...Er is niet genoeg volume aan grond om veel planten te hebben. En wat ze doen, ze gebruiken een organisch materiaal waar ze voedingsstoffen aan toevoegen zodat die plant eigenlijk veel te kleine wortels heeft in verhouding tot z'n volume. En omdat ze voedingsstoffen toevoegen, gaat ie lekker bloeien alsof ie op de beste plek ter wereld staat met een groot wortelstelsel. Maar t enige is wat ie gewoon hij is gewoon aan de dope, aan die voedingsstoffen. En als dat op de een of andere manier wegvalt. Ja het is tuinieren dan. En dat ziet er leuk uit, maar dan moet je je doelstelling daarop aanpassen.

[00:44:22.120] - HvR Ja, want wat nou als dat doel dan meer esthetisch is? Kan je in het algemeen zeggen van: bepaalde factoren, in hoe een LWS er uit ziet of hoe die is ontworpen, zorgt vaak voor een betere esthetische waardering? Of hangt dat ook weer af van waar je naar kijkt?

[00:44:39.190] - AdW Ja, die esthetische waardering dat is ook een persoonlijk iets. Maar over het algemeen vinden we iets met met veel kleur, wat het hele jaar door groen is, met veel bloemetjes.

Dat vinden we leuk. Ja en dat kan je doen doordat je als je wat rijk-bloeiende planten die ook nectar produceren toepast. Dan heb je ook nog vlindertjes die er op afkomen en bijen. Dus je maakt gewoon een een supermarkt voor een bepaalde beestjes en dat ziet er leuk uit en draagt gewoon ook bij. Want eigenlijk wat je doet is... Je produceert wat extra voedsel, niet in een natuurlijk systeem maar in een opgepept systeem. Maar dat geeft nog steeds voedsel. En daar kunnen ook veel insecten uit komen die vervolgens als voer dienen voor het ecosysteem. Je. Je geeft dus in feite wat kunstmest aan het systeem.

[00:45:28.130] - HvR Ja, je bootst eigenlijk iets na wat ergens anders niet bestaat.

[00:45:29.570] - AdW Ik kan me voorstellen, dan ziet je LWS er extra leuk uit.

[00:45:34.250] - HvR Ja.

[00:45:36.140] - AdW Maar ja, het heeft wel kosten want het is gewoon duur, zo'n LWS.

[00:45:41.030] - HvR Ja. Nee inderdaad, zeker. En zijn er dan ook voor die directe of indirecte groene facade... Zijn er binnen klimplanten dan ook soorten die groen blijven, bloeien en nectar geven? Of is dat vaak meer het geval bij planten op een LWS?

[00:46:02.510] - AdW Een klimop, die blijft groen het hele jaar door, dus dat is fijn. En die produceert ook wel nectar, maar die bloemen zijn niet erg opvallend. Wat je dan vaak ziet is dat ze een klimop variëteit gebruiken die van die lichte vlekken heeft in z'n bladeren. In feite is dat een virusziekte, maar wij vinden dat mooi. Dus daardoor krijg je een wat kleuriger beeld. Maar dat kan je bijvoorbeeld combineren. Zo eentje met met een ander, met een wingerd ofzo, die in het najaar van die mooie rode bladeren krijgt en die laat z'n blad wel vallen. Maar als je dan ook nog die altijd groene ertussendoor hebt, dan valt het mee.

[00:46:45.110] - AdW Je hebt een paar klimrozen wat ik wel te wel leuk vind... Rozen die je vooral, niet van die dubbele maar die meer natuurlijke rozen, die passen ook best wel in zo een systeem. Die zijn vaak heel robuust en dat zijn vaak wat wat dunne takjes die overal een beetje tussendoor gaan. Kamperfoelie is natuurlijk een prachtige, die klimt zelf ertussendoor. En zo zijn er nog wel wat meer te bedenken. Het ligt ook een beetje aan het type grond wat je hebt. Zuur en vochtig is vaak wat anders dan droog en kalkhoudend.

[00:47:24.260] - HvR Ja.

[00:47:24.860] - AdW Maar dat kan je... Zeker als je de grond zelf kan bepalen, want dat is vaak zo natuurlijk. In een stedelijk gebied is die grond al lang niet natuurlijk meer. Heel vaak wordt de toplaag afgegraven of bedekt met een zandlaag en dan kan je daar gewoon een bodemmengsel neerleggen die vaak met compost en zand gemaakt is.

[00:47:48.000] - HvR Dus daar heb je zelf ook invloed op? Dan kan je er gewoon voor kiezen, van we willen deze planten, dus deze grond of andersom. Ja, interessant.

[00:47:59.290] - HvR Volgens mij heb ik wel zo'n beetje alle onderwerpen aangesneden. Als laatste, wat bredere vraag. Welke aspecten zijn nou goed, qua biodiversiteit en plantkeuze dan, zouden goed zijn om mee te nemen in een ontwerp- kader? En dat ontwerp kader gaat eigenlijk vooral over: moeten we een groene gevel toepassen en welke soort? Dus is er nog iets waarvan u denkt, naast wat we allemaal hebben besproken, dat moet er echt nog verwerkt worden? Als óf iets wat de score op de potentie van elk systeem beïnvloedt. Of misschien meer aanbevelingen voor daarna, dus de tool aangeeft, stel je wil ontwerpen voor diversiteit, dan is dit belangrijk...

[00:49:04.670] - AdW Ik denk dat je zo'n groene muur vaak als onderdeel van een systeem moet zien. Dus als je bijvoorbeeld wil dat er vogels ook gaan nestelen in je groene wal, dan moet het ook rustig zijn. Dus als je je klimplanten direct naast een deur hebt, waar de hele tijd mensen naar binnen lopen dan zal dat niet lukken. Je moet dus zorgen dat ook een wandelpad wat verder weg is en bijvoorbeeld dat je nog wat struiken hebt op maaiveld, dat er echt een wat afstand is, dat er rust is. Dat is heel belangrijk voor vooral broedende vogels dan, maar bijvoorbeeld ook een egel. Die kan dan, die heeft ook een rustige plek nodig.

[00:49:43.820] - AdW En variatie in je systeem hè. Want allerlei dieren, die hebben ook water nodig. Dus als je in de buurt ook water hebt waar ze iets kunnen drinken. Een libelle bijvoorbeeld. Die zitten heel graag... Als die libelle larven uit het water komen en dan willen ze graag een territorium bevechten. Maar dat kunnen ze de eerste dagen nog niet, want ze zijn nog jong en onervaren. Dus dan vliegen ze weg, ergens naar een rustig plekje. En dat kan klimplanten ook die op tien, twintig of dertig meter van het water af zijn. Zo'n plekje kan heel erg mooi voor ze zijn, dus daar moeten ze dan wel. Als er water in de buurt is, dan kan een groene wal van belang zijn voor libellen. Om eens iets te geven. En hetzelfde geldt een beetje voor als je op maaiveld een bloem- en kruidenrijk weitje hebt, waar dus veel bloemen zijn, waar vlinders nectar kunnen halen, maar die willen dan 's nachts, willen ze wel op een rustig plekje tussen de vegetatie kunnen kruipen en dat kan die functie van die groene wal zijn.

[00:50:51.460] - AdW Dus het is ook onderdeel van wat je met je hele groene omgeving doet. Alleen een groene wall heeft minder waarde dan als het onderdeel is van een divers systeem waar nog meer dingen aangeboden worden.

[00:51:05.900] - HvR Ja.

[00:51:07.390] - AdW En hetzelfde geldt bijvoorbeeld helemaal... Zo'n groene muur op grondniveau, kan je bijvoorbeeld ook wat boomstronken en takken-hopen, die helemaal vochtig en donker liggen waar niks gaat groeien, maar wat wel een mooie schuilplaats is voor allerlei slakken, larven en dergelijke. Die als het bijvoorbeeld heel warm en droog is vanuit de groene wal terug kunnen trekken in zo'n koele vochtige omgeving. En dan maak je het dus mogelijk. Want dieren en planten die... De gemiddelde omstandigheden zijn niet zo belangrijk als de extreme. Als het namelijk heel extreem is dan gaan ze dood. Dus je moet zorgen dat ze ook bij extreme omstandigheden. Dat is dus heel erg koud, heel erg droog, heel erg warm. Ook nog een plekje kunnen vinden.

[00:51:59.240] - AdW En dat soort dingen zijn heel erg nuttig en dat kan natuurlijk bij klimplanten ook. Bijvoorbeeld vogelnestjes, die kan je ophangen aan een muur waar die klimplanten omheen gaan. En in zo'n nestkastje. Op een gegeven moment is ie misschien helemaal overgroeid, maar dat geeft niet. Dan gaan de spinnen overwinteren. Zoiets blijft wel nuttig. Dus zorg dat het onderdeel is van een systeem waar de de planten en dieren die je zoekt het hele jaar door alles kunnen vinden wat ze nodig hebben.

[00:52:35.010] - HvR Ja, dus als ik het goed begrijp, dat je eigenlijk beredeneert vanuit het systeem en de behoeftes die dieren die je wil, hebben. En dat je dan goed kijkt: biedt ons hele systeem, met onder andere de groene gevel, genoeg habitat daarvoor?

[00:53:00.180] - AdW Laten we zeggen er zijn weinig soorten die alleen van groene gevel kunnen leven.

[00:53:03.910] - HvR Nee precies.

[00:53:07.610] - AdW Maar het is dus zeker een nuttige toevoeging en het kan voor sommige soorten. Bijvoorbeeld de huismus, die heeft echt dicht struweel nodig en dat kan ook. Kan ook een vuurdoorn zijn die tegen een gevel opgegroeid is. Die heeft echt zo'n soort plek nodig. Een zonnige, donkere, en veilige struik waar ze een groot deel van tijd in doorbrengen. Als dat ontbreekt, ook al hebben ze een nestplaats en hebben ze een plek om te eten. Maar als er dus een paar goeie struiken waar ze zich in terug kunnen trekken... Als dat ontbreekt dan kunnen ze er gewoon niet overleven. Dus het kan echt een een essentiële toevoeging zijn in een leefgebied.

[00:53:48.960] - HvR Ja, duidelijk. Ik hoor veel terug wat ik heb gelezen, het biedt zeker wat goede inzichten denk ik.

[00:54:06.480] - AdW Ja, ik denk het meeste wat ik ook vertel dat zal ook ergens anders wel staan hoor.

[00:54:12.000] - HvR Nee klopt, maar het is toch fijn om even te bevestigen... Fijn om te horen, het ene is echt belangrijk, het andere iets minder belangrijk. En ja, dat je het iets meer naar de praktijk kan trekken. Wat als je een groene gevel wil, hoe kan je die dan goed ontwerpen? Ja dank. Ik denk dat ik wel zo'n beetje door al mijn vragen heen ben.

[00:54:44.860] - AdW Mooi, prima, Nu ga je je scriptie schrijven of je bent er al weer bezig neem ik aan?

[00:54:51.010] - HvR Ja zeker, eigenlijk heb ik bijna mijn kader wel af. Alleen nu moet ik het dan echt nog even helemaal afmaken en dan ga ik het testen op een project wat al is afgerond.

Het Stadskantoor in Venlo. Daar hebben ze een groene gevel op toegepast. Dus dat ga ik eigenlijk achteraf testen of mijn tool dan zou hebben geholpen of tot een andere keuze voor een ander systeem zou hebben geleid. En eigenlijk is het doel van mijn tool om een iets beter geïnformeerde keuze te maken. En ook inderdaad om dan duidelijk te maken van: wat is dan het doel van de gevel? Om eigenlijk het ontwerpproces wat inzichtelijker te maken, want ja, mijn beeld is nu dat het vooral voor esthetische waarde of ook iets subjectiever wordt beoordeeld.

[00:55:42.760] - AdW Ja het is vaak ook PR hè.

[00:55:45.930] - HvR Ja. Er is heel veel onderzoek en er wordt nog maar weinig mee gedaan, of dat staat ook nog in de kinderschoenen. En het is ook goed om verwachtingen te scheppen. Als de render mooie groene gevels weergeeft, maar ze...

[00:56:03.070] - AdW In de winter allemaal dood zijn.

[00:56:04.480] - HvR Ja of het vijftien jaar duurt voordat die hele gevel groen is. Dan kan je dat beter bewust kiezen dan maar laten gebeuren natuurlijk.

[00:56:12.010] - AdW In je living world kan je allemaal tulpen zetten hoor.

[00:56:15.030] - HvR Ja.

[00:56:17.690] - AdW Ja, dat is op zich helemaal geen gek idee om daar bollen voor te gebruiken, want heel veel bollen die komen in een gebied waar er in de winter sneeuw ligt en in t voorjaar vochtig is. Dus wat we kunnen doen en in de zomer kurk droog is. Dus die doen het vaak prima in dit soort omstandigheden. Alleen het is maar tijdelijk en dan hangen al die dooie blaadjes daar een tijdje.

[00:56:38.720] - HvR Ja precies.

[00:56:39.260] - AdW Ja, je kan het wel combineren natuurlijk met iets anders. Er moet wel al een beetje aan de... Hoewel niet alles, want blauwe druifjes, die kunnen best wel in de schaduw. Maar krokussen kunnen nog redelijk wat, tulpen die hebben wel veel zon nodig denk ik. Narcissen... Maar dat zou kunnen. Ik bedoel, het ziet er grappig uit en...

[00:56:59.920] - HvR Voor een zuidgevel met veel zon, misschien dat ze het dan beter doen.

[00:57:03.230] - AdW Ja, die kunnen bij wijze van spreken ook helemaal uitdrogen in de zomer, dat hoeft geen probleem te zijn.

[00:57:08.380] - HvR Oh ja.

[00:57:09.700] - AdW Want in de week in de zomer zijn ze gewoon, sterven ze af, houden ze alleen die bol over en die bol heeft geen water nodig, die zit in de grond.

[00:57:15.910] - HvR Ja.

[00:57:17.660] - AdW Dan ontwerp je een vegetatie die past bij de condities die je hebt op je gevel, in plaats van dat je je condities aanpast door moeten gaan beregenen.

[00:57:32.960] - HvR Ja, dus je kan twee kanten op redeneren.

[00:57:35.240] - AdW Je hebt een groen dak, je het ook een bruin dak. Dat concept ken je?

[00:57:41.400] - HvR Niet echt eigenlijk.

[00:57:42.900] - AdW Dat is een groen dak zonder ontwerp. Je brengt alleen maar substraat aan of je kan eventueel nog inzaaien. Maar je wacht dan wat er binnenkomt. Ik heb wel eens een keer een brandnetel dak ontworpen. Brandnetels zijn best wel goede planten, want die zijn ontzettend sterk, kunnen heel goed tegen droogte en vormen voedsel voor allerlei vlinders. Dus... En hebben geen onderhoud nodig. En een brandnetel dak. Dat doe je natuurlijk niet op een plek die esthetisch van belang is, maar als ie volledig uit het zicht is.

[00:58:13.370] - AdW Dan is er helemaal niks mis mee om een brandneteldak te hebben, want dat is in stedelijk gebied een steeds zeldzamer wordende plant, terwijl het een belangrijke voedselplant is voor verschillende rupsen. Dus dat soort dingen. Als het esthetisch niet beperkend is, dan kan je d'r hele grappige dingen doen.

[00:58:34.080] - HvR Maar inderdaad, het komt dan uiteindelijk toch er weer op neer: wat is het doel van de gevel? Of wat wil je er mee bereiken qua biodiversiteit of planten of andere functies?

[00:58:43.260] - AdW Maar dan voeg je dus op het grotere geheel een functie toe.

[00:58:51.980] - HvR Ja, interessant. Ik heb heel veel aantekeningen en ook de opname, dus ik kan er lekker mee aan de slag met al deze informatie. En als ik iets af heb qua product of een mooie tool, dan zal ik dat ook delen.

[00:59:08.560] - AdW Dat is leuk.

[00:59:09.430] - HvR Ja, ja.

[00:59:10.150] - AdW Zeker ja, want ook in onze ecologengroep zijn er genoeg mensen die... Ja, wij kijken hier met interesse naar en proberen zelf ook eens wat uit. Maar dit is nog iets wat in ontwikkeling is, dus het is echt best interessant.

[00:59:22.300] - HvR Klopt, zeker.. Nou bedankt in ieder geval en ik stuur wel mailtje als ik nog andere vragen heb.

[00:59:39.380] - AdW Ja prima. Ja en wat je aan literatuur gegevens verzameld hebt, daar ben ik wel heel erg geïnteresseerd in.

[00:59:46.370] - HvR Ja ik heb een stukje biodiversiteit als één van ecosysteemdiensten dus. Maar ja, dat kan ik dan als het af is wel even opsturen.

[00:59:57.320] - AdW Ja nee, maar ik werk bijvoorbeeld ook wel met projecten van BREEAM. Ken je dat?

[01:00:01.160] - HvR Ja.

[01:00:01.520] - AdW Ja dus daar wordt ook vaak gevraagd naar groene muren, groene daken en zo. Dus als jij je literatuur lijstje hebt dan ben ik daar ook wel in geïnteresseerd.

[01:00:11.780] - HvR Ja kan ik zeker even kijken. Zal ik even kijken of wat goede bronnen heb. Want er is zeker wat over te vinden en ook best wel weer. Verschillende landen en soorten onderzoek..

[01:00:25.060] - AdW Ja. En dat scheelt heel erg. Je moet heel goed kijken in welk land een bepaald onderzoek gedaan is. Ja, want in de natte tropen is het echt anders dan hier.

[01:00:35.030] - HvR Ja klopt ja, d'r zijn heel veel onderzoeken in. Italië bijvoorbeeld, maar ook in Azië wel. Maar dat zijn eigenlijk twee gebieden waar heel veel studies over zijn. Terwijl in Nederland valt wel mee of Duitsland op een beetje vergelijkbaar hoogte. Nee dat heeft in dat veel invloed. Ja. En super, bedankt!

[01:00:59.560] - AdW Prima! Succes verder.

[01:01:01.570] - HvR Wie weet tot ziens. Ja, bedankt voor de tijd in ieder geval.

[01:01:04.990] - AdW Okido, doeg.

[01:01:06.310] - HvR Doeg!

11.5 Existing design guidelines and standards

Chapter 5 establishes the relevance of design considerations to achieve a functioning, cost-effective and sustainable VGS that performs in terms of delivering the desired benefits. Research and practice have found that an early integration of facade greening into the design and planning process is beneficial to coordinate the implications of different design criteria and to enable green care and maintenance (Hollands & Korjenic, 2021; Moghtadernejad et al., 2020; Chew et al., 2019).

Given the potential of VGS, some cities are putting policy drivers in place to enhance implementation of VGS, such as the stipulation in the new construction regulations of Vienna to green 20% of the façade area (Hollands& Korjenic, 2021). A scheme for high-rises in Singapore which finances up to 50% of the installation costs of green roofs and VGS has resulted in greening of more than 110 existing buildings (Giordano et al., 2017). However, in most cases European cities, including London, choose to develop and provide technical and design guidelines. Although these existing guidelines provide a practical insight into the possibilities for VGS, few include the full life cycle of VGS and they are mostly country- or context-specific (Giordano et al., 2017). Other guidelines focus on 'design for maintainability' (Chew et al., 2019) rather than balancing a more complete consideration of functional criteria.

Four attempts in literature to facilitate the complex design process of VGS are further analysed. All define criteria to choose the most suitable VGS, but each has its own particular focus, such as on technical requirements or benefits. Table **??** provides a brief of the scopes and limitations found.

Source	Applicability and limitations	Included parameters (requirements, indicators, criteria)
Technical standard proposal (Giordano et al., 2017)	- Only LWS - Plant database based on indoor comfort - Based on Italian standard for green roofs	- Ecological requirements - Detail examples - Maintenance strategies
Process tree (Perini et al., 2013)	- Only energy savings as microclimatic benefit - Simplified design choices - Lacks comparable scoring	- Architectural and structural building characteristics - Plant species - Materials, dimensions, weight, durability, environmental impact, costs
Automated design process (Hollands & Korjenic, 2021)	- Five system common in Austria - Type of system and size of green based on personal preference - Austrian norm for parameter structure - Excluding irrigation	- Optimal placement based on orientation, size, maintenance - Plant recommendations - Cost benchmarks
Multi-criteria valuation of benefits (Den Hartog, 2022)	- Context of distribution centres in NL - Wellbeing and water management excluded - Ecosystem services as only decision criteria - System components as performance indicators	- Context-specific weighing of benefits - Classification according to system components and categorized plant species - Utility scoring based on achievable ecosystem services

Figure 11.1: Overview of scope and limitations of four existing design guidelines and standards

Technical standard proposal by Giordano et al. (2017) [39]. Giordano et al. (2017) proposed a first technical standard drafted by academics for the design and planning of VGS. The purpose of this standard was to make available harmonized information to the target group consisting of stakeholders in design, production, operation and repair of VGS. From interviews with manufacturers, agronomists, architects and researchers, and qualitative literature research, a methodological framework formed the basis for the standard proposal.

The resulting standard proposal starts with ecological requirements, specified according to life cycle category impact, quantitative requirement and traffic light indicator. The subsequent sections 'project and design' and 'construction and monitoring' discuss details and guidelines. Regarding maintenance, the standard proposal proposes a distinction between routine maintenance (irrigation equipment check, pruning) on an average or high frequency, and special maintenance (repairs and replacements). Limitations of this standard are the inclusion of merely living wall systems, ecological requirements, and detailing mainly relating to a plant database focussed on indoor comfort effectiveness. Although the standard is in accordance with the Italian standard UNI11235 for green roofs, Giordano et al. (2017) claim that the standard is based on a robust framework applicable at a global scale.

Process tree by Perini et al. (2013) [67]. Perini et al. (2013) developed a process tree that provides a full perspective on the main parameters to choose the most viable type of greening system. A first scheme guides towards a first indicative choice of VGS typology and plant species. After architectural (presence of windows) and structural (light or heavy envelope) characteristics that determine the possibility of fixing, the scheme provides the possibilities for microclimatic benefits achievable, system types and plant species. A second scheme considers materials, dimensions, weight and durability, which results in an indication for energy savings, environmental impact and costs range. As such, the process tree takes into account critical aspects such as building characteristics, environmental impact and costs. Irrespective of this relatively comprehensive scope, the process tree is based on a simplification of the design choices, merely includes energy savings as ecosystem service and lacks an overall comparable scoring of alternatives.

Automated design process by Hollands & Korjenic (2021) [37]. A simplification of VGS decision-making is also offered by an integration into Building Information Modelling (BIM) by Hollands & Korjenic (2021). Through a combination of data-driven automation and manual input, the process evaluated simulated greening variants based on defined decision criteria. In selecting BIM settings and objects, the type of system and size of green needs to be manually put it, based on personal preference. In the following simulation, an optimal placement of green is based on orientation, desired size and maintenance considerations (such as accessibility). Plant recommendations and costs benchmarks are included, but not very comprehensive. Although the process provides the most efficient placement of VGS on facades, it is limited to five common VGS in Austria, based on an Austrian norm for digital parameter structures and excludes irrigation.

Valuation of benefits by Den Hartog (2022) [45]. Whereas Hollands & Korjenic (2021) automated the effect of design choices on the VGS, Den Hartog (2022) focusses on mapping the benefits provided by VGS through ecosystem services. A multi-criteria decision making model on the ecosystem services of VGS was developed, in order to facilitate quantitative impact assessment and evidence-based decision-making. The research classified VGS based on the three main system components vegetation, substrate and support system, as these were found to be key variables for the performance. Although Den Hartog identified possible key performance indicators (KPIs), the resulting decision matrix uses utility scores to quantify the relation between choices for system components and the performance in terms of ecosystem services. The research notes that a case-specific weighing of the ecosystem services can allow the model to be applied in practice.

Limitations of the decision-making model are the excluded ecosystem services of wellbeing and greywater treatment as well as the focus on the context of distribution centres in the Netherlands. More importantly, Den Hartog reasons that the ecosystem approach is a suitable way to evaluate the diversity of benefits of VGS. The model therefore equals performance of a VGS type to the degree to which ecosystems can be delivered. However, this literature review shows that the performance is also evaluated in terms of environmental impact and (social) cost-benefit analyses. On top of that, performance is not only dictated by system components, but also affected by maintainability, durability, building characteristics and climatic conditions. As such, a decision for a VGS cannot be based purely upon ecosystem services benefits.

From the design considerations as well as the existing guidelines and standards, it can be concluded that there is a lack of comprehensive tools and guidelines that efficiently integrate VGS into the decision-making, design and planning processes. Different decision criteria and scopes as well as geographical limitations in terms of norms and climate conditions make the available design guidelines oftentimes incomplete and incomparable.

11.6 Criteria: Excluded ecosystem services

The following ecosystem services associated with VGS are excluded from the scope of this study, because limited evidence was found in literature.

- Educational effects
- Reduction of sun glare
- Solar energy generation (in combination with PV-panels)
- Food production
- Fire risk reduction
- Recreation
- Filtering rainwater runoff

11.7 Performances

11.7.1 Maximum external wall surface temperature differences ΔT_{ow}

This appendix reviews findings on maximum external wall surface temperature differences.

Cooling period For direct green facades (DGF), maximum ΔT_{ow} during summer ranges from 1.2 °C [86] (no direct sunlight) to 13 °C [259] in a warm temperature climate (C) (table 11.5). Climate types are considered in terms of the Köppen-Geiger classification. Within this range, other experimental studies found maximum reductions of 8.3 °C and 12.6 °C, with average reductions of 5.7 °C and 0.7 °C, respectively [126, 260]. This suggests that plants absorb and reflect a considerable amount of solar radiation [26].

Maximum ΔT_{ow} for indirect green facades (IDGF) can be estimated between 13.9 °C to 16.4 °C in warm temperature climate (C) (table 11.5). Data analysis comparing the thermal performance of green facades (DGF and IDGF) from 26 articles showed that during hot periods ($T_o >$ 30 °C) the external wall surface temperature with GF was always cooler than the external wall without GF, with a mean ΔT_{ow} of 3.5±4.1 ∘C [10]. Although one study determined that all-day cooling on GF is 39.9% dependent on transpiration and 60.1% on shading during clear summer days, other studies found a more limited shading contribution of 25-30% [261].

For LWS, considerable maximum ΔT_{ow} for similar conditions (warm temperate climate, summer) range up to 23 °C [262]. Similarly, Scharf, Pitha, and Oberarzbacher [263] reports summer ΔT_{ow} for LWS of 10-15 °C. Reductions for LWSC range between 16 °C and 23 °C (appendix 11.7.1). LWSMT performs at 6.9-9.3 °C, whereas LWSMB often reaches lower reductions, varying from 5.0 to 20.8 °C. The tendency of larger reductions by LWSMT than LWSMB is reflected in an experimental study by Salonen et al. [25]. For LWSL, one study found a ΔT_{ow} of 8.4 °C [123].

Ultimately, review studies conclude that LWS provide slightly larger cooling effects in summer than GF (table 11.2) [26].

Heating period In addition to the cooling effect of VGS, there is also strong empirical evidence of a heating effect in colder conditions. Predominantly, insulation created by VGS vegetation canopy reduces heat losses from the building into the atmosphere, hence the energy efficiency for heating increases [152]. External wall surface temperatures of GF are warmer during cool and cold conditions, with a mean ΔT_{ow} of 2.8 ± 12.5 °C [10]. Within this range, direct green facades in the UK were able to enhance surface wall temperatures in winter by 0.5 °C (mean) [101], up to 3.0 °C [102]. The latter study also observed that the colder the temperature, the more effective the insulation [102].

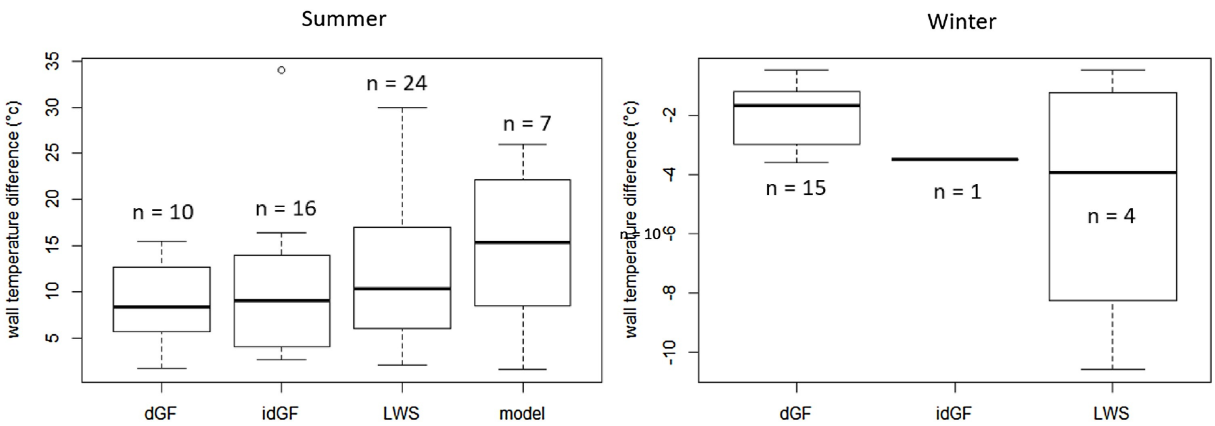


Figure 11.2: ΔT_{ow} in summer (left) and winter (right) (N.B.: summer values are cooling/decreasing, winter values are warming/increasing) (n = number of studies, dGF = direct GF, idGF = indirect GF, LWS = living wall system, model = modelling studies, adopted from [26]

For LWS, wintertime ΔT_{ow} are less well reported, although a handful of studies indicate a increase around 4 °C (figure 11.2). Tudiwer and Korjenic [264] found increases of ΔT_{ow} by 3.5 °C for a LWSMT and 0.5°C for a LWSMB. Behind a LWSL, an outlying maximum increase of 10.6 °C was found [123].

In an attempt to estimate the heat mitigation efficiency of GF, Bakhshoodeh, Ocampo, and Oldham [10] applied linear regression on (in)direct GF performances. They derived ΔT_{ow} normalized by the temperature difference between external wall without GF and ambient air . The results showed that indirect GF reduce the external surface wall temperature more effectively than direct GF, in hot and warm conditions. Also, the temperatures of external walls behind indirect GF were warmer than those of direct GF, during cold periods. Therefore, using IDGF under cold, warm and hot conditions would lead to more savings in building heating and cooling costs, than when using DGF.

***Maximum* external wall surface temperature difference (˚C)**	**Cooling/ heating period**	**Period**	**Climate**	**Orien-tation**	**VGS type**	**Plant species**	**Type of study**	**Source**
				DGF				
-13	Cooling	s	Cfa	W	DGF	*Hedera* or *Parthenocissus*	Exp.	\cite{Hoyano1988}
-8.3 (av. 5.7)	Cooling	s	Cfb	E	DGF	*P. triscuspidata*	Exp.	\cite{Konto2009}
-1.2	Cooling	a	Cfb	NW	DGF	*H. Helix*	Exp.	\cite{Perini2011T}
-12.6 (av. 0.7)	Cooling	s	Dfa	E	DGF	*P. triscuspidata*	Exp.	\cite{Suso2014}
-15.5	Cooling	s	Dfb	SW, E	DGF	*P. triscuspidata*	Exp.	\cite{Hoelscher2016}
-13.5	Cooling	s	Dfb	SW, E	DGF	*H. helix*	Exp.	\cite{Hoelscher2016}
-1.7	Cooling	s	Cfb	-	DGF	*H. helix*	Exp.	\cite{Otte2017T}
+0.5 (mean)	Heating	w	Cfb	N	DGF	*H. Helix*	Exp.	\cite{Bolton2014}
+3.0	Heating	w	Cfb	Several	DGF	*H. helix*	Exp.	\cite{Cameron2015}
+1.7	Heating	w	Cfb	-	DGF	*H. helix*	Exp.	\cite{Otte2017T}
				IDGF				
-4.4	Cooling	w	Af	-	IGFT	-	Exp.	\cite{Wong2010}
-10.5	Cooling	s	Dfb	W	IDGF	*Fallopia baldschuanica*	Exp.	\cite{Hoelscher2016}
-13.9	Cooling	s	Cfb	E-S-W	IDGF	*P. triscuspidata*	Exp.	\cite{Coma2017}
-15	Cooling	s	Cfa	E	IGFT	*P. triscuspidata*	Exp.	\cite{Perez2017LAI}
-16	Cooling	s	Cfa	S	IGFT	*P. triscuspidata*	Exp.	\cite{Perez2017LAI}
-16.4	Cooling	s	Cfa	W	IGFT	*P. triscuspidata*	Exp.	\cite{Perez2017LAI}

Figure 11.3: [Part 1 of table] Maximum ΔT_{ow} (ms = multi-seasonal, s = summer, w = winter, a = autumn; adapted from [43], [26] and individual studies, with more extensive VGS types)

LWSC								
-20	Cooling	s,a	Cfa	SW	LWSC	15 species, including *Juniperus communis, Sedum spurium,* and *Geranium sanguineum*	Exp.	\cite{Mazzali2013}
-16	Cooling	s,a	Cfb	SW	LWSC	*Zoysia sp.*	Exp.	\cite{Mazzali2013}
-18.9	Cooling	ms	Dfc	S-E	LWSC	Grass	Exp.	\cite{Medl2017T}
-23	Cooling	s	Cfb	S	LWSC	*L. nitida L.*	Exp.	\cite{Bianco2017}
LWSM								
-10.0	Cooling	ms	Af	-	LWSMB	-	Exp.	\cite{Wong2010}
-11.6	Cooling	ms	Af	-	LWSMB	-	Exp.	\cite{Wong2010}
-10.9	Cooling	ms	Af	-	LWSMB	-	Exp.	\cite{Wong2010}
-6.9	Cooling	ms	Af	-	LWSMT	-	Exp.	\cite{Wong2010}
-9.3	Cooling	ms	Af	-	LWSMT	-	Exp.	\cite{Wong2010}
-16.0	Cooling	w,s	Cwa	W, W-SW	LWSMB	Perennial grass	Exp.	\cite{Cheng2010}
-5.0	Cooling	a	Cfb	W	LSWMB	Evergreen perennial	Exp.	\cite{Perini2011T}

Figure 11.4: [Part 2 of table] Maximum ΔT_{ow} (ms = multi-seasonal, s = summer, w = winter, a = autumn; adapted from [43], [26] and individual studies, with more extensive VGS types)

-20.8	Cooling	s	Cfa	W	LWSMB	-	Exp.	\cite{Chen2013}
-12	Cooling	s,a	Csa	SW	LWSMB	*Cynodon sp., Stenotaphrum secondatum., Dicondra sp., Paspalum vaginatum*	Exp.	\cite{Mazzali2013}
-13.8 ± 9.5 (av.)	Cooling	ms	Csa	S	LWSMB	*Sedum L.*	Exp.	\cite{Oli2014}
-20.1	Cooling	s	Csa	E-S-W	LWSMB	*Rosemarinus officinalis, Helichrysum thianschanicum*	Exp.	\cite{Coma2017}
-15	Cooling	s	Cfb	E, W	LWSMB	*Sedum, Mentha, Thymus, Vinca, Campanula, Delosperma*	Exp.	\cite{Djed2017}
-11.6	Cooling	s	Cfb	S	LWSMB	-	Exp.	\cite{Sal2022}
-9.3	Cooling	s	Cfb	S	LWSMT	*Sedum, Bergenia*	Exp.	\cite{Sal2022}
+3.5	Heating	w	Dfb	S	LWSMT	-	Exp.	\cite{Tudi2017}
+0.5	Heating	w	Dfb	S	LWSMB	-	Exp.	\cite{Tudi2017}
LWSL								
-8.4	Cooling	s	Cfb	-	LWSL	*Lamium galeobdolon, Carex sp. Alchemilla sp., Host*	Exp.	\cite{Otte2017T}
+10.6	Heating	w	Cfb	-	LWSL	*Lamium galeobdolon, Carex sp. Alchemilla sp., Host* or *Ferns, Geranium sp. Carex sp.*	Exp.	\cite{Otte2017T}

Figure 11.5: [Part 3 of table] Maximum ΔT_{ow} (ms = multi-seasonal, s = summer, w = winter, a = autumn; adapted from [43], [26] and individual studies, with more extensive VGS types)

11.7.2 Other indicators: heat flux and indoor temperatures

This appendix reviews other indicators of thermal regulation.

Heat flux

A reduction of heat flux is enabled by heat absorption by plants and moist substrates for evapotranspiration, and can explain lower facade temperatures [48]. For example, a heat transfer difference (ΔQ) of -57 W/m^2 was derived for a LWSC in summertime conditions for which ΔT_{ow} is -20 °C [114]. In a relative sense, Djedjig, Belarbi, and Bozonnet [94] found ΔQ of -97% and -80%, for summer (reduction in heat gain) and winter (reduction in heat loss), respectively. During winter, 56-70% less heat loss was found for LWSC [262]. In a quantitative sense, the influence on the calculated thermal resistance (R) in winter lies between 0.31 and 0.68 m^2K/W , for a corresponding ΔT_{ow} of 0.5 °C (LWSMB) and 3.5°C (LWSMT), respectively [264]. Anyway, these heat flux reductions show the moderating effect of VGS on summer- and wintertime heat transfer through VGS facades.

Indoor temperatures

Indoor temperatures can be reduced by 10 °C [15], but the effect on the indoor temperatures in absolute terms is often smaller than on the external wall surface temperature.

Some studies characterise thermal performance in terms of the inner surface wall temperature difference (ΔT_{iw}). Olivieri, Olivieri, and Neila [265] found a lower average ΔT_{iw} of 8.62 ± 2.68 °C than the ΔT_{ow} of -13.8±9.5 °C (table 11.1). Other studies confirm this disparity [94, 260], although they found ΔT_{iw} reductions up to 5 °C. Likewise, another experimental study found an average ΔT_{iw} of 2.5 °C for a DGF [266].

Table 11.1: ΔT_i and ΔT_{iw} for corresponding ΔT_{ow} (adapted from [26]; for more parameters, e.g. climate, see table 11.5)

Maximum external wall surface temperature difference ΔT_i (°C)	Maximum external wall surface temperature difference ΔT_{iw} (°C)	Maximum external wall surface temperature difference ΔT_{ow} (°C)	Cooling / heating period	VGS type	Source
	-1.6 (max.), -0.9 (av.)	-8.3 (av. 5.7)	Cooling	DGF	[260]
-1.1		-20.8	Cooling	LWSMB	[122]
	-8.32 ± 2.68 (av.)	-13.8 ± 9.5 (av.)	Cooling	LWSMB	[265]
	-5 (max.)	-15	Cooling	LWSMB	[94]
-8.6 (max.)		-8.4	Cooling	LWSL	[123]
+5.5 (max.)		+10.6	Heating	LWSL	[123]

For the notable cooling effect on the exterior wall surface of 20.8 °C for a LWSMB in summer, the indoor ambient air cooling effect (ΔT_i) was only 1.1 °C [122]. On the contrary, Ottelé and Perini [123] found a maximum ΔT_i decrease nearly equivalent to ΔT_{ow} (table11.1). Other authors also demonstrated indoor micro-climatic changes with average ΔT_i reductions of 2.4 °C [267]. Moreover, the heating effect in winter also translates to indoor ambient air temperature increments [123]. This confirms cooling (-5 °C) and buffering (+7 C°) effects detected in the building during summer and winter in earlier studies [263].

However, no conclusive remarks for typology-specific thermal performance can be derived from these indoor temperatures as there are not enough results available for a meta-analysis [26].

11.7.3 PM mitigation

This appendix includes detailed PM mitigation study results.

Overview of numerical studies on the impact of green walls on atmospheric PM levels including model name, PM fraction [µm], deposition velocity (v_d) [m s^{-1}], GW dimensions as Wall Leaf Area Index (WLAI) [m^2 m^{-2}] or Leaf Area Density (LAD) [m^2 m^{-3}], GW surface area [m^2], species, model scale (H/W is the aspect ratio of a street canyon), wind speed [m s^{-1}], wind direction relative to the street axis [°], PM reduction efficiency based on mass values (E_M) or on concentrations (E_C) [%] and if the models are validated and if so their R^2 value. n.q. - not quantified.

Author	Model	PM fraction [µm]	v_d [cm s^{-1}]	WLAI [m^2 m^{-2}] or LAD [m^2 m^{-3}]	Surface area [m^2]	Species	Model scale	Wind speed [m s^{-1}]	Wind direction [°]	E_M [%][a]	E_C [%][b]	Validated
Currie and Bass (2008)	UFORE	10	0.64	n.q.	12,160,000	*Juniper*	H/W = 1	n.q.		16.6		No
							H/W = 1	2	90		10.8	
Pugh et al. (2012)	CiTTy-Street	10	0.64	2 m^2 m^{-2}	20	n.q.	H/W = 2	2	90		32.0	Only without GW
							H/W = 2	0.5	90		61.9	
					40				90		±65 [c]	R^2 = 0.79 (without GW)
								3	45		±90 [c]	
									0		±100 [c]	
Morakinyo et al. (2016)	ENVI-met	2.5	0.1	2 m^2 m^{-3}	80	n.q.	Open road		90		±70 [c]	R^2 = 0.89 (with GW)
								1	45		±90 [c]	
									0		±100 [c]	
		10	0.25 - 1						90	39.6		
Jayasooriya et al. (2017)	iTree eco	2.5	0.04 ± 0.01–9 ± 5	n.q.	288,200	*Laurus nobilis*	City scale	n.q.	90	42.9		No
				1.0;	300		H/W = 0.5	2.1	90		4.9 [d]	R^2 = 0.910 (6.5 m height)
Qin et al. (2018)	PHOENICS	10	0.64	3.5;	600	*Parthenocissus vitacea*	H/W = 1.0	2.1	90		9.3 [d]	R^2 = 0.974 (1.5 m height)
				6.0 m^2 m^{-3}	900		H/W = 2.0	2.1	90		28.3 [d]	

[a] Calculated with Eq. (6) by the authors of this review.
[b] Calculated with Eq. (7) by the authors of the particular article.
[c] Derived from graphs, at 1.4 m height within 1 m behind the GW.
[d] Values for a green wall with LAD 1 m^2 m^{-3} and coverage 300 m^2 (all results are given in Fig. 6).

Figure 11.6: Overview of numerical modelling studies on PM reduction efficiency (adopted from [144])

11.7.4 Air purification: Gaseous pollutants

Together with particulate matter, nitrogen oxides (NOx) are main pollutants of concern for their health effects ([8]). Nitrogen oxides can also lead to the formation of a secondary pollutant, low-level ozone (O3), in a photochemical reaction with VOCs (volatile organic chemicals). Other gaseous pollutants include SO2, which contributes to the acidification of soil, and NH3.

Mechanism

Plants can take up gaseous pollutants primarily through their stomata ([142]). NO2 and SO2 are converted into nitrates and sulphates in the plant tissue ([67]). Volatiles (VOCs) can be directly absorbed through the cuticle ([8]).

Performance

Very limited studies are available on the effectiveness of VGS on gaseous pollutants removal. Pugh et al. [148] reports up to 43% reduction in NO2 street-level concentrations in street canyon environments with VGS (see table 5.18). Other authors describe, but not quantify, a significantly lower concentration of toxins in the area near a LWS ([268]), or a reduction in background pollution by LWS ([184]). Table **??** shows the quantified performances of NO2, O3 and SO2 found in different modelling studies.

Pollutant	Indicator	Performance	Species	Wind speed (m/s)	Aspect ratio (H/W)	LAD (m2/m2)	Deposition velocity (cm/s)	Coverage	Type of study	Source
NO2	Reduction efficiency (%)	6.4	-	2	1	2	0.3	100%	Modelling study	\cite{Pugh2012}
		19.9	-	2	2	2	0.3	100%	Modelling study	\cite{Pugh2012}
		42.9	-	0.5	2	2	0.3	100%	Modelling study	\cite{Pugh2012}
	Reduction (mg/year)	0.23	*Juniper*	-	1	-	0.64	-	Modelling study	\cite{Currie2008}
	Reduction (kg/year)	87	*Laurus nobilis*	-	City scale	-	TBD	-	Modelling study	\cite{Jay2017}
O3	Reduction (mg/year)	1.09	*Juniper*	-	1	-	0.64	-	Modelling study	\cite{Currie2008}
	Reduction (kg/year)	298	*Laurus nobilis*	-	City scale	-	TBD	-	Modelling study	\cite{Jay2017}
SO2	Reduction (mg/year)	0.23	*Juniper*	-	1	-	0.64	-	Modelling study	\cite{Currie2008}
	Reduction (kg/year)	26	*Laurus nobilis*	-	City scale	-	TBD	-	Modelling study	\cite{Jay2017}

Two modelling studies show a potential for VGS to mitigate O3 and SO2. Still though, because reduction efficiencies (%) of O3 and SO2 were not determined, only performance claims regarding NO2 removal can be made. Pugh et al. [148] indicates that an increasing canyon aspect ratio (1 to 2) results in a higher NO2 reduction efficiency (6.4 to 19.9%), and that decreasing the wind speed (2 to 0.5 m/s) can even further increase the efficiency (19.9 to 42.9 %). As such, canyon geometry and - to a lesser extent - wind speed can be considered parameters affecting NO2 reduction efficiency.

Because of the lack of studies that validate these data with experimental studies, compare different species or VGS typologies, or determine the contribution of system components (e.g. vegetation), a system-specific (range of) performance for gaseous pollutants removal cannot be reasonably assumed.

11.7.5 Greywater treatment: study parameters

Study	Type VGS	Substrate	Vegetation	Temp (°C)	Operational factors				
					Flow (L/day)	HLR (L/m2/day)	HRT (h)	OLR(g_{COD}/ m²/day)
(1)	Pilot/real	LECA (lightweight expanded clay aggregates)	Lettuce, marigolds	-8-14	360	670-980	50.4	161.5
(2)	Lab/synthetic	68% sand mixed with 5% cedar mulch, 16% coarse sand, 16% gravel	*Stretlitzia Nicolai, Phormium* spp. *Canna lilies, Strelitzia reginae, Lonicera japonica, Carex appresa, Phragmites australis, Vitis vinifera, Pharthenocissus tricuspidate, Pandorea jasminoides, Billardiera scandens*	20-24	2.5-5	55-100	96-48	5.7-15.4
(3)	Pilot/real	50% light expanded clay mixed with 50% coco coir or sand	*Abelia, Wedelia, Portulaca, Alternanthera, Duranta, Hemigraphis*	-	240	1000	0.2-0.67	60
(4)	Lab/synthetic	100% coir or rockwool, or phyto-foam, or perlite, or vermiculite, or growstone, or expanded clay, or river sand	No plants	-	3	382	0.25-2.5	95.5
(5)	Lab/synthetic	Coco coir and perlite (proportion 2:1)	No plants	25-35	3	382	-	48.1-122.2

Figure 11.7: Design and operational parameters for greywater treatment studies

11.7.6 Private costs details

This appendix shows how the cost ranges adopted in this study were determined, mainly on the basis of Rosasco [41].

Type of VGS	Category	Cost	Cost Range (\cite{Rosasco2018})	Time Frame	Cost Range (€/m2)	Total	Other studies (€/m2)	Limitation/assumptions
Direct green facade	Initial	Design	6%–10% of installation cost	One time	2-5	**37 - 51**		
		Dig + pot	450 –550 (€ m^{-1})	One time	30 - 37		Rosa2013: 520 eu/m-1	Assuming facade height 15 m
		Plant species and installation	18–28 (€ m^{-1})	One time	1.2 - 1.9		Rosa2013: 22 eu/m-1	Assuming facade height 15 m
		Irrigation system	4–7	One time	4–7		Perini2011: 30-45 (grown climbing plants)	
	Maintenance	Pruning	2.5–3.5	Annual		**3 - 4,4**	Rosa2013: 2.8	
		Irrigation (H_2O)	0.2–0.5	Annual				
		Pipes replacement (irrigation system)	0.3–0.4	Annual			Manso2021: 5,57 eu/m2/y	
	Disposal	Green layer disposal	30–45	One time (end of lifespan)		**30 - 45**	Rosa2013: 31	
Indirect green facade	Initial	Design	6%–10% of installation cost	One time	9-28	**HDPE: 146- 219; Steel: 206 - 284**		
(HDPE or steel)		Dig + pot	400–550 (€ m^{-1})	One time	27-37		Rosa2016: IGFT (Steel): 425 /m > 28 /m2; Rosa2013 IGFT Steel: 36; Rosa2013 IGFT (HDPE): 520 /m > 35 /m2	
		Supporting system and transportation	35–110	One time	HDPE: 35-45; Steel: 95-110		Rosa2013: IGFT (Steel): 94 /m2; Rosa2016: IGFT (Steel): 105; Rosa2013 HDPE: 36 /m2	Transportation based on city of Genoa, Italy (Rosa2013), with production companies being 300-340 km away.

		Installation of supporting system	70–100	One time	70-100		Rosasco2018: total inst 125 hdpe: 240 steel mesh	
		Plant species and installation	18–28 (€ m^{-1})	One time	1.2 - 1.9		Rosa2013: IGFT (HDPE): 22 /m; Rosa2013: IGFT (Steel): 1.5 /m2; Rosa2016: IGFT (Steel): 1.5 /m2	
		Irrigation system	4–7	One time	4-7			
	Maintenance	Pruning	2.5–3.5	Annual		**3,0 - 4,4**		
		Irrigation (H_2O)	0.2–0.5	Annual				
		Pipes replacement (irrigation system)	0.3–0.4	Annual			Manso2021: 5,57 eu/m2/y	
	Disposal	Green layer disposal	160–220	One time (end of lifespan)		**160 - 220**	Manso2021: 95 eu/m2	
	Tax incentives	Tax reduction	Depends on local regulation	One time or annual				
Indirect green facade	Initial	Design	6%–10% of installation cost	One time	12-41			
with planter boxes		Supporting system and **transportation**	35–110 (€ m^{-2})	One time	HDPE: 35-45; Steel: 95-110	**HDPE: 202-306; Steel: 293-406**		
(HDPE or steel)		Installation of supporting system	70–100	One time				
		Plant species	25–50	One time				
		Planter boxes	35–70	One time	HDPE: 35-45; Steel: 60-70			

		Irrigation system	25–35	One time			Perini2011: HDPE 100-150, coated steel 400-500, zinc-coated steel (galvanized) 600-800 (TOTAL); Rosasco2018: 165 HDPE, 330 steel	
	Maintenance	Pruning	4–6	Annual		**10.5 - 15.5**		
		Irrigation (H_2O)	1.0–1.5	Annual				
		Plant species replacement (5%)	3.5–5.0	Annual				
		Pipes replacement (irrigation system)	2–3	Annual				
	Disposal	Green layer disposal	160–220	One time (end of lifespan)		**160 - 220**	Manso2021: 95 eu/m2	
	Tax incentives	Tax reduction	Depends on local regulation	One time or annual				
Living wall system	Initial	Design	6%–10% of installation cost	One time	14 - 59			
		Panels, installation, and transportation	160–450 (€ m^{-2})	One time				
		Plant species	25–50	One time	Total: 185 - 500 (panels and plant species)	**224 - 594**		
		Irrigation system	25–35	One time			Manso2021: 750 eu/m2	
							Riley2017: 400 - 570	
							Perini2011: felt 350 – 750 eu/m2 (me: 550)	

							Perini2011: plant boxes HDPE 400-600 (trough planters > 500), foam substrate 750-1200 (framed boxes modular > 975)	
	Maintenance	Pruning and panels adjustment	12–18	Annual				
		Irrigation (H2O)	1.0–1.5	Annual				
		Panels replacement (5%)	5–8	Annual		**23.5 - 35.5**		
		Plant species replacement (10%)	3.5–5.0	Annual				
		Pipes replacement (15%)	2–3	Annual			Manso2021: 18,98 eu/m2/y	
	Disposal	Green layer disposal	180–240	One time (end of lifespan)		**180 - 240**	Manso2021: 239 eu/m2	

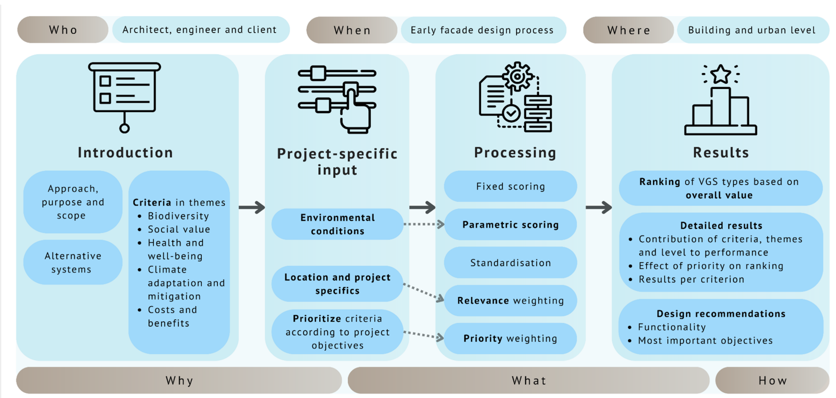
11.8 Appendix: Excel tool

Multi-criteria tool for selection and design of vertical greening systems

Introduction

Welcome! This tool allows engineers and architects of building projects to apply multi-criteria decision-making to the early-phase selection and design of vertical greening systems (VGS) on building facades.
The tool assesses different VGS types on a set of criteria and results in a ranking of the most suitable VGS for the specific project. As such, it supports a well-argued choice for a VGS.

The first tab 'Introduction' introduces the goal, scope, alternatives and criteria. Under the tab 'project-specific input', project parameters can be defined by the user. The 'processing' tab applies weighting and standardisation to the performances. Under the tab 'results', the overall performance of the VGS types is shown. More elaborate results follow afterwards. The final tab 'Design recommendations' provides recommendations specific for the project priorities. The framework below shows these concepts and phases.



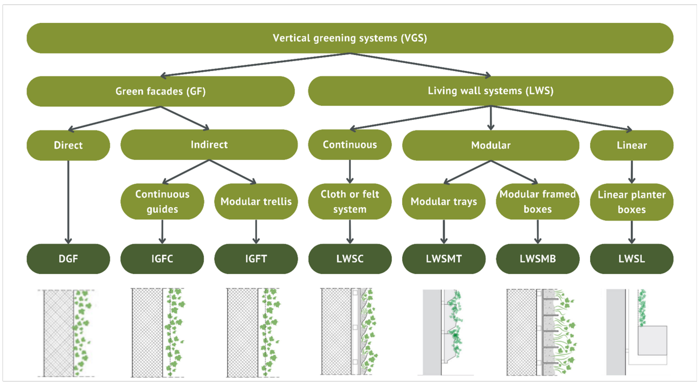
Scope

Project phase: The tool can be applied in early design phases, allowing VGS to be integrated from the start.

Building types: The tool is applicable for residential and non-residential building projects in the Netherlands. Depending on the function and client, different emphases can be expressed in the 'priority' weighting.

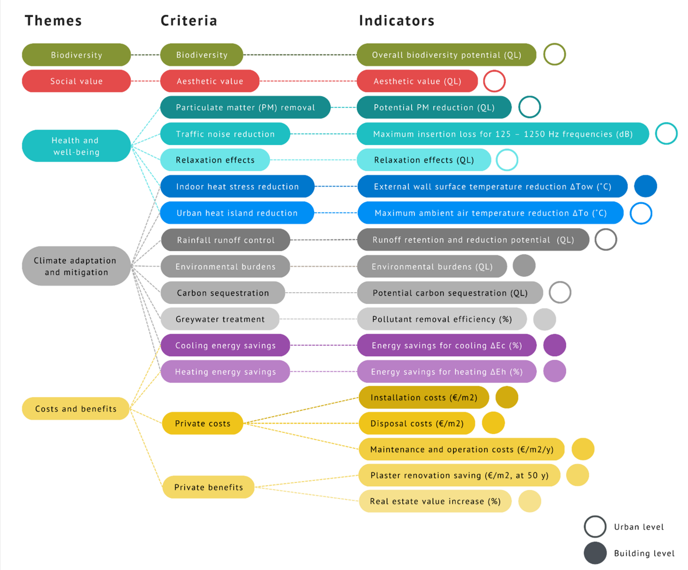
Alternatives

The figure below shows the seven different types of VGS.



Criteria

The figure below shows the criteria that the types are assessed on. They are grouped in 5 themes, and expressed in an indicator. The criteria are further explained in the next tab.



Legend

Some criteria are expressed in a qualitative indicator (QL) on a discrete seven-point scale. This is the case when not enough quantitative data is present in literature to make solid claims about quantified performances. The table below explains this scale.

Performance	Worst / very poor	Poor	Modest	Fair	Good	Very good	Excellent / best
Score	1	2	3	4	5	6	7

Now, please proceed to 'Project-specific input' and fill in the green boxes to retrieve results.

Background

This tool has been developed as part of the Civil Engineering master thesis by Hugo van Reeuwijk (2023) at Delft University of Technology and RoyalHaskoningDHV.

TU Delft

Royal HaskoningDHV
Enhancing Society Together

Project-specific input

To achieve project-specific results, please fill in the green boxes. The blue boxes are values that are fixed and cannot be changed.

1. Project description

Instruction: Describe the building project by filling in the green boxes.

Variable	Description	Range/scope	Value/result	Unit	Formula	Explanation
Name						
Adress		The Netherlands				Format: Street and number, city
Client						

2. Potential: Environmental conditions

Instruction: Provide environmental conditions that will affect the scoring on some criteria. Click on the link to access the different websites.

Variable	Description	Range/scope	Value/result	Unit	Formula	Link	Explanation
H	Average building height in street, estimation		15	m		Webmapper	Retrieve from Webmapper; estimate average of buildings in 500 m radius around building
W	Average street width (facade to facade), estimation		52	m		Google Maps	Retrieve from Google Maps > 'Terrein' > 'Afstand meten' ; estimate average of buildings in 500 m radius aroun
H/W	Street aspect ratio	0-5	0,3	-	H/W		
$C_{district}$	Facade vegetation coverage in district, estimation	0-100	0	%		Google Earth	Retrieve from Google Earth or field observations, estimate for radius of 500 m around building
Climate	Climate type in Köppen-Geiger classification	Cfb	Cfb	-			(Further development: include more climate types)
Urbanity	Degree of urbanity of the neighbourhood		Niet stedelijk	-		Atlas Leefomgeving	Retrieve value from Atlas Leefomgeving > Search for address, retrieve 'Mate van stedelijkheid van de buurt'

3. Relevance weighting

Instruction: How relevant are criteria to the location and project? Select or provide variables that affect the weighting.

Retrieve values from Atlas Leefomgeving.

Variable	Description	Range/scope	Value/result	Unit	Formula	Link	Explanation
PM2,5	Particulate matter (PM2,5) in air (2020)		7	µg/m3		Atlas Leefomgeving	Retrieve value from Atlas Leefomgeving > Search for address, retrieve 'Fijnstof in de lucht (2020)'
Noise	Noise in the environment (Lden)		70	dB		Atlas Leefomgeving	Retrieve value from Atlas Leefomgeving > Search for address, retrieve 'Geluid in de omgeving'
Green space	Percentage area of green space within a circle with a radius of 500 m		36	%		Atlas Leefomgeving	Retrieve value from Atlas Leefomgeving > Search for address, retrieve 'Groen binnen 500 meter'
Heat island	Average ambient air temperature difference, relative to rural area		1,0	˚C		Atlas Leefomgeving	Retrieve value from Atlas Leefomgeving > Search for address, retrieve 'Zomerhitte in de stad'

Retrieve values from Klimaateffectatlas.

Variable	Description	Range/scope	Value/result	Unit	Formula	Link	Explanation
Heat stress	Severely lonely elderly over 75 (2020)		< 10	#/km2		Klimaateffectatlas	Retrieve value from Klimaateffectatlas > Select 'Ernstig eenzame 75+ers', then search for adress
Rainfall	Yearly precipitation (2016)		800-900	mm		Klimaateffectatlas	Retrieve value from Klimaateffectatlas > Select 'Jaarlijkse neerslag', then search for adress

Select the (planned) inclusion of cooling and heating systems.

Variable	Description	Range/scope	Value/result	Unit	Formula	Comment	Explanation
Cooling system	Presence of active cooling system (such as air conditioning or heat cold storage)		No			***Possible comment***	If a cooling system that consumes any energy is present, select 'yes'. If not known yet, select 'yes' .
Heating system	Presence of active heating system		Yes				(Further development: include 'no' option for heating system)

4. Priority weighting

What criteria have most priority? In cooperation with the client, allocate weights to the different criteria.
First, allocate a value of 10 to the least important criterion, using the drop-down menu. Then, allocate a multiple of 10 to the other criteria. This indicates their relative importance.
Allocate the highest values to the most important criteria, and lower values to less important criteria. Several criteria can have the same value, indicating that they are equally important.
The 'rank' list on the right shows the resulting ranking of criteria, according to the assigned 'priority' weights.

Criterion	Description	Range/scope	Weight	Unit	Rank	Explanation
BD	Biodiversity	10-100	100	-	1	Potential to provide plant species variety and density, as well as a habitat for birds, snails, insects, beetles and
AV	Aesthetic value	10-100	10	-	11	Potential for aesthetic appeal to citizens.
PM	Particulate matter removal	10-100	10	-	11	Potential to remove particulate matter, one of the major outdoor air pollutants.
TN	Traffic noise reduction	10-100	30	-	6	Potential to reduce traffic noise pollution on street level.
RE	Relaxation effects	10-100	50	-	3	Potential to bring psychological and physical relaxation, i.e., stress reduction, to citizens.
HS	Indoor heat stress reduction	10-100	50	-	3	Potential to reduce indoor heat stress by lowering indoor temperatures during summer heat waves.
UHI	Urban heat islands reduction	10-100	10	-	11	Potential to reduce outdoor air temperatures to combat the urban heat island effect (temperature rises in citi
RC	Rainfall runoff control	10-100	10	-	11	Potential for rainfall flow retention and reduction.
EB	Environmental burdens	10-100	50	-	3	Environmental burdens, e.g. from materials, maintenance and water use.
CS	Carbon sequestration	10-100	10	-	11	Potential to sequester carbon dioxide from the air.
GW	Greywater treatment	10-100	10	-	11	Potential to remove pollutants from greywater (e.g. from kitchen, shower) for irrigation of vertical greening sy
CE	Cooling energy savings	10-100	10	-	11	Potential to lower cooling costs in summer because of the insulation and shading by the vertical greening syst
HE	Heating energy savings	10-100	30	-	6	Potential to lower heating costs in winter because of the insulation by the vertical greening system.
PC-I	Private costs - Installation costs	10-100	20	-	8	Costs for design, materials, irrigation system and installation.
PC-MO	Private costs - Maintenance and operation costs	10-100	20	-	8	Annual costs for pruning, irrigation and replacements.
PC-DC	Private costs - Disposal costs	10-100	20	-	8	Costs for disposal of system at the end of the lifetime.
PB-PR	Private benefits - Plaster renovation saving	10-100	10	-	11	Savings from less building facade maintenance because of protection of building facade by vertical greening sy
PB-VI	Private benefits - Real estate value increase	10-100	60	-	2	Increase of the economic property value because of the vertical greening system.

Processing

This tab lays out the processing of input parameters towards an overall performance per VGS type. First, the scores for PM, UHI and PB-VI are calculated based on location-specific input parameters. Second, the scores are standardised with global scaling, so that the scores can be compared and added. Third, the criteria are weighted according to their relevance for the specific location and project. Fourth, the criteria are weighted according to the priorities of the client. This results in the overall performances.

1. Parametric scoring

Input parameters

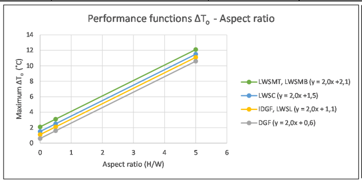
Parameter	Description	Value	Unit	Explanation
H/W	Street aspect ratio	0,3	-	From project-specific input
$C_{district}$	Facade vegetation coverage in district	0	%	From project-specific input
Urbanity	Degree of urbanity of the neighbourhood	Niet stedelijk	-	From project-specific input

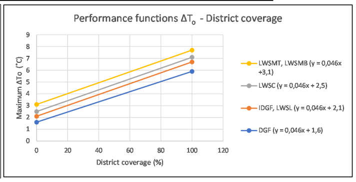
Performance PM, from H/W and $C_{district}$, derived from table:

Criterion	Env. cond.	Options	Env. cond.	Options	DGF (2-4)	IDGF, LWSL (2-5)	LWSC (4-6)	LWSMT/B (4-7)	Unit
PM	H/W	>1,5	$C_{district}$	>40	4	5	6	7	QL
	H/W	>1,5	$C_{district}$	20-40	4	4	6	6	QL
	H/W	>1,5	$C_{district}$	<20	3	3	5	5	QL
	H/W	≤1,5	$C_{district}$	>60	4	4	6	6	QL
	H/W	≤1,5	$C_{district}$	10-60	3	3	5	5	QL
	H/W	≤1,5	$C_{district}$	<10	2	2	4	4	QL

Performance UHI, from H/W and Cdistrict

Performance	Description	Unit	Formula
$UHI_{H/W}$	Performance UHI, based on H/W	˚C	Figure 'Performance functions ΔTo - Aspect ratio', x = H/W
$UHI_{Cdistrict}$	Performance UHI, based on $C_{district}$	˚C	Figure 'Performance functions ΔTo - District coverage', x = $C_{district}$
UHI_{total}	Total performance UHI	˚C	($UHI_{H/W}$ + $UHI_{Cdistrict}$ / 2)





Performance PB-VI, from Urbanity

Criterion	Env. cond.	Options	DGF, IGFC, IFGT	LWSC, LWSMT, LWSMB	LWSL	Unit
PB-VI	Urbanity	Niet stedelijk	3,0	6,0	4,5	%
		Weinig stedelijk	5,0	10,0	7,5	%
		Matig stedelijk	5,0	10,0	7,5	%
		Sterk stedelijk	3,0	6,0	4,5	%
		Zeer sterk stedelijk	2,0	4,0	3,0	%

Performance matrix (P) - not standardised, not weighted

Criterion	BD	AV	PM	TN	RE	HS	UHI	RC	EB	CS	GW	CE	HE	PC-I	PC-MO	PC-D	PB-PR	PB-VI
Indicator	Potential	Potential	Potential	IL	Potential	ΔTow	ΔTo	Potential	Potential	Potential	Removal	ΔEc	ΔEh	Costs	Costs	Costs	Benefit	Benefit
Unit	QL	QL	QL	dB	QL	˚C	˚C	QL	QL	QL	%	%	%	€/m2	€/m2/y	€/m2	€/m2	%
DGF	2	3	2	0	6	9,4	1,4	1	7	2	0	20	8	44	3,7	38	284	3
IGFC	3	3	2	6,5	6	12,7	1,9	1	6	2	0	37	8	214	3,7	190	499	3
IGFT	3	3	2	6,5	6	12,7	1,9	1	5	2	0	37	8	214	3,7	190	499	3
LWSC	5	3	4	8,4	3	19,5	2,3	3	1	4	0	26	20	409	29,5	210	622	6
LWSMT	6	7	4	5,4	3	13,3	2,9	5	3	5	82,5	34	20	409	29,5	210	622	6
LWSMB	6	6	4	4,7	3	8,5	2,9	6	3	5	82,5	59	20	409	29,5	210	622	6
LWSL	5	4	2	3,1	5	8,4	1,9	3	4	3	0	34	15	302	13	190	527	4,5

Legend
Fixed scoring
Parametric scoring

2. Standardisation

Upper and lower bounds for global scaling standardisation (value of 0 for lowest score of a general facade measure, value of 100 for highest score of a general facade measure)

Criterion	BD	AV	PM	TN	RE	HS	UHI	RC	EB	CS	GW	CE	HE	PC-I	PC-MO	PC-D	PB-PR	PB-VI
Indicator	Potential	Potential	Potential	IL	Potential	ΔTow	ΔTo	Potential	Potential	Potential	Removal	ΔEc	ΔEh	Costs	Costs	Costs	Benefit	Benefit
Unit	QL	QL	QL	dB	QL	˚C	˚C	QL	QL	QL	%	%	%	€/m2	€/m2/y	€/m2	€/m2	%
Lower bound (worst score)	0	0	0	0	0	0	0,0	0	0	0	0	0	0	594	35,5	240	0	0
Upper bound (best score)	7	7	7	15	7	23	10	7	7	7	100	97	50	0	0	0	750	15
Value function $P_{standardised}$	(P/7)*100	(P/7)*100	(P/7)*100	(P/15)*100	(P/7)*100	(P/23)*100	(P/10)*100	(P/7)*100	(P/7)*100	(P/7)*100	P	(P/97)*100	(P/50)*100	((594-P)/594)*100	((35,5-P)/35,5)*100	((240-P)/240)*100	(P/750)*100	(P/15)*100

Legend	
P = performance (unit)	

Performance matrix ($P_{standardised}$) - standardised, not weighted (dimensionless 0-100)

Criterion	BD	AV	PM	TN	RE	HS	UHI	RC	EB	CS	GW	CE	HE	PC-I	PC-MO	PC-D	PB-PR	PB-VI
Indicator	Potential	Potential	Potential	IL	Potential	ΔTow	ΔTo	Potential	Potential	Potential	Removal	ΔEc	ΔEh	Costs	Costs	Costs	Benefit	Benefit
Unit	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
DGF	29	43	29	0	86	41	14	14	100	29	0	21	16	93	90	84	38	20
IGFC	43	43	29	43	86	55	19	14	86	29	0	38	16	64	90	21	67	20
IGFT	43	43	29	43	86	55	19	14	71	29	0	38	16	64	90	21	67	20
LWSC	71	43	57	56	43	85	23	43	14	57	0	27	40	31	17	13	83	40
LWSMT	86	100	57	36	43	58	29	71	43	71	82,5	35	40	31	17	13	83	40
LWSMB	86	86	57	31	43	37	29	86	43	71	82,5	61	40	31	17	13	83	40
LWSL	71	57	29	21	71	37	19	43	57	43	0	35	30	49	63	21	70	30

3. Relevance weighting

Input parameters

Parameter	Description	Value	Unit	Explanation
PM2,5	Particulate matter (PM2,5) in air (2020)	7	µg/m3	From project-specific input
Noise	Noise in the environment (Lden)	70	dB	From project-specific input
Green space	Percentage area of green space in 500 m radius	36	%	From project-specific input
Heat stress	Severely lonely elderly over 75 (2020)	< 10	# / km2	From project-specific input
Heat island	Average ambient air temperature difference, rel. to rural area	1	˚C	From project-specific input
Rainfall	Yearly precipitation (2016)	800-900	mm	From project-specific input
Cooling s.	Presence of active cooling system (HVAC)	No	-	From project-specific input

To achieve a weighting for relevance, the following scale with percentiles is adopted for w_R:

Relevance	Not relevant	Little relevant	Somewhat relevant	Relevant	Quite relevant	Very relevant
w_R	0	0-0.25	0.25-0.50	0.50-0.75	0.75-1.00	1.00

Criterion	Weighting variable	Description	Options	Unit	Relevance	Weight w_R	Explanation	Source of options
PM	PM2,5	Particulate matter (PM2,5) in air (2020)	< 5	µg/m3	Not relevant	0,00	Lower than WHO recommended value	RIVM, 2020
			≥ 5 and < 10	µg/m3	Somewhat relevant	0,33	Between recommended value and WHO Interim Targets 3/4	
			≥ 10 en < 25	µg/m3	Relevant	0,67	Between WHO Interim Targets 3/4 and WHO Interim Target 2	
			≥ 25	µg/m3	Very relevant	1,00	Above WHO Interim Target 2	
TN	Noise	Noise in the environment (L_{den})	< 46	dB	Not relevant	0,00	Lower than EEA indicator for noise pollution (55 dB)	RIVM, 2020
			≥ 46 and < 51	dB	Not relevant	0,00	Lower than EEA indicator for noise pollution (55 dB)	
			≥ 51 and < 56	dB	Not relevant	0,00	Lower than EEA indicator for noise pollution (55 dB)	
			≥ 56 and < 61	dB	Quite relevant	0,80	Higher than EEA indicator for noise pollution (55 dB)	
			≥ 61	dB	Very relevant	1,00	Possibly higher than EEA indicator for high noise pollution (65 dB)	
RE	Green space	Percentage area of green space in 500 m radius	≥ 60	%	Somewhat relevant	0,40	Very good access to urban green space	RIVM, 2020
			≥ 50 and < 60	%	Relevant	0,55	Good access to urban green space	
			≥ 40 and < 50	%	Relevant	0,70	Fair access to urban green space	
			≥ 30 and < 40	%	Quite relevant	0,85	Poor access to urban green space	
			< 30	%	Very relevant	1,00	Bad access to urban green space	
HS	Heat stress	Severely lonely elderly over 75 (2020)	< 10	# / km2	Relevant	0,55		Gezondheidsmonitor / RIVM, 2020
			10-30	# / km2	Relevant	0,70		(Severely longely elderly over 75 are the most vulnerable
			30-100	# / km2	Quite relevant	0,85		population group for heat stress, due to their low thirst stimulus
			> 100	# / km2	Very relevant	1,00		and no other people alerting them to drink enough and cool down.)
UHI	Heat island	Average ambient air temperature difference, relative to rural area	< 0,5	˚C	Not relevant	0,00	Very good	RIVM, 2020
			≥ 0,5 and < 1	˚C	Somewhat relevant	0,25	Good	
			≥ 1 and < 1,5	˚C	Relevant	0,50	Fair	
			≥ 1,5 and < 2	˚C	Quite relevant	0,75	Poor	
			≥ 2	˚C	Very relevant	1,00	Bad	
RC	Rainfall	Yearly precipitation (2016)	< 800	mm	Quite relevant	0,80	Below average	RIVM, 2016
			800-900	mm	Quite relevant	0,90	Average	
			>900	mm	Very relevant	1,00	Above average	
CE	Cooling s.	Presence of active cooling system	Yes	-	Not relevant	0,00		
			No	-	Very relevant	1,00		

4. Priority weighting

Calculation of the priority weighting

Criterion	BD	AV	PM	TN	RE	HS	UHI	RC	EB	CS	GW	CE	HE	PC-I	PC-MO	PC-D	PB-PR	PB-VI
Indicator	Potential	Potential	Potential	IL	Potential	ΔTow	ΔTo	Potential	Potential	Potential	Removal	ΔEc	ΔEh	Costs	Costs	Costs	Benefit	Benefit
Unit	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Weight $w_{P,\ 10\text{-}100}$ (10-100)	100	10	10	30	50	50	10	10	50	10	10	10	30	20	20	20	10	60
Weight w_P (0.0-1.0)	0,196	0,020	0,020	0,059	0,098	0,098	0,020	0,020	0,098	0,020	0,020	0,020	0,059	0,039	0,039	0,039	0,020	0,118

Formula
$w_{P,\ 10\text{-}100,\ criterion} / \sum(w_{P,\ 10\text{-}100})$

Priority weight options
10
20
30
40
50
60
70
80
90
100

5. Total weighting: full weighting

Calculation of total weight

Criterion	BD	AV	PM	TN	RE	HS	UHI	RC	EB	CS	GW	CE	HE	PC-I	PC-MO	PC-D	PB-PR	PB-VI
Indicator	Potential	Potential	Potential	IL	Potential	ΔTow	ΔTo	Potential	Potential	Potential	Removal	ΔEc	ΔEh	Costs	Costs	Costs	Benefit	Benefit
Unit	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Weight w_R	1,00	1,00	0,33	1,00	0,85	0,55	0,5	0,90	1,00	1,00	1,00	0,00	1,00	1,00	1,00	1,00	1,00	1,00
Weight w_P	0,196	0,020	0,020	0,059	0,098	0,098	0,020	0,020	0,098	0,020	0,020	0,020	0,059	0,039	0,039	0,039	0,020	0,118
Total weight $w_{full\ weight}$	0,196	0,020	0,006	0,059	0,083	0,054	0,010	0,018	0,098	0,020	0,020	0,000	0,059	0,039	0,039	0,039	0,020	0,118

Legend
Fixed relevance (1,00)
Project-specific relevance/priority

Formula
$w = w_R * w_P$

Performance matrix ($P_{full\ weight}$) - standardised, weighted (dimensionless)

Criterion	BD	AV	PM	TN	RE	HS	UHI	RC	EB	CS	GW	CE	HE	PC-I	PC-MO	PC-D	PB-PR	PB-VI	Total score, full weighting
Indicator	Potential	Potential	Potential	IL	Potential	ΔTow	ΔTo	Potential	Potential	Potential	Removal	ΔEc	ΔEh	Costs	Costs	Costs	Benefit	Benefit	
Unit	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
DGF	5,60	0,84	0,18	0,00	7,14	2,20	0,14	0,25	9,80	0,56	0,00	0,00	0,94	3,63	3,51	3,30	0,74	2,35	41,21
IGFC	8,40	0,84	0,18	2,55	7,14	2,98	0,19	0,25	8,40	0,56	0,00	0,00	0,94	2,51	3,51	0,82	1,30	2,35	42,94
IGFT	8,40	0,84	0,18	2,55	7,14	2,98	0,19	0,25	7,00	0,56	0,00	0,00	0,94	2,51	3,51	0,82	1,30	2,35	41,54
LWSC	14,01	0,84	0,37	3,29	3,57	4,57	0,22	0,76	1,40	1,12	0,00	0,00	2,35	1,22	0,66	0,49	1,63	4,71	41,21
LWSMT	16,81	1,96	0,37	2,12	3,57	3,12	0,28	1,26	4,20	1,40	1,62	0,00	2,35	1,22	0,66	0,49	1,63	4,71	47,77
LWSMB	16,81	1,68	0,37	1,84	3,57	1,99	0,28	1,51	4,20	1,40	1,62	0,00	2,35	1,22	0,66	0,49	1,63	4,71	46,34
LWSL	14,01	1,12	0,18	1,22	5,95	1,97	0,19	0,76	5,60	0,84	0,00	0,00	1,76	1,93	2,49	0,82	1,38	3,53	43,73

	Performance $P_{full\ weight}$	Total score, full weighting
Formula	$P_{full\ weight,\ criterion} = w_{full\ weight,\ criterion} * P_{standardised,\ criterion}$	$\sum(P_{full\ weight,\ criterion})$

6. Total weighting: equal priority weighting

Calculation of total weight, mean weight for priority (all criteria same priority, but different relevance)

Criterion	BD	AV	PM	TN	RE	HS	UHI	RC	EB	CS	GW	CE	HE	PC-I	PC-MO	PC-D	PB-PR	PB-VI
Indicator	Potential	Potential	Potential	IL	Potential	ΔTow	ΔTo	Potential	Potential	Potential	Removal	ΔEc	ΔEh	Costs	Costs	Costs	Benefit	Benefit
Unit	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Weight w_R	1,00	1,00	0,33	1,00	0,85	0,55	0,5	0,90	1,00	1,00	1,00	0,00	1,00	1,00	1,00	1,00	1,00	1,00
Weight $w_{P,\ equal\ priority}$	0,056	0,056	0,056	0,056	0,056	0,056	0,056	0,056	0,056	0,056	0,056	0,056	0,056	0,056	0,056	0,056	0,056	0,056
Total $w_{equal\ priority\ weight}$	0,056	0,056	0,018	0,056	0,047	0,031	0,028	0,050	0,056	0,056	0,056	0,000	0,056	0,056	0,056	0,056	0,056	0,056

Legend
Fixed relevance (1,00)
Project-specific relevance/priority

Formula
$w_{P,\ equal\ priority} = 1 / n_{criteria} = 1/18$
$w = w_R * w_{P,\ equal\ priority}$

Performance matrix ($P_{equal\ priority\ weight}$) - standardised, mean weight for priority (dimensionless)

Criterion	BD	AV	PM	TN	RE	HS	UHI	RC	EB	CS	GW	CE	HE	PC-I	PC-MO	PC-D	PB-PR	PB-VI	Total score, equal priority weighting
Indicator	Potential	Potential	Potential	IL	Potential	ΔTow	ΔTo	Potential	Potential	Potential	Removal	ΔEc	ΔEh	Costs	Costs	Costs	Benefit	Benefit	
Unit	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
DGF	1,59	2,38	0,52	0,00	4,05	1,25	0,39	0,71	5,56	1,59	0,00	0,00	0,89	5,14	4,98	4,68	2,10	1,11	36,93
IGFC	2,38	2,38	0,52	2,41	4,05	1,69	0,52	0,71	4,76	1,59	0,00	0,00	0,89	3,55	4,98	1,16	3,70	1,11	36,40
IGFT	2,38	2,38	0,52	2,41	4,05	1,69	0,52	0,71	3,97	1,59	0,00	0,00	0,89	3,55	4,98	1,16	3,70	1,11	35,61
LWSC	3,97	2,38	1,05	3,11	2,02	2,59	0,64	2,14	0,79	3,17	0,00	0,00	2,22	1,73	0,94	0,69	4,61	2,22	34,28
LWSMT	4,76	5,56	1,05	2,00	2,02	1,77	0,80	3,57	2,38	3,97	4,58	0,00	2,22	1,73	0,94	0,69	4,61	2,22	44,88
LWSMB	4,76	4,76	1,05	1,74	2,02	1,13	0,80	4,29	2,38	3,97	4,58	0,00	2,22	1,73	0,94	0,69	4,61	2,22	43,90
LWSL	3,97	3,17	0,52	1,15	3,37	1,12	0,52	2,14	3,17	2,38	0,00	0,00	1,67	2,73	3,52	1,16	3,90	1,67	36,17

	Performance $P_{equal\ priority\ weight}$	Total score, equal priority weighting
Formula	$P_{equal\ priority\ weight,\ criterion} = w_{equal\ priority\ weight,\ criterion} * P_{standardised,\ criterion}$	$\sum(P_{equal\ priority\ weight,\ criterion})$

7. Performance per theme, benefit/burden and urban/building level

Performance matrix - average performance per theme (weighted)

Theme	Biodiversity	Social value	Health and well-being	Climate adaptation and mitigation	Costs and benefits
DGF	5,60	0,84	1,93	1,74	2,71
IGFC	8,40	0,84	2,61	1,66	2,10
IGFT	8,40	0,84	2,61	1,49	2,10
LWSC	14,01	0,84	2,41	1,30	1,74
LWSMT	16,81	1,96	1,89	1,78	1,74
LWSMB	16,81	1,68	1,61	1,67	1,74
LWSL	14,01	1,12	1,90	1,39	2,03

*Performance matrix - **average** per theme (equal priority weighting)*

Theme	Biodiversity	Social value	Health and well-being	Climate adaptation and mitigation	Costs and benefits
DGF	1,59	2,38	1,24	1,30	2,70
IGFC	2,38	2,38	1,84	1,27	2,20
IGFT	2,38	2,38	1,84	1,17	2,20
LWSC	3,97	2,38	1,88	1,44	1,77
LWSMT	4,76	5,56	1,53	2,41	1,77
LWSMB	4,76	4,76	1,35	2,42	1,77
LWSL	3,97	3,17	1,34	1,38	2,09

*Performance matrix - **total** performance per theme (equal priority weighting)*

Theme	Biodiversity	Social value	Health and well-being	Climate adaptation and mitigation	Costs and benefits
DGF	1,59	2,38	6,21	10,38	18,90
IGFC	2,38	2,38	9,19	10,16	15,38
IGFT	2,38	2,38	9,19	9,37	15,38
LWSC	3,97	2,38	9,41	11,56	12,42
LWSMT	4,76	5,56	7,64	19,30	12,42
LWSMB	4,76	4,76	6,74	19,37	12,42
LWSL	3,97	3,17	6,69	11,01	14,65

Performance matrix - total performance per benefit/burden

	Overall score without priva	Score private costs
DGF	22,14	14,80
IGFC	26,71	9,69
IGFT	25,92	9,69
LWSC	30,92	3,36
LWSMT	41,51	3,36
LWSMB	40,54	3,36
LWSL	28,76	7,41

Performance matrix - total performance per level (urban/building)

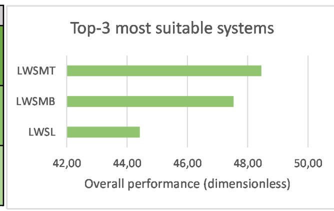
	Urban level	Building level
DGF	11,23	25,70
IGFC	14,57	21,83
IGFT	14,57	21,04
LWSC	18,48	15,80
LWSMT	23,73	21,15
LWSMB	23,39	20,51
LWSL	17,24	18,94

Factsheet key results

This factsheets presents the most suitable VGS systems for the specific project. More elaborate results can be found below.

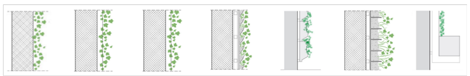
Rank	System	Overall performance	Average installation costs (€/m2)
1	LWSMT	48,45	409
2	LWSMB	47,53	409
3	LWSL	44,42	302

Dimensionless performance that includes costs

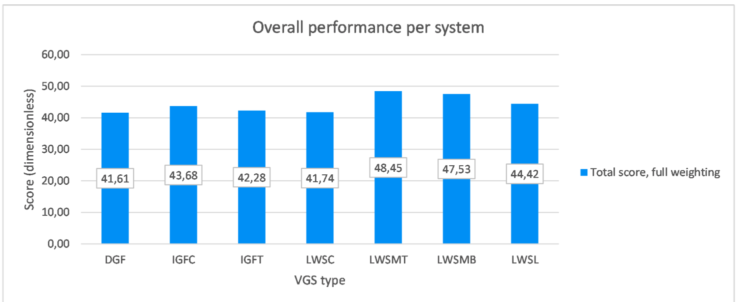


Overall performance

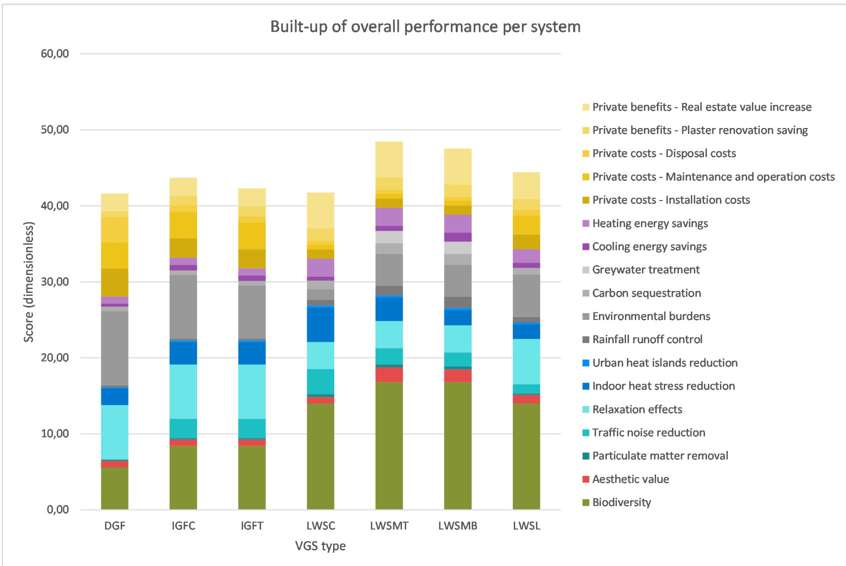
Given the project-specificity and priorities, the overall performance on the suitability of the different VGS types is:



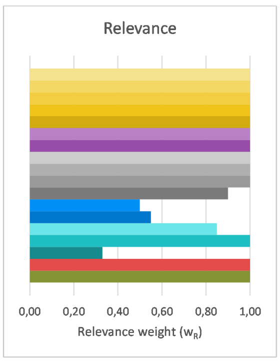
VGS type	DGF	IGFC	IGFT	LWSC	LWSMT	LWSMB	LWSL
Overall performance	41,61	43,68	42,28	41,74	48,45	47,53	44,42
Ranking	7	4	5	6	1	2	3

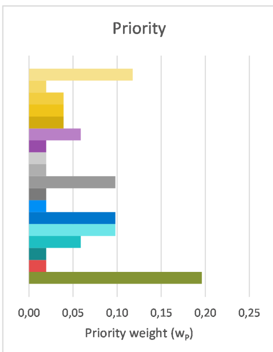


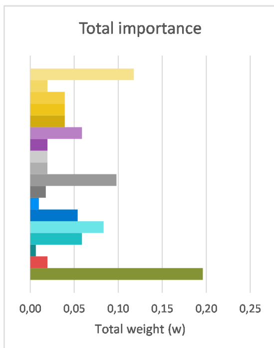
The overall performance is the sum of weighted scores, as shown below. Hover over a bar to see numerical values.



Weighting takes places based on both relevance (objective) and priority (subjective). The multiplication of both results in the total importance.



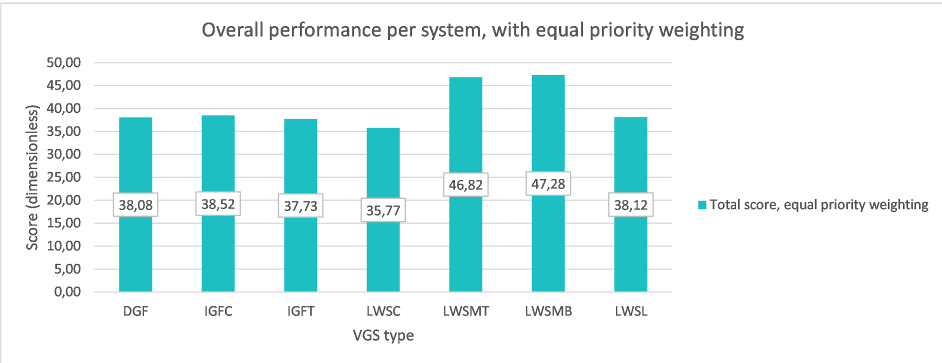




Overall performance for equal priority

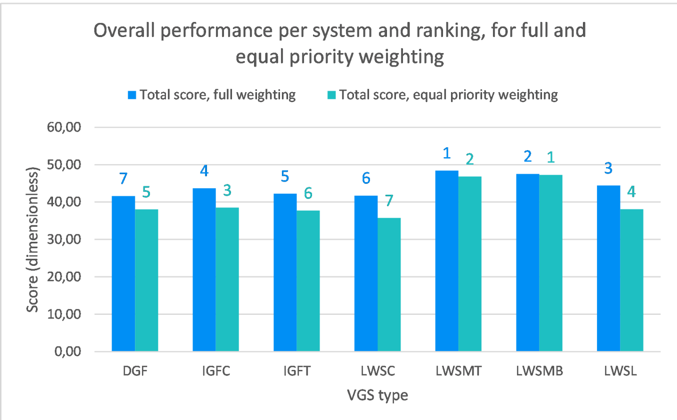
When all criteria are of equal priority (mean weighting for w_p), the overall performance on the suitability of the different VGS types is:

VGS type	DGF	IGFC	IGFT	LWSC	LWSMT	LWSMB	LWSL
Overall performance	38,08	38,52	37,73	35,77	46,82	47,28	38,12
Ranking	5	3	6	7	2	1	4



Comparing the performance for full weighting and equal priority weighting, the ranking might be different for the two scenarios:

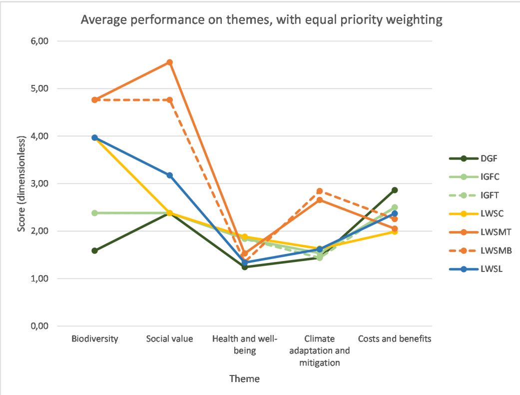
VGS type	DGF	IGFC	IGFT	LWSC	LWSMT	LWSMB	LWSL
Overall performance (full weighting)	41,61	43,68	42,28	41,74	48,45	47,53	44,42
Ranking (full weighting)	7	4	5	6	1	2	3
Overall performance (equal priority weig	38,08	38,52	37,73	35,77	46,82	47,28	38,12
Ranking (equal priority weighting)	5	3	6	7	2	1	4

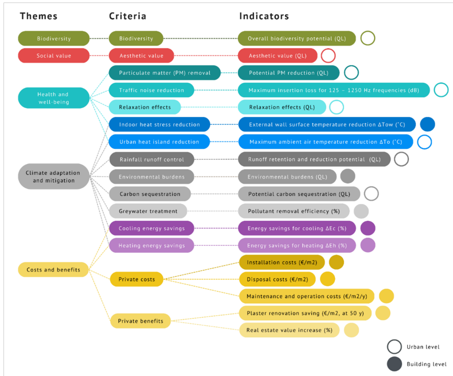


Performance on themes

When all criteria are of equal priority (mean weighting for w_p), the average performance per theme is:

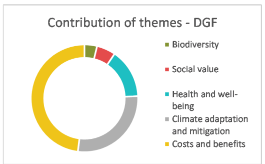
VGS type	DGF	IGFC	IGFT	LWSC	LWSMT	LWSMB	LWSL
Biodiversity	1,59	2,38	2,38	3,97	4,76	4,76	3,97
Social value	2,38	2,38	2,38	2,38	5,56	4,76	3,17
Health and well-being	1,24	1,84	1,84	1,88	1,53	1,35	1,34
Climate adaptation and mitigation	1,44	1,54	1,44	1,63	2,66	2,84	1,62
Costs and benefits	2,86	2,50	2,50	1,99	2,05	2,26	2,37

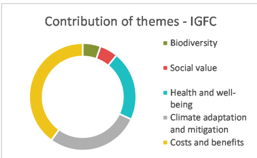


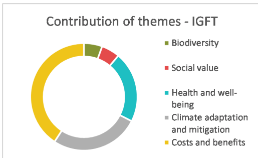


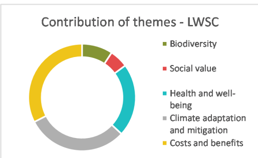
Explanation
See value tree on the right to see which criteria fall under what theme.

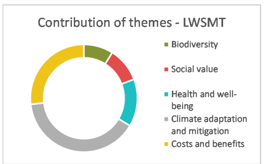
The following diagrams show the total contribution per theme to the performance with equal priority:

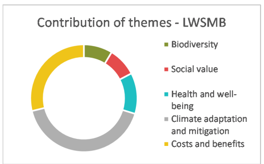


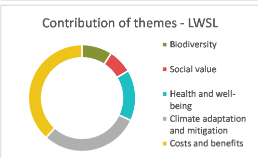










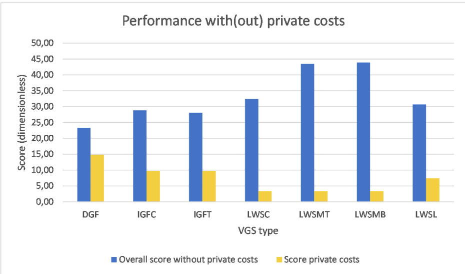


Note: Since themes have some overlapping criteria, the contribution diagrams do not add up to the total performance.

Performance with(out) private costs

When all criteria are of equal priority, the overall performance with(out) private costs is:

VGS type	DGF	IGFC	IGFT	LWSC	LWSMT	LWSMB	LWSL
Score without private costs	23,28	28,83	28,04	32,41	43,46	43,92	30,71
Score private costs costs	14,80	9,69	9,69	3,36	3,36	3,36	7,41

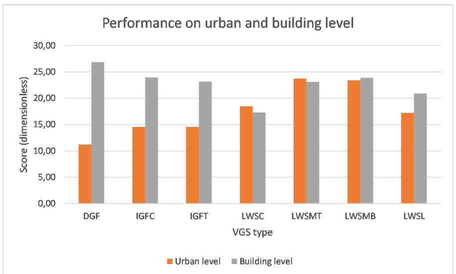


Note
Overall score without private costs: includes environmental burdens (good = small) and private benefits
A high score on private costs indicates relatively low costs

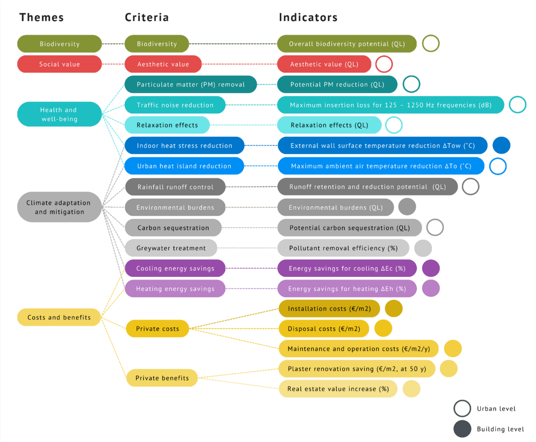
Performance on building and urban level

When all criteria are of equal priority (mean weighting for w_p), the aggregated performance on urban and building level is:

VGS type	DGF	IGFC	IGFT	LWSC	LWSMT	LWSMB	LWSL
Performance on urban level	11,23	14,57	14,57	23,16	23,73	23,39	17,24
Performance on building level	26,85	23,95	23,16	17,29	23,09	23,89	20,88



Explanation
See value tree on the right for which criteria affect urban or building level.

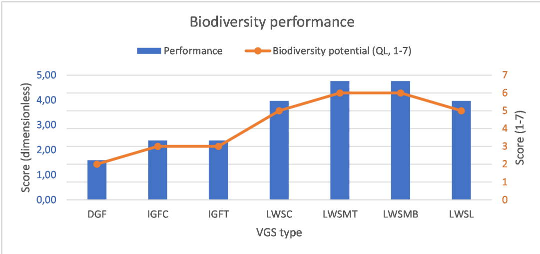


Performance on criteria

Regardless of priorities (mean weighting for w_p), the diagrams show the performance per criterion (blue), which is weighted for relevance. Also, the non-weighted and non-standardised performance in terms of the indicator per criterion is shown (orange).

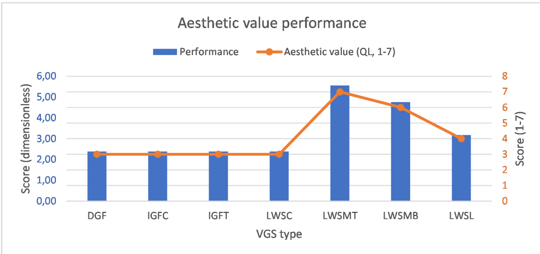
Biodiversity

VGS type	DGF	IGFC	IGFT	LWSC	LWSMT	LWSMB	LWSL
Performance	1,59	2,38	2,38	3,97	4,76	4,76	3,97
Biodiversity potential (QL, 1-7)	2	3	3	5	6	6	5



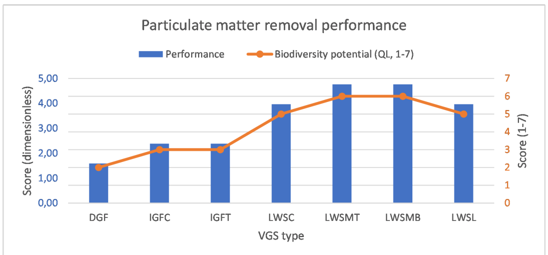
Aesthetic value

VGS type	DGF	IGFC	IGFT	LWSC	LWSMT	LWSMB	LWSL
Performance	2,38	2,38	2,38	2,38	5,56	4,76	3,17
Aesthetic value (QL, 1-7)	3	3	3	3	7	6	4



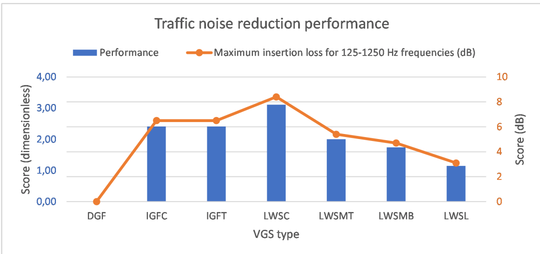
Particulate matter removal

VGS type	DGF	IGFC	IGFT	LWSC	LWSMT	LWSMB	LWSL
Performance	0,52	0,52	0,52	1,05	1,05	1,05	0,52
Potential PM reduction (QL, 1-7)	2	2	2	4	4	4	2



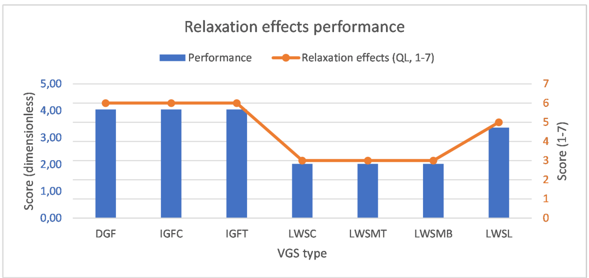
Traffic noise reduction

VGS type	DGF	IGFC	IGFT	LWSC	LWSMT	LWSMB	LWSL
Performance	0,00	2,41	2,41	3,11	2,00	1,74	1,15
Maximum insertion loss for 125-1250 Hz frequencies (dB)	0	6,5	6,5	8,4	5,4	4,7	3,1



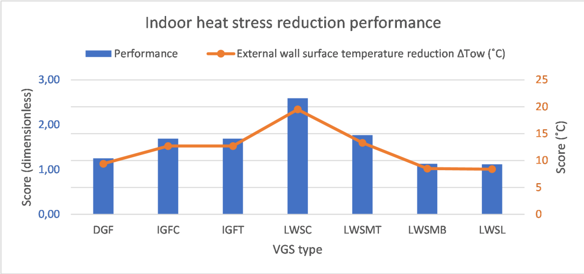
Relaxation effects

VGS type	DGF	IGFC	IGFT	LWSC	LWSMT	LWSMB	LWSL
Performance	4,05	4,05	4,05	2,02	2,02	2,02	3,37
Relaxation effects (QL, 1-7)	6	6	6	3	3	3	5



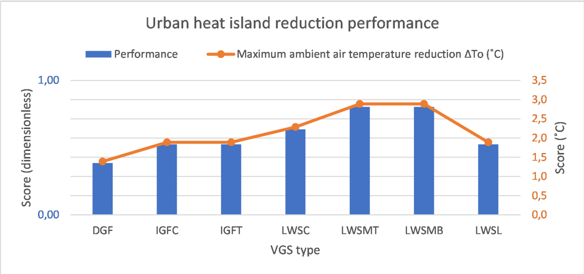
Indoor heat stress reduction

VGS type	DGF	IGFC	IGFT	LWSC	LWSMT	LWSMB	LWSL
Performance	1,25	1,69	1,69	2,59	1,77	1,13	1,12
External wall surface temperature reduction ΔT_{ow} (˚C)	9,4	12,7	12,7	19,5	13,3	8,5	8,4



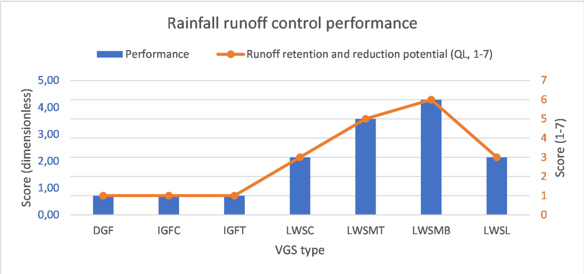
Urban heat island reduction

VGS type	DGF	IGFC	IGFT	LWSC	LWSMT	LWSMB	LWSL
Performance	0,39	0,52	0,52	0,64	0,80	0,80	0,52
Maximum ambient air temperature reduction ΔT_o (˚C)	1,4	1,9	1,9	2,3	2,9	2,9	1,9



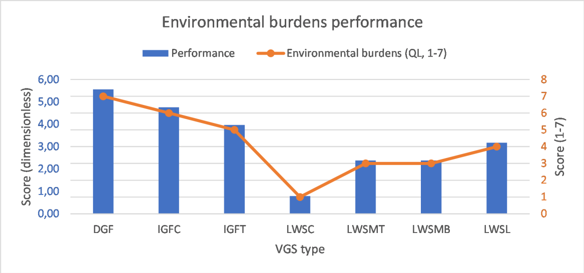
Rainfall runoff control

VGS type	DGF	IGFC	IGFT	LWSC	LWSMT	LWSMB	LWSL
Performance	0,71	0,71	0,71	2,14	3,57	4,29	2,14
Runoff retention and reduction potential (QL, 1-7)	1	1	1	3	5	6	3



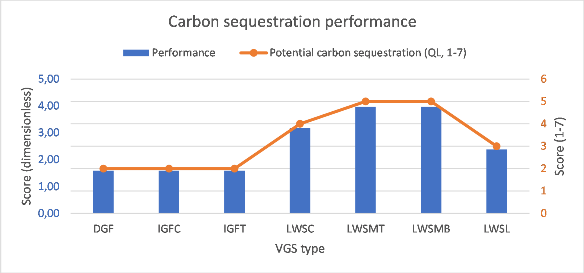
Environmental burdens

VGS type	DGF	IGFC	IGFT	LWSC	LWSMT	LWSMB	LWSL
Performance	5,56	4,76	3,97	0,79	2,38	2,38	3,17
Environmental burdens (QL, 1-7)	7	6	5	1	3	3	4



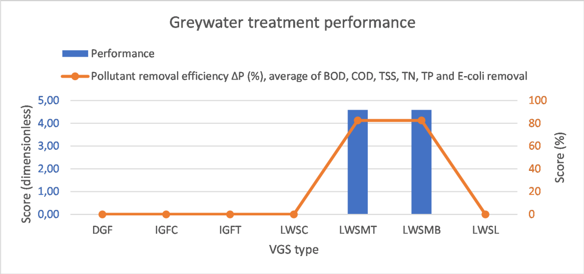
Carbon sequestration

VGS type	DGF	IGFC	IGFT	LWSC	LWSMT	LWSMB	LWSL
Performance	1,59	1,59	1,59	3,17	3,97	3,97	2,38
Potential carbon sequestration (QL, 1-7)	2	2	2	4	5	5	3



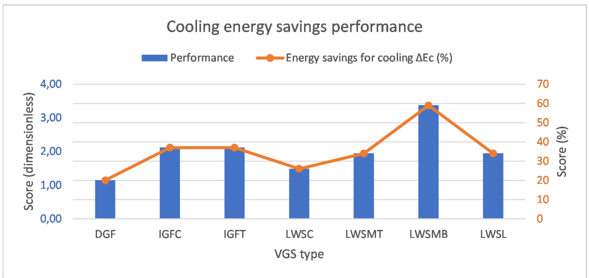
Greywater treatment

VGS type	DGF	IGFC	IGFT	LWSC	LWSMT	LWSMB	LWSL
Performance	0,00	0,00	0,00	0,00	4,58	4,58	0,00
Pollutant removal efficiency ΔP (%), average of BOD, COD, TSS, TN, TP and E-coli removal	0	0	0	0	82,5	82,5	0



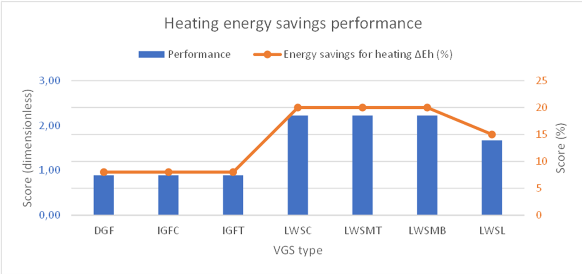
Cooling energy savings

VGS type	DGF	IGFC	IGFT	LWSC	LWSMT	LWSMB	LWSL
Performance	1,15	2,12	2,12	1,49	1,95	3,38	1,95
Energy savings for cooling ΔE_c (%)	20	37	37	26	34	59	34



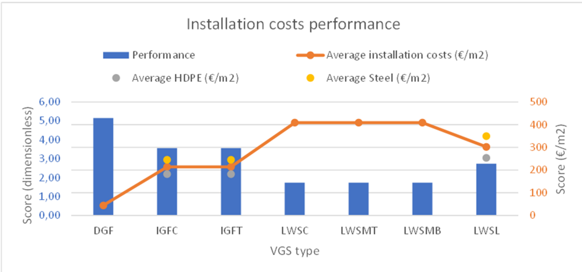
Heating energy savings

VGS type	DGF	IGFC	IGFT	LWSC	LWSMT	LWSMB	LWSL
Performance	0,89	0,89	0,89	2,22	2,22	2,22	1,67
Energy savings for heating ΔE_h (%)	8	8	8	20	20	20	15



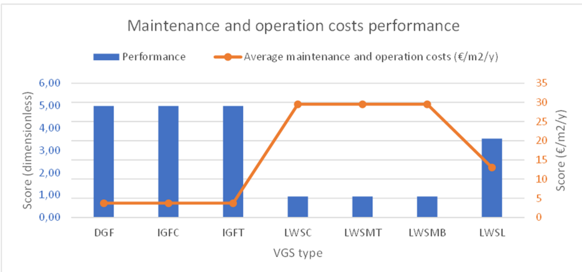
Installation costs

VGS type	DGF	IGFC	IGFT	LWSC	LWSMT	LWSMB	LWSL
Performance	5,14	3,55	3,55	1,73	1,73	1,73	2,73
Average installation costs (€/m2)	44	214	214	409	409	409	302
Average HDPE (€/m2)		182,5	182,5				254
Average Steel (€/m2)		245	245				349,5
Range	35-51	146-219 (HDPE)		224-594	224-594	224-594	202-306 (HDPE)
		206-284 (Steel)					293-406 (HDPE)



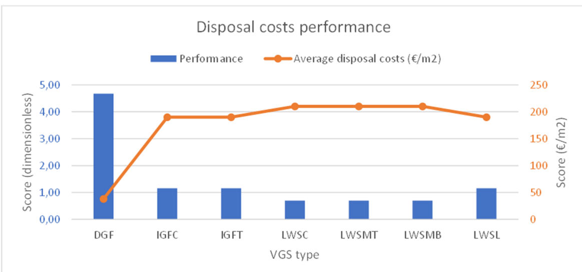
Maintenance and operation costs

VGS type	DGF	IGFC	IGFT	LWSC	LWSMT	LWSMB	LWSL
Performance	4,98	4,98	4,98	0,94	0,94	0,94	3,52
Average maintenance and operation costs (€/m2/y)	3,7	3,7	3,7	29,5	29,5	29,5	13
Range	3-4.4	3-4.4	3-4.4	23.5-35.5	23.5-35.5	23.5-35.5	10.5-15.5



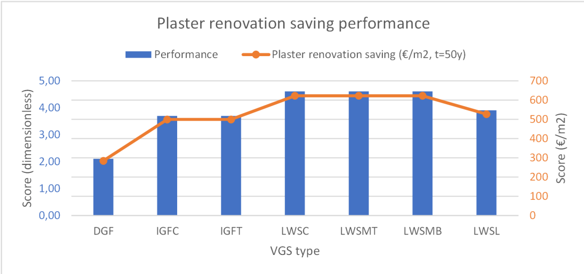
Disposal costs

VGS type	DGF	IGFC	IGFT	LWSC	LWSMT	LWSMB	LWSL
Performance	4,68	1,16	1,16	0,69	0,69	0,69	1,16
Average disposal costs (€/m2)	38	190	190	210	210	210	190
Range	30-45	160-220	160-220	180-240	180-240	180-240	160-220



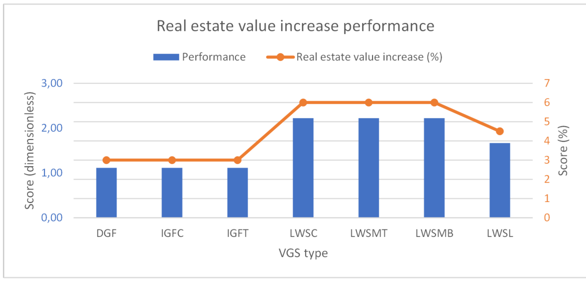
Plaster renovation saving

VGS type	DGF	IGFC	IGFT	LWSC	LWSMT	LWSMB	LWSL
Performance	2,10	3,70	3,70	4,61	4,61	4,61	3,90
Plaster renovation saving (€/m2, t=50y)	284	499	499	622	622	622	527



Real estate value increase

VGS type	DGF	IGFC	IGFT	LWSC	LWSMT	LWSMB	LWSL
Performance	1,11	1,11	1,11	2,22	2,22	2,22	1,67
Real estate value increase (%)	3	3	3	6	6	6	4,5



Design recommendations

Finally, design recommendations are given. Designing for functionality is a base-line requirement for healthy and green VGS. In addition, design recommendations specific for prioritized criteria are given. Depending on the ranking (relevance and priority), more emphases can be put on certain design recommendations.
The recommendations per criterion are categorised on the effect of the design aspect (large to small), and provided in a left-to-right sequence. So, apply these recommendations from the top-left to the bottom-right.

Design for: functionality

Orientation	Dimensions of the VGS	Vegetation	Substrate	Supporting structure	Other	Operation
		Plant species: Choose local plants for better survival chances. Choose plant species that are well-adapted to local conditions (e.g. wind, amount of sun/shadow, temperature) for good biomass development. Choose plants with low allergenicity.	Consider the suitability of the substrate conditions for the plant species. Use a substrate with well-draining behaviour and proper organic content (Ascione et al., 2020).	For designing the supporting structure, consider the water-tightness, mounting and suitability to climatic conditions.	Implement a maintenance strategy, with planned maintenance (e.g. with a service contract).	
					Design an irrigation system that ensures adaptive irrigation (avoid over-watering). Place plant species bearing in mind their water requirements as there will be a gradient of humidity along the living wall, or a apply a higher frequency irrigation with lower flows and shorter irrigation time to achieve a uniform water distribution(\cite{Perez2013W}).	
					For existing buildings or renovation projects, check the suitability of load-bearing capacity of the existing structure for the structural weight of different VGS systems.	

Ranking
7
11

Design for: indoor heat stress reduction and cooling energy savings

Effect		Orientation	Dimensions of the VGS	Vegetation	Substrate	Supporting structure	Other	Operation
	+++ (large)		Enlarge the VGS area, and therefore facade coverage, for maximum cooling capacity (\cite{Radic2019}; \cite{Jim2015})	Vegetation density: For GF: choose fast-growing climber species to attain maximum LAI over time (\cite{Bakh2022}). For LWS: choose pre-vegetated systems to ensure some vegetation density from start.				
			Consider the growth speed differences between VGS types (GF are assumed fully grown in scoring, but they cover the facade over the course of years)					
	++ (medium)	Prioritize VGS on south-facing facades, and there-after west and east facades, for maximum indoor cooling (\cite{Bakh2022}; \cite{Susca2022})						
	+ (small)			Plant species: N.A.	Moisture content: Ensure adequate irrigation for evaporative (ET) cooling (\cite{Koch2020}, Interview A)		Air gap width: For IDGF: Enlarge the air gap width to maximise insulation barrier (\cite{Bakh2022})	
					Depth: N.A.			

5 **Design for: heating energy savings**

Effect		Dimensions of the VGS	Orientation	Vegetation	Substrate	Supporting structure	Other	Operation
	+++ (large)	1. Enlarge the VGS area, and therefore facade coverage, for maximum heating capacity (\cite{Radic2019}; \cite{Jim2015})		4. Vegetation density: For limiting heat loss: For GF: choose fast-growing climber species to attain maximum LAI over time (\cite{Bakh2022}). For LWS: choose pre-vegetated systems to ensure some vegetation density from start				
		2. Consider the growth speed differences between VGS types (GF are assumed fully grown in scoring, but they cover the facade over the course of years)		4. Vegetation density: For (facades that) gaining solar energy: choose species with low LAI.				
	++ (medium)			3. Plant species: For facades that should limit heat loss (e.g. north, with dominant cold (<20 C) conditions): evergreen species. For facades that should gain solar energy (e.g. south): deciduous species, and/or species with low LAI.				
	+ (small)		2. Prioritize VGS on north-facing facades for a smaller heat loss (\cite{Poddar2017}).		Depth: N.A.		Air gap width: For IDGF: Enlarge the air gap width to maximise insulation barrier (\cite{Bakh2022})	

6 **Design for: urban heat islands mitigation**

Effect		Orientation	Dimensions of the VGS	Vegetation	Substrate	Supporting structure	Other	Operation
	+++ (large)		Enlarge the VGS area, and therefore facade coverage, for maximum cooling capacity (\cite{Radic2019}; \cite{Jim2015})	Vegetation density: For GF: choose fast-growing climber species to attain maximum LAI over time (\cite{Bakh2022}). For LWS: choose pre-vegetated systems to ensure some vegetation density from start, and choose species with a large leaf area index (LAI) (\cite{Iaria2022})				
	++ (medium)							
	+ (small)	Prioritize VGS on south-facing facades, and there-after west and east facades, for maximum outdoor cooling (Interview A)	Height threshold: Limit VGS height above 20 m (\cite{Iaria2022})		Moisture content: Ensure adequate irrigation for ET cooling (\cite{Koch2020}, Interview A)			

18 **Design for: particulate matter removal**

Effect		Orientation	Dimensions of the VGS	Vegetation	Substrate	Supporting structure	Other	Operation
	+++ (large)		Enlarge the VGS area, and therefore facade coverage, for maximum PM removal (\cite{Pugh2012})					
	++ (medium)			Vegetation density: For GF: choose fast-growing climber species to attain maximum LAI over time (\cite{Weer2018b}). For LWS: choose pre-vegetated systems to ensure some vegetation density from start, and choose species with a large leaf area index (LAI) (\cite{Weer2018b})				
				Plant species: Choose evergreen species for year-round mitigation (\cite{Rowe2011}). Choose species with small (area < 200 mm2), hairy and rough leaves (\cite{Weer2018a}; \cite{Hel2022}).				
	+ (small)		Height threshold: Limit VGS height above 20 m (\cite{Iaria2022})	Plant arrangement: LWS: Place tall and short plants in alternating order of different heights (\cite{Weer2019a})				

11 **Design for: carbon sequestration**

Effect		Orientation	Dimensions of the VGS	Vegetation	Substrate	Supporting structure	Other	Operation
	+++ (large)			Plant species: Choose evergreen species for year-round mitigation (\cite{Perini2018A}) .				
	++ (medium)		Enlarge the VGS area, and therefore facade coverage, for maximum carbon sequestration	Vegetation density: For GF: choose fast-growing climber species to attain maximum LAI over time. For LWS: choose pre-vegetated systems to ensure some vegetation density from start, and choose species with a large leaf area index (LAI).	Depth: N.A.			
	+ (small)							

5 **Design for: traffic noise reduction**

Effect		Orientation	Dimensions of the VGS	Vegetation	Substrate	Supporting structure	Other	Operation
	+++ (large)		Enlarge the VGS area, and therefore facade coverage, for maximum maximum noise reduction (\cite{Wong2010N})	Vegetation density: For GF: choose fast-growing climber species to attain maximum LAI over time. For LWS: choose pre-vegetated systems to ensure some vegetation density from start, and choose species with a large leaf area index (LAI). Plant species: Choose evergreen species for year-round mitigation (\cite{Perez2018N})	Moisture content: LWS: Ensure adequate irrigation (\cite{Yang2013}).			
	++ (medium)				Choose a light-density and high-porosity substrate (such as perlite or mineral wool) (\cite{Horo2013})		Reflective façade behind VGS:Apply highly reflective façade materials behind the VGS (\cite{Rent2013})	
	+ (small)				Depth: LWS: Enlarge substrate depth (\cite{Yang2013})			

1 **Design for: biodiversity**

Effect		General	Dimensions of the VGS	Vegetation	Substrate	Supporting structure	Other	Operation
	+++ (large)	Design for target species (e.g. birds, pollinators, beetles or spiders) that suit the local ecosystem	Enlarge the VGS area, and therefore facade coverage, for maximum biodiversity value (\cite{Fila2019}; Interview C)	Vegetation density: For GF: choose fast-growing climber species to attain maximum LAI over time, and minimize pruning to create bushy habitats for birds (\cite{Radic2019}). For LWS: choose pre-vegetated systems to ensure some vegetation density from start, and choose species with a large leaf area index (LAI). Plant species: Choose native or established species (Interview C). Apply plant diversity for variability (\cite{Rowe2022}). For pollinators (e.g. bees) and insects: choose flowering species (\cite{Thorpert2022}). For winter-active animals (e.g. insects, birds): choose evergreen species (\cite{Chiquet2014} Interview C).				
	++ (medium)							
	+ (small)		For birds: limit VGS height above their flying zone (Interview C)		Enlarge the substrate depth to allow for rooting opportunities (\cite{Mayrand2018})		For birds: place nesting boxes (Interview C)	

16 **Design for: rainfall runoff control**

Effect		General	Dimensions of the VGS	Vegetation	Substrate	Supporting structure	Other	Operation
	+++ (large)	Connect VGS to nearby roofs to capture rainwater.			Enlarge the substrate depth to allow for retention capacity (\cite{Wouw2017})			
	++ (medium)			Vegetation density: LWS: choose pre-vegetated systems to ensure some vegetation density from start + species with large LAI (\cite{Dover2018})	Moisture content: Minimize irrigation by choosing drought-tolerant plants (\cite{Manso2021})			
	+ (small)							

11 **Design for: greywater treatment**

Effect		General	Dimensions of the VGS	Vegetation	Substrate	Supporting structure	Other	Operation
	+++ (large)	Connect VGS to greywater outlets.			Material: Combine organic (e.g. coconut coir) with mineral (e.g. perlite) substrates (\cite{Prod2017}; \cite{Masi2016})			
					Depth: Enlarge the substrate depth to allow for removal capacity (\cite{Pradhan2020})			
	++ (medium)			Plant species: Choose species that have a high tolerance for water-logged, high-nutrient environments (\cite{Addo2017}). For phosphorous removal: choose specific plant species that are effective in P-removal (\cite{Fowdar2017}).				For nitrogen removal: Limit the hydraulic loading rate (HLR) to up to 500 L/m2/day (\cite{Boano2020})
								For organic matter removal: Limit the hydraulic loading rate (HLR) to up to 800 L/m2/day (\cite{Boano2020})
	+ (small)							

11 **Design for: aesthetic value**

Effect		General	Dimensions of the VGS	Vegetation	Substrate	Supporting structure	Other	Operation
	+++ (large)		Enlarge the VGS area, and therefore facade coverage, for maximum aesthetic value (\cite{Radic2019})	Plant species: Apply a diversity of species and colours (\cite{Hoyle2017}; \cite{Thorpert2022}). Integrate flowering species (>25%) (\cite{Hoyle2017}). Choose evergreen species (Interview C).				
	++ (medium)							
	+ (small)							

4 **Design for: relaxation effects**

Effect		General	Dimensions of the VGS	Vegetation	Substrate	Supporting structure	Other	Operation
	+++ (large)			Plant species: Limit diversity of plant species (\cite{Hoyle2017}). Limit flowering species (\cite{Hoyle2017}).				
	++ (medium)							
	+ (small)							

4 **Design for: minimal environmental burdens**

Effect		General	Dimensions of the VGS	Vegetation	Substrate	Supporting structure	Other	Operation
	+++ (large)					Choose materials with end-of-life re-use or recycling potential, e.g. steel or aluminium (Interview A)		
	++ (medium)			Plant species: Choose species with low water demand and that are available in near-by nurseries (\cite{Nata2015}).	Apply recycled materials for part of the substrate (\cite{Perini2018LCA})			
	+ (small)							

8 **Design for: minimal private costs**

Effect		General	Dimensions of the VGS	Vegetation	Substrate	Supporting structure	Other	Operation
	+++ (large)					IDGF and LWSL planter boxes: Choose HDPE over steel (\cite{Rosasco2018}). Choose local suppliers for lower transportation costs (\cite{Rosa2013})		
	++ (medium)		Limit the VGS area, for minimum total costs.	Plant species: Choose plant species with a slow growing speed to limit pruning (\cite{Rosasco2018}). Choose species with low water demand.				
	+ (small)							

#N/A **Design for: private economic benefits**

Effect		General	Dimensions of the VGS	Vegetation	Substrate	Supporting structure	Other	Operation
	+++ (large)							
	++ (medium)		Enlarge the VGS area, and therefore facade coverage, for maximum real estate value increase (\cite{Rosa2013})				Check whether tax incentives or subsidies are applicable.	
	+ (small)							

Appendix: Neutral scenario sensitivity analysis

Project-specific input

To achieve project-specific results, please fill in the green boxes. The blue boxes are values that are fixed and cannot be changed.

1. Project description

Instruction: Describe the building project by filling in the green boxes.

Variable	Description	Range/scope	Value/result	Unit	Formula	Explanation
Name	Sensitivity analysis					
Adress	Utrecht	The Netherlands				Format: Street and number, city
Client						

2. Potential: Environmental conditions

Instruction: Provide environmental conditions that will affect the scoring on some criteria. Click on the link to access the different websites.

Variable	Description	Range/scope	Value/result	Unit	Formula	Link	Explanation
H	Average building height in street, estimation		24	m		Webmapper	Retrieve from Webmapper; estimate average of buildings in 500 m radius around building
W	Average street width (facade to facade), estimation		20	m		Google Maps	Retrieve from Google Maps > 'Terrein' > 'Afstand meten' ; estimate average of buildings in 500 m radius aroun
H/W	Street aspect ratio	0-5	1,2	-	H/W		
$C_{district}$	Facade vegetation coverage in district, estimation	0-100	2	%		Google Earth	Retrieve from Google Earth or field observations, estimate for radius of 500 m around building
Climate	Climate type in Köppen-Geiger classification	Cfb	Cfb	-			(Further development: include more climate types)
Urbanity	Degree of urbanity of the neighbourhood		Zeer sterk stedelijk	-		Atlas Leefomgeving	Retrieve value from Atlas Leefomgeving > Search for address, retrieve 'Mate van stedelijkheid van de buurt'

3. Relevance weighting

Instruction: How relevant are criteria to the location and project? Select or provide variables that affect the weighting.

Retrieve values from Atlas Leefomgeving.

Variable	Description	Range/scope	Value/result	Unit	Formula	Link	Explanation
PM2,5	Particulate matter (PM2,5) in air (2020)		9	µg/m3		Atlas Leefomgeving	Retrieve value from Atlas Leefomgeving > Search for address, retrieve 'Fijnstof in de lucht (2020)'
Noise	Noise in the environment (Lden)		48	dB		Atlas Leefomgeving	Retrieve value from Atlas Leefomgeving > Search for address, retrieve 'Geluid in de omgeving'
Green space	Percentage area of green space within a circle with a radius of 500 m		20	%		Atlas Leefomgeving	Retrieve value from Atlas Leefomgeving > Search for address, retrieve 'Groen binnen 500 meter'
Heat island	Average ambient air temperature difference, relative to rural area		1,0	°C		Atlas Leefomgeving	Retrieve value from Atlas Leefomgeving > Search for address, retrieve 'Zomerhitte in de stad'

Retrieve values from Klimaateffectatlas.

Variable	Description	Range/scope	Value/result	Unit	Formula	Link	Explanation
Heat stress	Severely lonely elderly over 75 (2020)		10-30	#/km2		Klimaateffectatlas	Retrieve value from Klimaateffectatlas > Select 'Ernstig eenzame 75+ers', then search for adress
Rainfall	Yearly precipitation (2016)		800-900	mm		Klimaateffectatlas	Retrieve value from Klimaateffectatlas > Select 'Jaarlijkse neerslag', then search for adress

Select the (planned) inclusion of cooling and heating systems.

Variable	Description	Range/scope	Value/result	Unit	Formula	Comment	Explanation
Cooling system	Presence of active cooling system (such as air conditioning or heat cold storage)		Yes			***Possible comment***	If a cooling system that consumes any energy is present, select 'yes'. If not known yet, select 'yes' .
Heating system	Presence of active heating system		Yes				(Further development: include 'no' option for heating system)

4. Priority weighting

What criteria have most priority? In cooperation with the client, allocate weights to the different criteria.
First, allocate a value of 10 to the least important criterion, using the drop-down menu. Then, allocate a multiple of 10 to the other criteria. This indicates their relative importance.
Allocate the highest values to the most important criteria, and lower values to less important criteria. Several criteria can have the same value, indicating that they are equally important.
The 'rank' list on the right shows the resulting ranking of criteria, according to the assigned 'priority' weights.

Criterion	Description	Range/scope	Weight	Unit	Rank	Explanation
BD	Biodiversity	10-100	10	-	1	Potential to provide plant species variety and density, as well as a habitat for birds, snails, insects, beetles and
AV	Aesthetic value	10-100	10	-	1	Potential for aesthetic appeal to citizens.
PM	Particulate matter removal	10-100	10	-	1	Potential to remove particulate matter, one of the major outdoor air pollutants.
TN	Traffic noise reduction	10-100	10	-	1	Potential to reduce traffic noise pollution on street level.
RE	Relaxation effects	10-100	10	-	1	Potential to bring psychological and physical relaxation, i.e., stress reduction, to citizens.
HS	Indoor heat stress reduction	10-100	10	-	1	Potential to reduce indoor heat stress by lowering indoor temperatures during summer heat waves.
UHI	Urban heat islands reduction	10-100	10	-	1	Potential to reduce outdoor air temperatures to combat the urban heat island effect (temperature rises in citi
RC	Rainfall runoff control	10-100	10	-	1	Potential for rainfall flow retention and reduction.
EB	Environmental burdens	10-100	10	-	1	Environmental burdens, e.g. from materials, maintenance and water use.
CS	Carbon sequestration	10-100	10	-	1	Potential to sequester carbon dioxide from the air.
GW	Greywater treatment	10-100	10	-	1	Potential to remove pollutants from greywater (e.g. from kitchen, shower) for irrigation of vertical greening sy
CE	Cooling energy savings	10-100	10	-	1	Potential to lower cooling costs in summer because of the insulation and shading by the vertical greening syst
HE	Heating energy savings	10-100	10	-	1	Potential to lower heating costs in winter because of the insulation by the vertical greening system.
PC-I	Private costs - Installation costs	10-100	10	-	1	Costs for design, materials, irrigation system and installation.
PC-MO	Private costs - Maintenance and operation costs	10-100	10	-	1	Annual costs for pruning, irrigation and replacements.
PC-DC	Private costs - Disposal costs	10-100	10	-	1	Costs for disposal of system at the end of the lifetime.
PB-PR	Private benefits - Plaster renovation saving	10-100	10	-	1	Savings from less building facade maintenance because of protection of building facade by vertical greening sy
PB-VI	Private benefits - Real estate value increase	10-100	10	-	1	Increase of the economic property value because of the vertical greening system.

Appendices: case study Venlo

11.9 Case study Venlo: interview

Nick Hendrikx is a project manager of building projects at RHDHV.

- Speakers: Hugo van Reeuwijk (HvR) and Nick Hendrikx (NH).
- Date: 1-6-2023.
- HvR introduces thesis topic and aim of interview: to test the tool on the case study of city hall Venlo.

[00:00:02.970] - HvR Dit is eigenlijk de tool. Dit is dan de eerste tab en dat introduceert eigenlijk waar deze tool voor is en welke onderdelen er zijn. Dus eigenlijk wat ik heb gedaan is: de wetenschappelijke benadering is dan dat ik een multi criteria analyse, dat ik die methodologie eigenlijk toepas op de selectie van een groen gevel systeem. Alleen gvels en geen daken heb ik meegenomen. En dit stuk gaat dan over de introductie en dan daarna is het dan input parameters van het project. Dus dat maakt dan de uitkomst die er uit komt. Project specifiek. Dan is er processing. Dat is eigenlijk de berekening van scores en daarna zijn er de resultaten. Dat zijn eigenlijk scores van verschillende systemen op criteria en die criteria die zal ik zo laten zien. Maar dat is eigenlijk de uitkomst. En de uitkomst is dan ook dat er een soort ranking is. Dus welk systeem scoort het hoogst op alle criteria bij elkaar? Dat is eigenlijk de opzet ervan.

[00:01:27.610] - NH Oké, ja.

[00:01:30.120] - HvR En daarna komen er ook nog wat extra design recommendations om dan wat meer praktische dingen die ik in het onderzoek heb gevonden, om rekening mee te houden in het uiteindelijke ontwerp. En dat is ook eigenlijk waar deze tool voor bedoeld is om vrij vroeg in een ontwerpproces van een nieuwbouwproject of een renovatie bouwproject om daarin te helpen met waarom zou je een groene gevel toepassen? Dus dat is dit plaatje eigenlijk met die vier fasen. Het is bedoeld voor een vroege projectfase, waarbij dus ook nog niet de afmetingen of echte details in het ontwerp bekend zijn. Dus eigenlijk nog voor het voorlopig ontwerp. Dat is de bedoeling en ook voor een gebouw type. Dat staat natuurlijk wel vast bij een project, maar het is toepasbaar op meerdere soorten projecten en dit zijn dan de systemen. De soorten die ik heb geïdentificeerd en die dan worden vergeleken. Dus dat is een directe groene gevel. Dat is eigenlijk klimop direct tegen de gevel aan. Een indirecte groene gevel met lijnen zeg maar, dus met stalen lijnen die het ondersteunen.En dat is ook. Klimop, vaak een klimplant. En dat is dan er nog eentje die daar heel erg op lijkt, maar dan met een mesh. Dus een raster eigenlijk.

[00:03:13.330] - NH Oké.

[00:03:14.110] - HvR En dan de rechter vier. Dat zijn de Living Wall Systems en dat is volgens mij ook toegepast bij het Stadskantoor Venlo. En dan heb je dus dit zijn vilt-systemen, dus eigenlijk vilt pockets. Dat is vrij dun. En dan daarin groeien dan de planten. Dit zijn modulaire trays. Dat zijn meer plantenbakken, maar dan wat kleiner en onder elkaar. Dus vlak op elkaar. Dus de hele gevel is dan groen eigenlijk.

[00:03:41.240] - NH Ja.

[00:03:41.970] - HvR En deze lijkt daar heel erg op. Dat zijn dan modular boxes, maar daarbij groeit het dan meer op horizontaal. In een horizontale richting. En de laatste dat dat eigenlijk combinaties zijn. Het zijn plantenbakken, bijvoorbeeld elke drie meter en daartussen klimplanten. Dat zijn eigenlijk de systemen die ik heb geïdentificeerd.

[00:04:04.470] - NH Dit komt vanuit bestaande leveranciers. Of zijn dit gewoon echt systeem typologieën die meerdere leveranciers kunnen leveren.

[00:04:12.810] - HvR Ja, dat eigenlijk. Dus ik. Ik heb echt wel in de literatuur gekeken. En daaruit komen dan deze algemene typologieën. En er zijn nog veel meer subtypes, zeg maar. Maar om het een beetje duidelijk te houden heb ik deze categorieën eigenlijk gekozen omdat die dan ook het meest verschillen in prestaties.

[00:04:32.220] - NH Ja. Oké.

[00:04:36.020] - HvR Ja, en dan zijn dit de criteria waar ze op worden beoordeeld en die zijn dan gegroepeerd in vijf thema's. Daar kijken we zo ook nog naar. Maar dat gaat eigenlijk om. Eigenlijk heb ik in de literatuur gekeken welke aspecten zijn er allemaal bekend over bepaalde voordelen of nadelen van groene gevels? Ja dus. Dat gaat dan zowel over echt kosten, maar ook wat meer op stadsniveau. En dan gaat het over klimaatadaptatie, gezondheid en dan nog sociale waarden en biodiversiteit. Die hebben natuurlijk een impact op een verschillend niveau. Dus de dichte cirkels, dat is meer. Dat heeft meer impact op gebouw niveau en de open cirkels. Dat hebben meer invloed op stadsniveau of op straatniveau. Eigenlijk vanaf de buitenkant dus. Dat onderscheid heb ik al proberen te maken om het een beetje te zien van wat is nou een voordeel meer voor een private eigenaar of wat is meer voor de algemene maatschappij bevorderlijk? En dat is eigenlijk een beetje de opzet. Dan kunnen we nu misschien wel kijken naar deze tweede tab.

[00:05:56.580] - HvR Dat is dan de input. Dat begint eigenlijk met de projectbeschrijving. Dus de naam van het project, het adres en de client. Om gewoon even duidelijk te maken van waar, welk project. Gaan we deze tour voor gebruiken? Maar die heb ik alvast even ingevuld zodat we dat niet meer hoeven te doen. En dan kijken we naar de bepaalde omgevingscondities, want die hebben dan invloed op hoe goed of welke potentiële score op bepaalde criteria er kan zijn, bijvoorbeeld voor fijnstof reductie. En als er hele smalle straten zijn met hoge gebouwen, dan is er meer kans op een fijnstof reductie dan als het hele open brede straten zijn, dan ja dan waait die fijnstof eigenlijk ook makkelijker weg. Ja dus voor dan zijn eigenlijk de groene vakjes wat dan kan worden ingevuld door een engineer of een manager zoals jij. Dus op deze site kan je dan gebouw-hoogtes zien in de omgeving van het gebouw en kan je een schatting makenvan de gemiddelde bouwhoogte. Dat is ongeveer 29/30 meter en een inschatting van de gemiddelde straat breedte. Dat was dan ongeveer 25 meter en daar komt dan een verhouding uit. Dus dat wordt ook wel de street aspect ratio genoemd. Dus eigenlijk hoe smal is de straat? En deze waarde heeft dan invloed op de score uiteindelijk.

[00:07:44.750] - NH Oké.

[00:07:49.050] - HvR En hetzelfde geldt eigenlijk voor deze twee goede dingen. Die kan je ook van bepaalde websites halen. Daar gaat het om de hoeveel groene gevels er in de buurt zijn. En dat. Ja, dat heb ik nu even aangenomen dat je dat Google Earth kan zien of als je er zelf rondloopt. Voor nu heb ik dat even op 1% geschat. De kans lijkt me vrij klein dat daar heel veel groene gevels in een cirkel eromheen liggen.

[00:08:17.990] - NH Wat jij zegt radius van 500 meter. Ja.

[00:08:21.740] - HvR Omdat het dus op district level is, dus dat is dan even een aanname.

[00:08:25.190] - NH Ja, dan denk ik dat je geen andere gebouwen die een groene gevel hebben. Ze zijn wel met nieuwbouw bezig. Direct naast het stadskantoor, maar daar zit geen goede gevel bij. Volgens mij is alleen maar PV panelen.

[00:08:39.980] - HvR Ja.

[00:08:41.180] - NH Je hebt de Maas redelijk dichtbij liggen daar, dus je hebt. In principe wordt die cirkel van 500 meter een beetje afgekapt omdat je de Maas hebt.

[00:08:52.510] - HvR Ja nee dus dan zou het misschien wel beter zijn als ik het gewoon op nul zet. Dat is dan misschien wat realistischer dan 1%. Hier is het ook klimaattype, maar dat is gewoon het Nederlandse klimaat, dus dat is op zich. Kan dat niet worden veranderd en dit gaat over de mate van stedelijkheid. Op deze site kan je je adres invoeren en dan zie je van het CBS de dichtheid van adressen. En dan zijn hier zeg maar diezelfde opties die daar die er zijn. Die heb ik hier ook aangegeven dat je dus kan aanklikken van nou welke is hier van toepassing? En dat heb ik even gecheckt en dat is hier sterk stedelijk.

[00:09:41.040] - NH Daar heb ik wel verbaasd over. Wat geeft die? Ik zeg Rotterdam en Amsterdam zou ik als sterk stedelijk zien.

[00:09:48.600] - HvR Ja.

[00:09:49.530] - NH Maar Venlo is een andere categorie stad. Weet je wel dat?

[00:09:53.520] - HvR Ja, precies. Maar er is ook nog een zeer sterk stedelijk, dus dat is dan daar ook. En dit gaat vooral om de dichtheid van adressen. Dus niet per se het aantal mensen op de hoogbouw of hoe dicht alle oppervlakken zijn zeg maar. Maar het gaat meer om alleen die adressen. Dus het heeft dan ook in deze tool alleen invloed op de vastgoed waarde, in hoeverre die kan toenemen of niet.

[00:10:21.340] - NH Oh op die manier want je hebt een aantal woontorens, Heb je daar in de buurt liggen, dan heb je natuurlijk en een hele hoge dichtheid van adressen.

[00:10:30.390] - HvR Ja, precies. En dan is er het volgende onderdeel dat gaat over wat is nou relevant? Want je kan scores aanneem voor bijvoorbeeld fijnstof reductie. Maar als er meer fijnstof is, dan is fijnstof reductie ook wat relevanter natuurlijk. Dus daarvoor heb ik dit stuk er in gezet. Weer die groene vakken worden dan ingevuld en dus op basis van de Atlas Leefomgeving. Is er een fijnstof waarde die daar gemeten is en dat is dan in 2020 en die kan je dan hier invullen. Al die waardes heb ik ook alvast even ingevuld zodat we daar niet veel tijd aan kwijt zijn. Maar dat geldt dus voor fijnstof concentratie dus dat als die dan hoger is, dan geeft ook een hogere weging voor de relevantie van dat criterium. En hetzelfde geldt voor omgevingsgeluid. Daar wordt een gemiddelde over de dag, nacht en avond. En ook de hoeveelheid groen in de omgeving. Dat is ook een bepaald percentage en dat heb ik allemaal overgenomen van die websites. Dat kan dan de gebruiker van deze tool ook zelf daar ophalen en dan invullen.

[00:12:04.650] - NH De weging van de verschillende criteria wordt die dan berekend op basis van de die PM-waarde?

[00:12:17.640] - HvR Ja.

[00:12:18.300] - NH Kun je die ook zelf nog bijstellen? Dat je zegt van joh, ik wil eigenlijk een groene gevel die vooral de luchtkwaliteit beïnvloedt of die vooral een reductie van het akoestisch perspectief levert. Is dat ook een knop waar je aan kan draaien?

[00:12:32.100] - HvR Ja dus die weging, die bestaat eigenlijk uit twee dingen, dus de relevantie, dat ligt gewoon vast op basis van deze parameters en de prioriteit. Dus dat is dan waar de klant of de ontwerper zelf nog kan aangeven van wat is nou wel of niet belangrijk En de totale weging is dan de ene weging maal de andere weging. Dus eigenlijk alleen als één van beide echt nul is dan wordt die er uit gehaald. Maar als. Stel het is hier laag, maar hier heel hoog. Dan komt daar soort gemiddelde totale beweging weer uit. Dus ook op die manier kan je nog wel invloed uitoefenen op de weging. En eigenlijk heb ik gekozen voor die combinatie omdat op sommige aspecten kan het ook lastig zijn om al heel vroeg te weten: is dit een prioriteit? En dan heb je natuurlijk veel aan die relevantie van ja, dan geeft dat wat een wat betrouwbaarder beeld en ook wat minder wensdenken van we willen heel graag fijnstofreductie, maar als er weinig fijnstof is kan dat natuurlijk ook niet.

[00:13:46.040] - NH Is nou die value die die PM2,5 hebt staan. Is dat nou een relatief hoge waarde of is dat een lage waarde?

[00:13:53.630] - HvR Dan zou ik even moeten kijken bij dit stukje, bij Processing. Hier heb je de verschillende waardes voor. Voor die PM2,5 en deze waardes zijn er dan, dus deze vier. Lager dan vijf is al heel goed en dat is ook lager dan de WHO advies waarde, dus die is dan niet relevant. Eigenlijk wordt dan aangenomen en die negen valt dus hier in, dus dan is het wel hoger dan de advies waarde, maar ligt nog lager dan een soort internal target van de WHO. Dus dan heb ik het geïnterpreteert als best wel relevant. Terwijl als je bouwt boven de tien of boven de 25 bent, dan is er echt wel een heel fijnstofprobleem.

[00:14:45.060] - NH Oké.

[00:14:46.560] - HvR Dus hier is dan deze weging voor de relevantie. In ieder geval is die weging dan 0.3. En dan kan je dus nog voor de prioriteit Kan je dat nog bijstellen eigenlijk. Als dat heel belangrijk is, dan kan je dat. Opplussen.

[00:15:03.110] - NH Oké.

[00:15:04.340] - HvR En ook weer die decibel. Dat is volgens mij ook vrij hoog, dus dat is dit. En dat komt denk ik vooral door de trein en de wegen in de buurt.

[00:15:14.170] - NH Ja, ligt vlakbij het brug, dat is het vrij verkeer intensief.

[00:15:17.680] - HvR Ja precies. Dus daar zie je dan dat die boven de 61 decibel zit en dat het dan dat dat dan dus de hoogste weging heeft. Als je vrij lage decibels hebt en dat is dan lager dan een indicator voor geluidsoverlast, ja dan neem ik aan. Dat is eigenlijk niet relevant om geluidsreductie. Om dat als doel te zien en het gaat dan om geluidsreductie in de omgeving. Dus dat is eigenlijk hoe het werkt. En van een andere website is dan ook een indicator voor hittestress is het aantal ernstig eenzame ouderen boven de 75. Dat was in ieder geval de meest geschikte indicator die ik kon vinden om eigenlijk op wijkniveau aan te geven van hoeveel hittestress er is. Als er heel veel mensen wonen in het is heel warm. Dan is natuurlijk meer prioriteit dan als het heel warm is, maar er is maar één boerderij met één iemand erin hebt.

[00:16:19.480] - NH Als je eenzaam bent, dan heb je eerder hittestress?

[00:16:23.230] - HvR Nee, dit is wel. Dit is wel onderzocht door het KNMI en ook nog wat andere organisaties. Dat is wel echt een goede indicator voor, omdat er hele jonge mensen, hele oude mensen zijn, gevoeliger voor hitte. En deze titel klinkt een beetje alsof het alleen gaat om eenzaamheid. Maar het gaat eigenlijk om dat de mensen oud zijn en dat ze dus minder sociaal contact hebben en daardoor minder goed worden geholpen met het aanpassen aan de hitte. Ja, dat is een beetje de redenatie die er achter zit.

[00:16:51.460] - NH Dat is wel grappig dat die indicator inderdaad gaat over eenzaamheid.

[00:16:55.130] - HvR Ja, precies. Ja precies. En daar zijn dan een paar opties zo, maar die kan je dan dus aanklikken.

[00:17:01.260] - NH Ja.

[00:17:02.080] - HvR En ook voor regen zijn er ook nog wat opties. Met de redenatie er achter. Als het ietsje minder regent is het iets minder relevant om wateropvang te genereren. Als het wat meer regent in de regio is dat nog wat relevanter, maar bijvoorbeeld voor geluid zijn die grenzen echt best wel duidelijk. Van onder zoveel decibel is het echt niet relevant en hier is dat meer een aanname. Dus dan heb ik ook die relevantie scores liggen wat dichter bij elkaar. Als bijvoorbeeld 0.8 of 0.9, dus dat zijn wat kleinere verschillen voor de dingen die nog wat onzekerder zijn.

[00:17:37.120] - NH Ja, ja.

[00:17:39.840] - HvR Dan als laatste input-parameter is er dan de aanname van. Is er een actief koelsysteem, een actief heating/verwarmingssysteem? Even kijken. Daar ben ik benieuwd van. Even soort van terug in de tijd, want. Ja, was er bij dit project eigenlijk een actief koelsysteem, bijvoorbeeld airconditioning?

[00:18:12.080] - NH Wat er gebruikt is, is een WKO-systeem voor verwarming en koeling. In het gebouw hebben we klimaatplafonds zitten, ook voor verwarming en koeling. Dus het is grotendeels een gekoeld gebouw ook.

[00:18:30.510] - HvR Ja ja, en er wordt inderdaad energie gebruikt om te koelen. Dat is eigenlijk de definitie die ik dan gebruik. Dat heeft dan invloed op of energiekosten van koeling kan worden bespaard. En als natuurlijk, als er helemaal niet wordt gekoeld, bijvoorbeeld in een gewoon woonhuis, dan kan je ook niks besparen. Dus vandaar dat deze parameter er in zit. Misschien wel goed om dan hierheen te gaan. Dit zijn eigenlijk alle criteria op een rij gezet.

[00:19:05.140] - NH Bij die criteria. De oriëntatie van de gevel. Neem je die ook mee? Of speelt die ook een rol?

[00:19:12.960] - HvR Nu nog niet, omdat in zo'n vroege fase je nog niet weet op welke oriëntatie je je gevel zou willen toepassen en waar er ook ruimte is. Maar wel hier in de design recommendations. Dus daar is dan een stuk oriëntatie en dan per criterium of per doel geef ik dan recommendations ervoor. Welke invloed heeft nou de oriëntatie keuze of de oriëntatie op het ontwerp en op het doel waarvoor ik wil ontwerpen. Bijvoorbeeld hier voor hittestress. Dat heeft natuurlijk. Meer effect als je die groen geeft op een zuidgevel met heel veel zon plaatst.

[00:20:00.930] - NH Ja, ja.

[00:20:04.250] - HvR Dus daarin heb ik het meegenomen. Dus dit is het ontwerp kant en hier is het meer het algemene systeem voor het gebouw eigenlijk. Ja.

[00:20:15.360] - NH Oké. Ik moest er ook aan denken toen je het over de akoestiek had, specifiek bij dit gebouw. Aan één kant ligt die drukke verkeersweg en het spoor. Ja, toevallig zit aan die zijde ook de groene gevel, maar de andere kant van het gebouw is veel minder belast met het geluid. Dus dan stel dat de groene gevel aan de andere zijde had gezeten, dan heb je hier een waarde ingevuld die misschien niet heel passend is uiteindelijk voor dit project.

[00:20:44.530] - HvR Ja klopt. En dat zou inderdaad nog een mooie toekomstige ontwikkeling zijn. En wat de aanname die ik doe is dat die scores die eruit komen dat het meer de maximaal haalbare scores zijn. Dus als de groene gevel op de goede plek plaatsts en in leven houdt. Ja, en daarvoor zijn er ook die ontwerp recommendations. Om dan die maximaal haalbare score het ook echt te halen.

[00:21:17.620] - NH Als je dit iteratief dan toepast? Dat je zegt van nou bij de eerste analyse gaat over wat is nu maximaal haalbaar. Ja dan worden de ontwerpkeuzes gemaakt en dan zou je nog een keer deze kunnen invullen om te kijken van goh, hoe ver zit ik nu op die maximale haalbaarheid schaal? Heb ik nu 80% gerealiseerd of meer of minder? Dus die zin, dat is op zich, dat is opzich wel ...

[00:21:43.020] - HvR Ja, ja, we kunnen nu misschien wel kijken naar die prioriteiten weging. Dus dat gaat dan eigenlijk om welke criteria zijn belangrijk in het project en welke zijn minder belangrijk? Dus het gaat eigenlijk ten opzichte van elkaar, relatief. Ja, dit zijn ze allemaal. Het zijn er heel wat en eigenlijk is dan de bedoeling om dan te beginnen met de minst belangrijke, met de minst belangrijke criteria om daar een score van tien aan te geven en dan te kijken. Relatief, van als het even belangrijk is ook tien en anders een tien, twintig of dertig. Dus eigenlijk een meervoud van tien. Aan de andere criteria te geven. En je ziet hier rechts ook dan de ranking die daarbij uitkomt. Dus één is het belangrijkste en daaronder is het minder belangrijk.

[00:22:41.440] - NH Kijk, bij dit project. We zijn eigenlijk begonnen met het ontdekken wat de ambitie was van de opdrachtgever. De opdrachtgever zei: ik wil een circulair gebouw en dat was in in 2010/2011. Ja, en toen noemden ze dat nog cradle to cradle.

[00:23:06.190] - HvR Ja precies, dat zag ik in een paar documenten.

[00:23:08.770] - NH Ja, en dat. Dat is echt een containerbegrip van joh. We willen cradle to cradle bouwen. We willen vooroplopen met cradle to cradle. De eerste gemeente zijn die zo'n gebouw neerzet.Waar we als ontwerpteam heel erg mee geworsteld hebben aan de voorkant was: als je dat nu concreet maakt of smart maakt, wat is dat dan precies? Wat? Wat wil je nu? Kijk, duurzaamheid is al een heel breed begrip. Maar cradle to cradle en die circulariteit is ook al heel breed. Plus je kunt dat heel erg moeilijk meten. Je hebt. Je hebt een BREEAM-certificaat, LEED, GPR scores, maar op dat moment had je alleen maar binnen de cradle to cradle hoek certificaten. Dat je een c2c certificaat zou kunnen krijgen. Ja, dan kun je denken goh, is de optelsom van het aantal certificaten dan een maat voor hoe ver ik ben? Ja, dat was een beetje een beetje het stoeien. Dus uiteindelijk wat er gedaan is, is dat we hebben gezegd we hebben vier gebieden waarop we echt iets willen doen en dat ging over materiaal reductie en ook weten wat er in materialen zit. Dat ging over energiebesparing. Dat ging over waterkringloop en dat ging over luchtkwaliteit. Ja, en eigenlijk de laatste twee. En dan met name de luchtkwaliteit. Dat was de drijfveer voor deze groene gevel.

[00:24:36.430] - HvR Ja, precies.

[00:24:37.480] - NH Dus. Ik realiseer me dat dat dat er veel meer factoren zijn die een rol kunnen spelen. Maar eigenlijk wat er gedaan is, is primair met de bril van luchtkwaliteit. We willen: Als gevolg van het plaatsen van dat gebouw moet de luchtkwaliteit aan de buitenkant verbeteren. Ja, vanuit die optiek is die groene gevel erin gekomen, dus dat betekent eigenlijk dat die, precies waar jij nu staat, dat die fijnstof reductie, die was belangrijk. En alle andere zaken. Dan zou ik zeggen van die is bijna negentig of honderd. Ja, een stukje greywater-treatment, dat zit daar een beetje in, maar het is meer dat het dat die groene gevel gebruik maakt van een grijs water circuit wat er ook al vanuit andere redenen in zou zitten. Dus je zou die op de veertig zetten. En alle andere factoren, die zijn niet echt afgewogen. Dat was meer een nice to have, weet je wel. Bijkomend effect, maar geen drijfveer om die groene gevel te kiezen.

[00:25:47.840] - HvR Ja precies.

[00:25:48.950] - NH Dus dat maakt het invullen van het tabelletje heel eenvoudig ja.

[00:25:52.760] - HvR En ik las ook nog dat die geluidsisolatie, dat dat ook nog wel een rol heeft gespeeld. Of in dit geval dat het een voordeel wat werd genoemd. Maar was dat ook een enigszins prioriteit in het proces?

[00:26:04.870] - NH Nee, dat is meer. Dat moet je meer zien in de context van ja, ik moet het niet marketing noemen, maar van goh, we hebben toch wel een heel aantal voordelen van die groene gevel.

[00:26:18.130] - HvR Ja precies, dat was eigenlijk meer een soort bijkomstigheid.

[00:26:20.830] - NH Ja, meer achteraf.

[00:26:25.460] - HvR Ja, ja.

[00:26:27.190] - NH Kijk. En biodiversiteit is ook wel iets wat achteraf eraan is toegevoegd hè. Iemand heeft een keer een duif zien broeden in die gevel, we zijn heel biodivers. Dus ja, het zijn elementen die kom je in de in de hoek van de marketing zeker tegen. Ja, die zitten meer op van goh, achteraf is gezegd van die gevel heeft wel veel meer kwaliteiten, maar het is geen drijver om deze systeem keuzes te maken.

[00:26:55.910] - HvR Ja, precies. Dus in het begin van het proces was dat nog geen punt, dat werd meegenomen.

[00:27:03.880] - NH Het is dus geen criterium geweest om die groene gevel te kiezen. In het ontwerp zijn een aantal leveranciers aan tafel komen zitten. Die hebben een proefstuk geleverd en die zijn op de TU Eindhoven gemeten op het criterium fijnstof reductie. En volgens mij ook een aantal andere stofjes, maar de resultaten daarvan hebben de rangorde gegeven in, welke leverancier uiteindelijk dan in de ontwerp documenten terecht is gekomen.

[00:27:35.020] - HvR Ja. Zal ik dan ook voor esthetische waarde ook tien invullen? En voor geluid, stressreductie, hittestress aan de binnenkant.

[00:28:16.550] - NH Die groene gevel staat ook wel een centimeter of vijftien van het gebouw zelf af, van de thermische schil. Ik vraag me af hoeveel effect het daadwerkelijk heeft.

[00:28:25.070] - HvR Ja precies. Er zijn heel veel metingen op de gevel zelf maar niet per se binnen ook, dus dat is ook nog enigszins onzeker. De volgende criteria zijn wateropvang, environmental impact... Ik zag ook dat de omzet van CO2 en zuurstofook nog werd genoemd achteraf.

[00:29:01.040] - NH Ja, fijnstof is gemeten. Stikstof. Ik denk ook zuurstof of CO2 volgens mij. De testen die bij de TU Eindhoven zijn gedaan. Dat waren geen testen waarvan ik dacht daar durf ik mijn hand in het vuur te steken. Dat waseen afstudeeronderzoek en de conclusie was van de groene gevel dat hij bijvoorbeeld zuurstof zou afgeven, maar op een ander moment deed hij dat ook weer niet. En dat. Ja, maar dat waren net de momenten dat de lamp aanstond. Die rode lamp, weet je wel ...

[00:29:49.260] - HvR Ja precies. Is het misschien een idee om die dan bijvoorbeeld twintig te geven omdat het wel gemeten is en als een waarde is meegenomen?

[00:30:00.600] - NH Ja, dat lijkt me prima.

[00:30:03.090] - HvR Dan thermisch, maar dan het gevolg voor de energie behoefte van het gebouw.

[00:30:13.020] - NH Ja.

[00:30:14.070] - HvR Zal ik die ook op tien zetten?

[00:30:15.660] - NH Ja zou ik ook tien zetten.

[00:30:17.850] - HvR En dan gaat geldt dat dus ook voor hitte of voor verwarming. En dan zijn hier nog wat kosten. Wat kostenaspecten en economische voordelen. Zal ik die ook op tien zetten of toch iets hoger?

[00:30:34.180] - NH Ze hebben eigenlijk in de systeem afweging geen rol gespeeld.

[00:30:40.060] - HvR Oké. En in de keuze voor überhaupt een goed systeem is daar nog economische kosten of voordelen relevant voor geweest?

[00:30:47.340] - NH Nee, ook niet. Ik denk als je die hoog zet, dan ga je geen groene gevel kiezen.

[00:30:54.900] - HvR Nee, precies, maar dan kan je wel een bepaalde typologie kiezen, dus dan maak je de afweging. Ja, dan kan je het goedkopere systeem kiezen wat dan minder goed fijnstof zuivert. Maar ja. Die zet ik dan ook gewoon op tien. Dat zijn eigenlijk installatiekosten, onderhoudskosten en dan aan het einde om het af te ronden... Dan wordt er ook soms aangenomen dat de gevel beter wordt beschermd door het groene systeem, zodat daar dan minder onderhoud aan hoeft te worden gepleegd.

[00:31:28.510] - NH Oké, ook op 10 zetten.

[00:31:30.860] - HvR Zo te horen inderdaad komt dat niet bekend voor. En ook voor de vastgoed waarde. Die kan natuurlijk iets toenemen. Bijvoorbeeld de huurprijs, zal ik die ook op 10 zetten.

[00:31:43.790] - NH Ja.

[00:31:45.550] - HvR Nou super! Kijk, dan zien we de ranking van criteria. Dit is de belangrijkste prioriteit. Dus eerst fijnstof. Dan ook nog waten greywater, en dan de rest. Even kijken. We kunnen nu wel gaan naar de volgende stap. Dit is op zich niet zo heel interessant denk ik om helemaal door te nemen, maar eigenlijk. Deze tab verwerkt alle scores en die maakt het dan project-specifiek. Dus hier komen ook weer die drie inputs stukken terug. Dus die street aspect ratio en bijvoorbeeld stedelijkheid. Het is van invloed op die thermische performance. En ook worden de waardes dan gestandaardiseerd. Eigenlijk staan hier de waardes nog in decibel of temperatuur reductie of een percentage van de koelinglast die kan worden bespaard. Maar om die waarde te vergelijken moet je standaardiseren.

[00:32:55.100] - HvR En dat is eigenlijk wat hier gebeurt met bepaalde functies om te kijken van wat is... Nul is dan vaak de slechtste score en honderd de beste. Voor geluidsreductie zijn er ook andere maatregelen mogelijk, bijvoorbeeld gewoon een geluidsscherm op straat en dat reduceert dan vijftien decibel. Dus dat is dan als upper bound gekozen is. Dat is dan eigenlijk honderd. En dan bepaalde gevelsystemen. Die geven bijvoorbeeld ongeveer 5,4 decibel reductie, dus dan is dat ongeveer tweederde. Dus dat bijvoorbeeld 36 van de 100 score. Dus dat is eigenlijk hoe dit werkt.

[00:33:34.460] - NH Oké.

[00:33:37.360] - HvR En dan worden die wegingen nog toegepast op die gestandaardiseerde scores. En dan is dat dus die relevantie. Dus dat is op basis van de input parameters van die websites. En ook op basis van prioriteiten dus. Hier zie je dan eigenlijk die prioriteiten van net. En dat geeft dan een bepaalde wegingswaarde, dus dat wordt dan genormaliseerd en dan zie je hier eigenlijk dat deze een tien keer zo hoog weging heeft als de rest of als veel andere aspecten. Nou, dan wordt dat allemaal uitgerekend. Dus eigenlijk is dan de weging maalde de ene weging maal de andere weging. Maal de performance, de gestandaardiseerde performance. En daar komt dan. Daar komen dan scores uit, eigenlijk per systeem en op elk criterium. En daar kunnen we nu wel naar kijken. Dit zijn dan eigenlijk de resultaten. Dit zijn de gevel systemen met de afkortingen en het plaatje erbij. Dan zie je hier de overall performance. Dat is dus eigenlijk de opgetelde waarde van de weging maal al die scores.

[00:34:52.990] - NH Ja ja.

[00:34:54.560] - HvR En dan zie je hier die dynamiek. Dus hier is dan het living system met modular boxes wat net het hoogst scoort. Dit is dan de ranking die daaruit volgt en je ziet dat het eigenlijk redelijk vergelijkbare waarden zijn, dus zit elkaar in de buurt. Maar deze twee scoren dan wel het hoogst en dat komt ook vooral door die fijnstof weging, want dat zie je dan hieronder, dat waar die score dan is uit opgebouwd. Hier zie je wat het blauw is, de grijs waterzuivering en die fijnstof reductie en dan dat is het grijze, dus dan zie je ook dat dat hier hoger is dan bijvoorbeeld voor andere systemen.

[00:35:52.140] - NH Eigenlijk als ik dit zo zie hebben we per ongeluk gewoon de juiste keuze gemaakt.

[00:35:58.410] - HvR Ja, ik denk niet dat helemaal per ongeluk is, maar... Kijk natuurlijk achteraf inderdaad.

[00:36:05.120] - HvR Volgens mij ik zag één plaatje waarbij het leek dat het meer langwerpige bakken waren waar planten uit groeien. En die bakken, die zitten dan wel kort op elkaar, maar ik zag ook een ander plaatje wat meer leek alsof het horizontaal groeide, dus ik ben ook wel benieuwd om te zeker te weten: weet je nog wat voor systeem er is toegepast?

[00:36:24.020] - NH Ja, bedrijf Mostert de Winter heeft dat ontwikkeld, volgens mij dat wat jij hier dat dat derde van rechts is.

[00:36:35.990] - HvR Ja precies, dat.

[00:36:37.010] - NH Zijn inderdaad plantenbakken waar ze een beetje schuin allemaal in staan.

[00:36:41.240] - HvR Ja, maar dat zijn wel lineaire bakken, dus waar de grond zeg maar voor een meter of zoiets gewoon doorloopt zeg maar.

[00:36:49.430] - NH Exact.

[00:36:50.920] - HvR Ja, precies. En geen kleine vakjes met planten. Dat is inderdaad deze, maar dan zie je net. Nou, dat is dan achteraf een goeie keuze geweest denk ik.

[00:37:06.070] - NH Hier staat ook iets over de kosten in. Want zijn dat absolute kosten die hier input zijn geweest?

[00:37:14.800] - HvR We kunnen even kijken naar deze tab. Dat is dan per criterium en daarin staat ook wat dan de aangenomen kosten zijn, zeg maar. Ik zal even scrollen, naar beneden staat namelijk een beetje onderaan. Bijvoorbeeld hier voor de installatiekosten. Dat blauw is en de performance op die helemaal gestandaardiseerd is. Dus daarbij heb ik dan aangenomen van nul is het beste, dus die heeft ook de hoogste scores. Dus het goedkoopste systeem scoort het beste. En een duurder systeem scoort minder goed. Dat is eigenlijk dat komt. Bij een goedkoper systeem draagt dus de kosten meer bij aan de totale waarde of de totale score. En hier zie je dan dat dus voor het systeem dat is gekozen, dat dan... Er zijn een paar onderzoeken die eigenlijk heel veel kostengegevens bij elkaar hebben gezet en daar komt deze range uit. Die is vrij breed als installatiekosten per vierkante meter. Dus het gaat van 200 tot wel 600, dus die range is vrij breed, maar daarvan heb ik dan een gemiddelde genomen om dan deze score te krijgen.

[00:38:32.990] - HvR En je ziet hier eigenlijk dus dat deze drie systemen in ieder geval in dit model even duur zijn, en dat dan die indirecte opties wat goedkoper zijn. En directe systemen veel goedkoper en dit deze ergens ertussenin.

[00:38:49.480] - NH Ja, want neem jij die kosten nu mee? En dat performance getal wat je hieruit krijgt? Spelen de kosten daarin nog een rol?

[00:38:56.410] - HvR Ja, en ik zal even laten zien. Dat gele, dat grijs en oranje. Maar omdat die dus een lage weging hebben, zie je eigenlijk dat dat weinig uitmaakt.

[00:39:13.890] - NH Het is niet bepalend nee.

[00:39:16.020] - HvR Maar in een ander project kan ik me natuurlijk goed voorstellen dat dan kosten wel wat belangrijker worden gevonden. En dan zie je dus dat hier eigenlijk veel potentie zit om een goedkoper systeem toe te passen. Want stel je geeft hier bijvoorbeeld een vijftig weging aan, dan wordt dit vijf keer zo groot. Ongeveer dit gele blokje en dan komt het in de buurt van die living systems en dan kan je echt de afweging maken van oké, wat vinden we dan belangrijker of ja, dus daarvoor is het eigenlijk ook bedoeld deze tool. Niet per se om te zeggen van dit systeem moet je kiezen, maar wel waarop baseer je de keuze voor je systeem en wat is wel of niet belangrijk en wat zijn de doelen daarvoor?

[00:39:58.140] - NH Ik kan me ook voorstellen dat je als je in een ontwerptraject zit en je hebt het hier over met een opdrachtgever dat je wil laten zien van wat is nu de prestatie van je groene gevel op allerlei criteria, behoudens de kosten. Dus je laat de kosten even helemaal links liggen en dan krijg je een bepaalde rangorde. En dan zou je kunnen kijken van joh nu heb ik een bepaalde pot geld. Welke gevel geeft mij nu de grootste prestatie per te investeren euro? Want misschien dat je wel een afweging wil maken van goh. Eigenlijk zou ik naar gevel vier toe moeten, die heeft de hoogste prestatie, maar die gevel is wel hartstikke duur. Als ik nu fors minder investeer, maar mijn prestatie gaat maar relatief marginaal omlaag, dan heb ik voor elke geïnvesteerde euro heb ik meer performance. Volgens mij als ik jou goed begrijp, nu zitten de kosten eigenlijk al verwerkt in die performance factor. Ja, maar zou je dat spel nog steeds kunnen kunnen kunnen spelen hiermee?

[00:41:12.630] - HvR Dat denk ik wel tenminste. Er zijn hier nog wat andere grafieken met dan een soort andere indelingen en bijvoorbeeld hier hoeveel draagt welk thema bij? Je zou natuurlijk ook nog. Ik zou natuurlijk ook nog een extra diagram kunnen toevoegen met wat als we de kosten er uit laten. En wat als we dus alleen op de milieu-voordelen focussen. Wat is dan de score? Dat kan ik als variatie hieronder natuurlijk toevoegen.

[00:41:53.950] - NH Ik vindt het een hartstikke mooie tool die je gemaakt hebt en ik denk dat het nog net de praktische toepasbaarheid nog extra kan verbeteren als je de kosten ook even kunt kunt parkeren. Je puur kunt richten op de prestatie en als vervolgstap nog een keer de kosten kunt introduceren om te zien: De hoogte van de prestatie ten opzichte van de investering, zodat je daar een soort...

[00:42:24.520] - HvR Een soort verhouding ja, dat is een heel goed idee, want er zijn ook onderzoeken waarbij ze dan al die voordelen proberen te monetariseren, dus alles in geldwaardes uitdrukken. Nou, dat is dan waar ik voor mijn onderzoek niet voor heb gekozen omdat daar dan zoveel aannames onder liggen dat het eigenlijk. Ja, dat is natuurlijk ook heel interessant, maar je kan. Dit is wat iets meer science-based zeg maar. Dat je echt kijkt van hoeveel geluid zou het echt kunnen toevoegen in plaats van een soort wensdenken van: er is ooit een groene gevel geweest die zoveel decibel heeft gegeven en dat gaan we dan toepassen op alle situaties.

[00:42:56.950] - NH Ja.

[00:42:57.670] - HvR Maar inderdaad, dat kostenaspect loskoppelen, dat kan ik natuurlijk wel doen. Ik zie hieronder ook wat meer diepgang. Dus hier heb ik bijvoorbeeld aangenomen. Stel alle prioriteiten zouden hetzelfde zijn, maar de weging voor die relevantie is er nog wel. Dan geeft dat dus weer een andere score. In dit geval is er eigenlijk wel enigszins hetzelfde van dat deze twee systemen nog steeds het beste scoren. Maar dan zie je hier van dus dat het dichter bij elkaar ligt en hieronder heb ik het dan ook aangegeven per thema, dus eigenlijk is dat enigszins dan al losgekoppeld. Die private kosten en die vastgoed toename, dat zit eigenlijk hier in. En de rest dan in deze en daar zie je ook hoe die systemen dan verschillen. Bijvoorbeeld dat vrij goedkope systeem gewoon direct klim op scoort eigenlijk vrij laag op heel veel thema's, maar dan op dat kostenaspect scoort die dan wel weer hoger.

[00:44:06.500] - HvR Dus enigszins zie je die dynamiek al hierin. En vooral deze scoort heel goed op heel veel thema's, maar dan qua kosten weer lager. Dus ja, daarin zie je enigszins al wel die afweging.

[00:44:22.800] - NH Ja, dat geeft heel veel inzicht.

[00:44:25.600] - HvR Ja. En hier zie je... Eigenlijk deze, maar dan de bijdrage van elk thema per systeem. Voor dat hele goedkope systeem zie je dat de kosten veel bijdragen aan die totale score. Terwijl bij andere, die scoren hoger op klimaatadaptatie. En dan heb ik het hier nog onderverdeeld naar wat heeft nou invloed op gebouw niveau, en wat meer op gebiedsniveau of stadsniveau? En dan zie je ook een bepaalde dynamiek. Het gekozen systeem geeft zowel op gebouw niveau als op stadsniveau voordelen. Dus dat is eigenlijk wat hier dan uit komt. En dat dat kan natuurlijk ook denk ik een goede tool zijn om met de klant in gesprek te gaan van: wat is dan het doel en wat is belangrijk in dit project?

[00:45:37.110] - NH Het zal vooral ook wel een soort van... Ik moet selectief gaan gaan kiezen van welke informatie wil je laten zien aan de klant. Want je kunt de klant eigenlijk redelijk doodslaan met alle data, alle informatie die er uit komt. Dus daar ligt ook wel een taak voor ons om dit goed te filteren zodat je daar een begrijpelijk plaatje neerlegt.

[00:46:00.430] - HvR Ja, klopt. Want misschien in het algemeen: als je nou naar deze resultaten kijkt, is dat dan duidelijk en bruikbaar?

[00:46:14.440] - NH Ja, ik denk het wel. De moeilijkheid zal erin zitten: hoe zeker weet zo'n opdrachtgever wat zijn prioritering is? Juist omdat het heel veelomvattend is. Dus dan moet de klant overal iets van vinden.

[00:46:29.920] - HvR Ja, precies.

[00:46:31.120] - NH Wat je vaak ziet is dat de opdrachtgever hun eigen eisen of wensen nog niet goed begrijpt. Dus dat ja, dat zal lastig zijn. Ja, die kostenfactor, daar had ik het al even over. En wat ik een lastige vind is dat je twee soorten wegen hebt. En die is bij mij nog niet echt geland. Zouden we de opdrachtgever ook klip en klaar kunnen maken van dit zijn de twee wegingen. Zodat hij dit ook snapt. Dat hij dit ook begrijpt.

[00:47:08.140] - HvR Ja. Ja dus inderdaad dat ik dan misschien hier nog wat duidelijker kan aangeven, want hier is het zowel prioriteit als omgevings-relevantie weging. En bijvoorbeeld hieronder is het dan alleen op relevantie, maar dat dat wat duidelijker blijkt. Duidelijk overkomt in deze plaatjes.

[00:47:32.590] - NH Ja, want moet de opdrachtgever zowel de prioriteit als de relevantie bepalen?

[00:47:39.610] - HvR Nee, de relevantie dat kan dan gewoon een consultant/engineer/architect invullen. En dat zijn dus gewoon waardes die van een website komen. Die zijn ook niet vrij te interpreteren. Dat is gewoon een gegeven eigenlijk. En dat is dan vooral locatie specifiek. Dus als je het adres hebt en de locatie dan kan je eigenlijk deze waardes gewoon ophalen van die websites.

[00:48:04.880] - NH Ja, ja, ja.

[00:48:06.310] - HvR Terwijl de prioritering, dat is natuurlijk wel echt op basis van wat de klant wil. Maar daarbij kan dan de gebruiker van deze tool natuurlijk wel zelf het ook toelichten of uitleggen of meedenken van: zouden we dit als prioriteit willen of niet? Dus eigenlijk is eigenlijk alleen die prioriteit heeft echt te maken met de klant en die relevantie, dat is gewoon gegeven. Dus dat is ook om te voorkomen inderdaad dat de klant zelf alle weging zou moeten geven aan een aspect.

[00:48:49.760] - HvR Hier zijn dan nog al die grafiekjes die ik net ook liet zien voor de kosten om dan te kijken van deze resultaten zijn natuurlijk dimensie loos, maar dat is meer een relatieve score. Maar dat zegt nog niet zoveel over hoeveel decibel zou je nou bijvoorbeeld echt kunnen reduceren? En dat is dan beter te zien onder deze tab, dus dan zie je in het blauw de performance. En dan in het oranje bijvoorbeeld. Dus hier zit eigenlijk ook de doorvertaling naar van welke claim of welke aanname kan je nou maken? Van hoeveel decibel gaan we dan echt reduceren. Dat is natuurlijk wel een aanname, er zit geen 3D model achter met metingen op de plek zelf, maar het is meer op basis van heel veel onderzoek. Wat is de gemiddelde waarde voor dit systeem in Nederland?

[00:49:52.510] - NH Ja, ja, ja. Ik denk dat als ik naar de opdrachtgever toe ga die hier mee stoeit. Ja, dan zou ik zeggen die wil inzicht in: wat zijn nu de uitgangspunten die zijn aangehouden? Dus dat zit hem vooral in die prioriteiten.

[00:50:08.350] - HvR Ja.

[00:50:09.220] - NH Dat zijn de prioriteiten van die criteria dan.

[00:50:11.750] - HvR Ja.

[00:50:12.970] - NH Al die reken-exercities dat is echt wel ons ding dan.

[00:50:15.880] - HvR Ja, ja, precies.

[00:50:16.990] - NH Dan wil ik als opdrachtgever weten van: wat is nu mijn rangorde qua systeemkeuze. Dus met deze uitgangspunten en met deze prioriteiten heb ik deze rangorde. Wat kosten die systemen en hoe kosteneffectief zijn ze? Dus die performance per te investeren euro. En hoe gevoelig zijn mijn resultaten nu? Stel dat je iets anders kiest in de prioriteiten, krijg ik dan een hele andere rangorde? Om een beetje gevoel voor de gevoeligheid te krijgen.

[00:50:50.710] - HvR De gevoeligheid van de resultaten voor die prioritering eigenlijk.

[00:50:53.890] - NH Ja precies. Ja, als je nu inderdaad... Er staat een wethouder op die vindt traffic noise reduction veel belangrijker dan is ingevoerd. Is dat dan bepalend voor het systeem? Dat je daar een beetje gevoel voor hebt. Ik denk als ik dat als informatie krijg, dat ik dan een keuze kan maken van, dan ga ik toch voor systeem één, twee, drie of vier?

[00:51:19.300] - HvR En wat je zegt, die gevoeligheid, dat wilde ik dan inderdaad nog los van deze tool zeg maar bekijken van hoe gevoelig is mijn tool voor de input parameters. Maar dat is ook wel goed om dan daarvan misschien een grafiekje of iets, wat aan te geven in de tool zelf. Ook dat je ziet van stel je voert het anders in, dan heeft dat heel veel effect of weinig effect op de ranking.

[00:51:42.640] - NH Ja, ja.

[00:51:45.080] - HvR Ja, en als laatste misschien ook goed om te laten zien dan design recommendations. Dat is nog vrij beperkt moet ik zeggen, maar dat was meer om aan te geven. Stel je hebt bepaalde doelen om dan niet alleen het goede systeem te kiezen, maar ook op bepaalde aspecten te letten tijdens het ontwerp. En dan zijn er aanbevelingen voor functionaliteit. Nou, dat je planten moet kiezen die goed kunnen overleven in de condities die er zijn, met wind en zon of schaduw of op de hoogte. En eigenlijk nog belangrijker zijn dan hier de design recommendations per criterium eigenlijk. Stel voor die fijnstof, dan kan je eigenlijk van linksboven naar rechtsonder. En hier zie je dan dus dat de grootte van de gevel eigenlijk het meeste invloed heeft.

[00:52:53.020] - HvR In totaal kan je meer fijnstof reduceren als je een grotere groene gevel toepast.Daarna kan je dan kijken bijvoorbeeld naar de plant dichtheid, want een grotere dichtheid reduceert meer fijnstof. Kies dan soorten die veel dichtheid geven of een systeem waar al planten in zijn geplant. In het onderzoek komt naar voren dat je vooral planten met een klein blad moet kiezen en harig en dat soort dingen. En hier zie je dan nog dingen die wat minder invloed hebben. Bijvoorbeeld dat het boven de twintig meter eigenlijk minder effect op fijnstof meer heeft. Meer om dan mee te geven van in de volgende ontwerpfase van waar moeten we op letten? En dan is eigenlijk ook de bedoeling dat dan niet per se dit als de waarheid wordt aangenomen. Meer van om dan ook als projectmanager te weten van waarop moeten we nou letten in het ontwerp? Ja, om een beetje duidelijkheid te krijgen.

[00:54:16.680] - NH Zou je dan die loop waar we het over hadden, er is in het ontwerp iets opgenomen. We hebben de gevel oriëntatie en de oppervlakte en bepaalde hoogte. Zou je dat een keer terug kunnen pakken op: welke performance hebben nu bereikt en zitten we nu op 80/90% van wat maximaal haalbaar is.

[00:54:33.540] - HvR Nou, dat zit er nu nog niet in. Maar ik denk dat het vooral haalbaar is voor die oriëntatie. Daarover zijn wel echt wat hardere claims te maken van de noord-oriëntatie reduceert vaak met zoveel graden Celsius. . En voor die andere parameters is eigenlijk het onderzoek nog wel beperkt. Dan is het lastig om te zeggen van, als ik altijd een bepaalde plantensoort toepas, dan geeft het altijd zoveel meer reductie. Ja dus eigenlijk om die relatie te kwantificeren. Dat is vrij lastig. Maar dat zou natuurlijk wel goed zijn voor een volgende iteratie van deze tool om dat dan ook te kwantificeren. Eigenlijk heb ik dat wel gedaan voor die omgevingsfactoren, daarvan heb ik wel een afhankelijkheid aangenomen en voor deze ontwerp aspecten heb ik dat meer het zo maar kwalitatief beschreven. Het zou mooi zijn om dat later ook nog te kwantificeren. Dat klopt ja.

[00:55:35.100] - NH Het is misschien... Het zal voor de besluitvorming van de opdrachtgever niet zo heel relevant zijn, verwacht ik, want de keuze is al gemaakt en het is meer dat je van jezelf dan weet: we zitten nu redelijk aan de maximum van wat haalbaar is, maar ik ben ook wel met je eens, dat moet wel iets uitkomen wat enigszins onderbouwd is. Als het allemaal een beetje op drijfzand is gebaseerd, dan zit er heel veel tijd en moeite te steken in zo'n check terwijl de waarde daarvan misschien toch wat beperkt is.

[00:56:08.820] - HvR Ja, nee, maar zeker voor onderzoek zou het nog heel interessant zijn. Ja, wat ook wel de les is, tenminste uit mijn onderzoek was dat het de crux is ook je kan het systeem kiezen en heel veel willen, maar je moet het ook echt doen. En daarin zijn die ontwerpkeuzes natuurlijk heel belangrijk. Zeker om het in leven te houden en om veel groen oppervlakte te krijgen. Dat is eigenlijk voor heel veel aspecten belangrijk. Om echt een soort fit for purpose ontwerp te maken. Dat is naar mijn idee ook wel belangrijk, maar daar kan je mee aan de slag met deze aanbevelingen.

[00:56:50.250] - HvR En misschien nog een korte laatste vraag. Welke partijen waren betrokken in de vroege fase van het ontwerpproces? Met het bepalen van we gaan de groene gevel toepassen en dit systeem. Was dat samen met de fabrikant of nog niet?

[00:57:09.410] - NH Nou, het is eigenlijk de de visie van de architect. Daar zat een goede gevel in.

[00:57:16.510] - HvR Ja precies.

[00:57:17.950] - NH Wat we in het ontwerp hebben toegevoegd is vooral een stuk functionaliteit van die gevel, we willen dat die ook een rol speelt in het ventilatiesysteem, zuiverend, dat soort dingen. Ja, en de leveranciers keuze, die is dus eigenlijk bepaald in een soort gezamenlijkheid van de architect, RHDHV, TU Eindhoven, de projectmanager van de gemeente zelf. En we hadden Mostert de Winter en Copijn als leverancier.

[00:57:53.830] - HvR Ja.

[00:57:55.960] - NH De derde weet ik even niet meer.

[00:57:58.240] - HvR En dan is uiteindelijk Mostert de Winter gekozen?

[00:58:01.390] - NH Ja, maar in het bestek is Copijn terecht gekomen. En de aannemer die heeft Mostert de Winter voorgesteld.

[00:58:14.800] - HvR Ja.

[00:58:18.040] - NH Waarbij volgens mij de typologie van de gevel, de soort gevel die is bij beide partijen hetzelfde. Allebei met bakjes op een bepaalde afstand van de echte gevel.

[00:58:31.080] - HvR Ja duidelijk. Er zijn nog dingen waarvan je zegt: dit vind ik nog van deze tool.

[00:58:46.450] - NH Nee, knap in elkaar gezet. Het geeft heel veel inzicht.

11.10 Case study Venlo: input and results

Project-specific input

To achieve project-specific results, please fill in the green boxes. The blue boxes are values that are fixed and cannot be changed.

1. Project description

Instruction: Describe the building project by filling in the green boxes.

Variable	Description	Range/scope	Value/result	Unit	Formula	Explanation
Name	City hall Venlo					
Adress	Hanzeplaats 1, Venlo	The Netherlands				Format: Street and number, city
Client	Munipality Venlo					

2. Potential: Environmental conditions

Instruction: Provide environmental conditions that will affect the scoring on some criteria. Click on the link to access the different websites.

Variable	Description	Range/scope	Value/result	Unit	Formula	Link	Explanation
H	Average building height in street, estimation		30	m		Webmapper	Retrieve from Webmapper; estimate average of buildings in 500 m radius around building
W	Average street width (facade to facade), estimation		25	m		Google Maps	Retrieve from Google Maps > 'Terrein' > 'Afstand meten' ; estimate average of buildings in 500 m radius aroun
H/W	Street aspect ratio	0-5	1,2	-	H/W		
$C_{district}$	Facade vegetation coverage in district, estimation	0-100	0	%		Google Earth	Retrieve from Google Earth or field observations, estimate for radius of 500 m around building
Climate	Climate type in Köppen-Geiger classification	Cfb	Cfb	-			(Further development: include more climate types)
Urbanity	Degree of urbanity of the neighbourhood		Sterk stedelijk	-		Atlas Leefomgeving	Retrieve value from Atlas Leefomgeving > Search for address, retrieve 'Mate van stedelijkheid van de buurt'

3. Relevance weighting

Instruction: How relevant are criteria to the location and project? Select or provide variables that affect the weighting.

Retrieve values from Atlas Leefomgeving.

Variable	Description	Range/scope	Value/result	Unit	Formula	Link	Explanation
PM2,5	Particulate matter (PM2,5) in air (2020)		9	µg/m3		Atlas Leefomgeving	Retrieve value from Atlas Leefomgeving > Search for address, retrieve 'Fijnstof in de lucht (2020)'
Noise	Noise in the environment (Lden)		67	dB		Atlas Leefomgeving	Retrieve value from Atlas Leefomgeving > Search for address, retrieve 'Geluid in de omgeving'
Green space	Percentage area of green space within a circle with a radius of 500 m		38	%		Atlas Leefomgeving	Retrieve value from Atlas Leefomgeving > Search for address, retrieve 'Groen binnen 500 meter'
Heat island	Average ambient air temperature difference, relative to rural area		1,5	˚C		Atlas Leefomgeving	Retrieve value from Atlas Leefomgeving > Search for address, retrieve 'Zomerhitte in de stad'

Retrieve values from Klimaateffectatlas.

Variable	Description	Range/scope	Value/result	Unit	Formula	Link	Explanation
Heat stress	Severely lonely elderly over 75 (2020)		30-100	#/km2		Klimaateffectatlas	Retrieve value from Klimaateffectatlas > Select 'Ernstig eenzame 75+ers', then search for adress
Rainfall	Yearly precipitation (2016)		< 800	mm		Klimaateffectatlas	Retrieve value from Klimaateffectatlas > Select 'Jaarlijkse neerslag', then search for adress

Select the (planned) inclusion of cooling and heating systems.

Variable	Description	Range/scope	Value/result	Unit	Formula	Comment	Explanation
Cooling system	Presence of active cooling system (such as air conditioning or heat cold storage)		Yes			***Possible comment***	If a cooling system that consumes any energy is present, select 'yes'. If not known yet, select 'yes' .
Heating system	Presence of active heating system		Yes				(Further development: include 'no' option for heating system)

4. Priority weighting

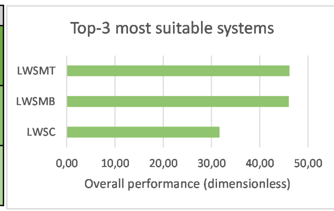
What criteria have most priority? In cooperation with the client, allocate weights to the different criteria.
First, allocate a value of 10 to the least important criterion, using the drop-down menu. Then, allocate a multiple of 10 to the other criteria. This indicates their relative importance.
Allocate the highest values to the most important criteria, and lower values to less important criteria. Several criteria can have the same value, indicating that they are equally important.
The 'rank' list on the right shows the resulting ranking of criteria, according to the assigned 'priority' weights.

Criterion	Description	Range/scope	Weight	Unit	Rank	Explanation
BD	Biodiversity	10-100	20	-	3	Potential to provide plant species variety and density, as well as a habitat for birds, snails, insects, beetles and
AV	Aesthetic value	10-100	20	-	3	Potential for aesthetic appeal to citizens.
PM	Particulate matter removal	10-100	100	-	1	Potential to remove particulate matter, one of the major outdoor air pollutants.
TN	Traffic noise reduction	10-100	10	-	10	Potential to reduce traffic noise pollution on street level.
RE	Relaxation effects	10-100	10	-	10	Potential to bring psychological and physical relaxation, i.e., stress reduction, to citizens.
HS	Indoor heat stress reduction	10-100	20	-	3	Potential to reduce indoor heat stress by lowering indoor temperatures during summer heat waves.
UHI	Urban heat islands reduction	10-100	10	-	10	Potential to reduce outdoor air temperatures to combat the urban heat island effect (temperature rises in citi
RC	Rainfall runoff control	10-100	10	-	10	Potential for rainfall flow retention and reduction.
EB	Environmental burdens	10-100	20	-	3	Environmental burdens, e.g. from materials, maintenance and water use.
CS	Carbon sequestration	10-100	20	-	3	Potential to sequester carbon dioxide from the air.
GW	Greywater treatment	10-100	40	-	2	Potential to remove pollutants from greywater (e.g. from kitchen, shower) for irrigation of vertical greening sy
CE	Cooling energy savings	10-100	20	-	3	Potential to lower cooling costs in summer because of the insulation and shading by the vertical greening syst
HE	Heating energy savings	10-100	20	-	3	Potential to lower heating costs in winter because of the insulation by the vertical greening system.
PC-I	Private costs - Installation costs	10-100	10	-	10	Costs for design, materials, irrigation system and installation.
PC-MO	Private costs - Maintenance and operation costs	10-100	10	-	10	Annual costs for pruning, irrigation and replacements.
PC-DC	Private costs - Disposal costs	10-100	10	-	10	Costs for disposal of system at the end of the lifetime.
PB-PR	Private benefits - Plaster renovation saving	10-100	10	-	10	Savings from less building facade maintenance because of protection of building facade by vertical greening sy
PB-VI	Private benefits - Real estate value increase	10-100	10	-	10	Increase of the economic property value because of the vertical greening system.

Factsheet key results

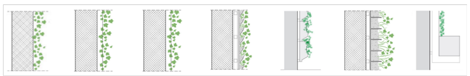
This factsheets presents the most suitable VGS systems for the specific project. More elaborate results can be found below.

Rank	System	Overall performance	Average installation costs (€/m2)
1	LWSMT	46,17	409
2	LWSMB	46,02	409
3	LWSC	31,67	409
		Dimensionless performance that includes costs	

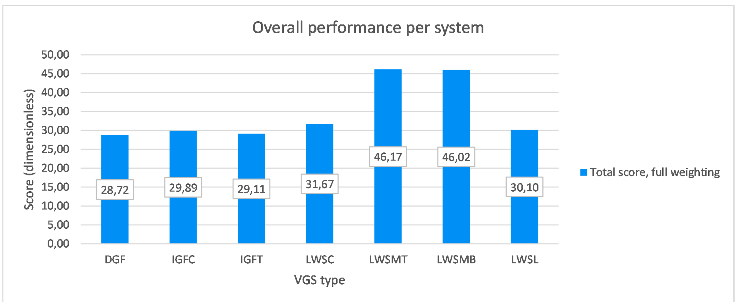


Overall performance

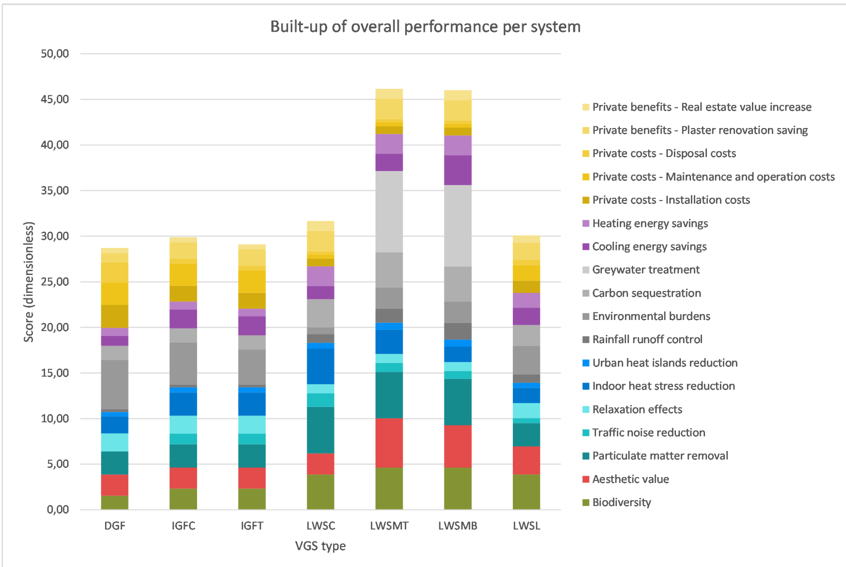
Given the project-specificity and priorities, the overall performance on the suitability of the different VGS types is:



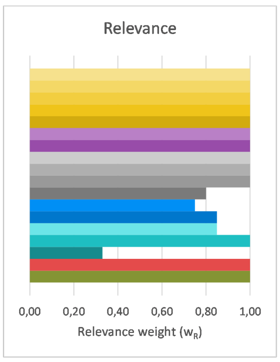
VGS type	DGF	IGFC	IGFT	LWSC	LWSMT	LWSMB	LWSL
Overall performance	28,72	29,89	29,11	31,67	46,17	46,02	30,10
Ranking	7	5	6	3	1	2	4

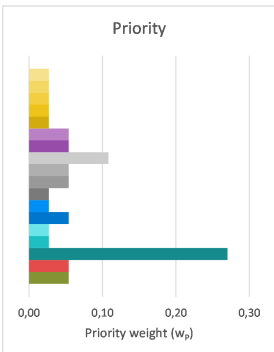


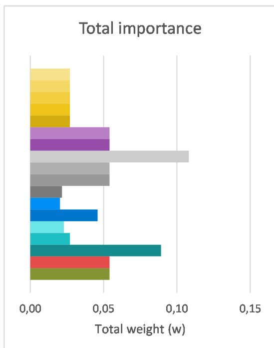
The overall performance is the sum of weighted scores, as shown below. Hover over a bar to see numerical values.



Weighting takes places based on both relevance (objective) and priority (subjective). The multiplication of both results in the total importance.



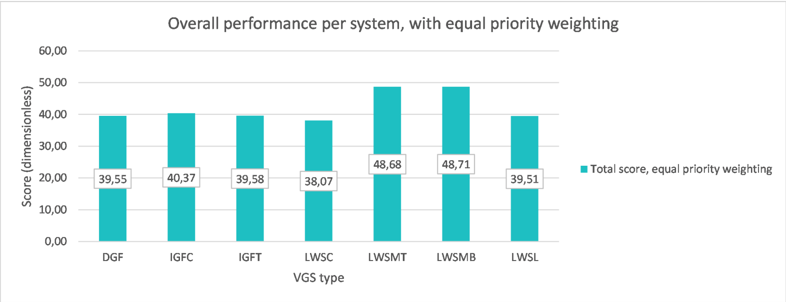




Overall performance for equal priority

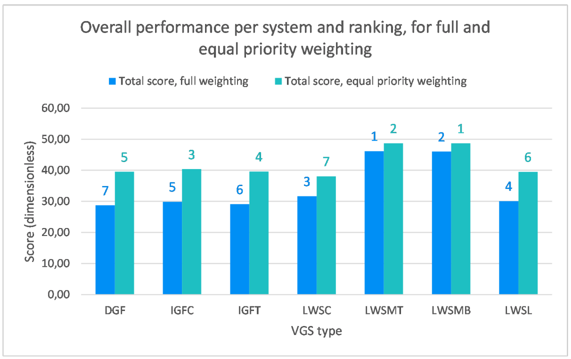
When all criteria are of equal priority (mean weighting for w_P), the overall performance on the suitability of the different VGS types is:

VGS type	DGF	IGFC	IGFT	LWSC	LWSMT	LWSMB	LWSL
Overall performance	39,55	40,37	39,58	38,07	48,68	48,71	39,51
Ranking	5	3	4	7	2	1	6



Comparing the performance for full weighting and equal priority weighting, the ranking might be different for the two scenarios:

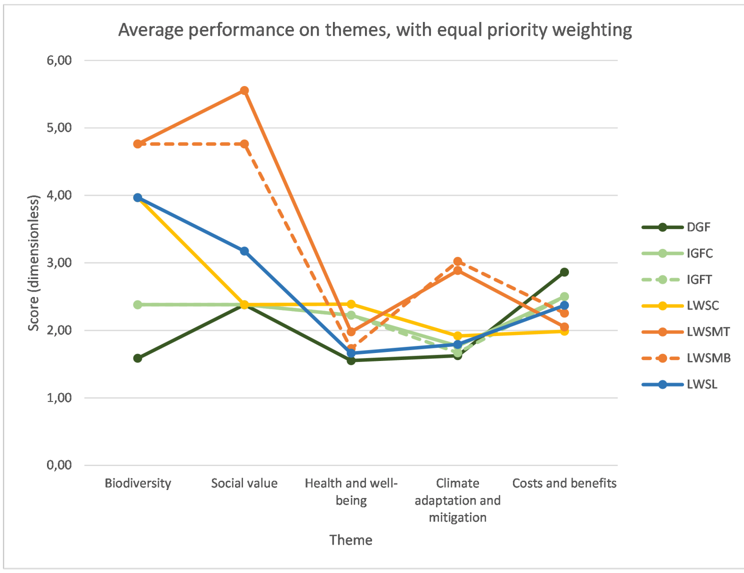
VGS type	DGF	IGFC	IGFT	LWSC	LWSMT	LWSMB	LWSL
Overall performance (full weighting)	28,72	29,89	29,11	31,67	46,17	46,02	30,10
Ranking (full weighting)	7	5	6	3	1	2	4
Overall performance (equal priority weig	39,55	40,37	39,58	38,07	48,68	48,71	39,51
Ranking (equal priority weighting)	5	3	4	7	2	1	6



Performance on themes

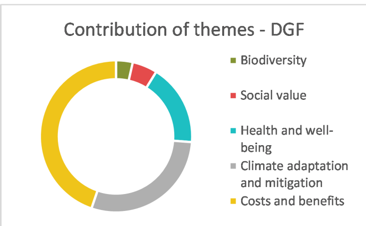
When all criteria are of equal priority (mean weighting for w_P), the average performance per theme is:

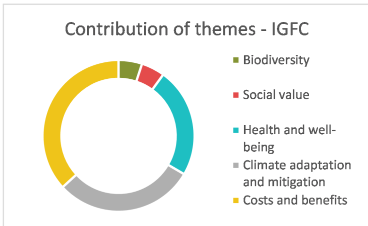
VGS type	DGF	IGFC	IGFT	LWSC	LWSMT	LWSMB	LWSL
Biodiversity	1,59	2,38	2,38	3,97	4,76	4,76	3,97
Social value	2,38	2,38	2,38	2,38	5,56	4,76	3,17
Health and well-being	1,55	2,23	2,23	2,39	1,98	1,73	1,66
Climate adaptation and mitigation	1,63	1,77	1,67	1,92	2,89	3,02	1,79
Costs and benefits	2,86	2,50	2,50	1,99	2,05	2,26	2,37

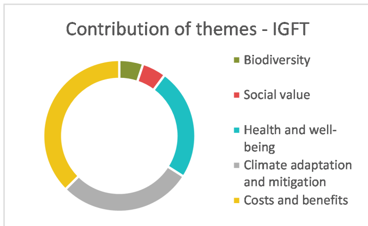


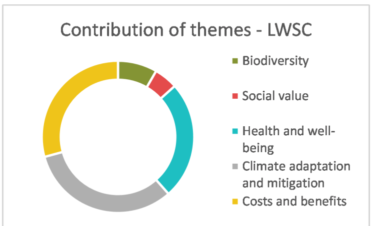
Explanation
See value tree on the right to see which criteria fall under what theme.

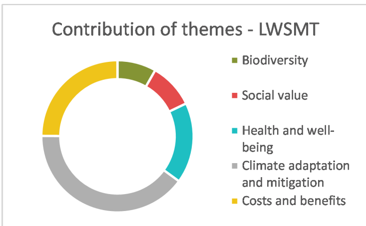
The following diagrams show the total contribution per theme to the performance with equal priority:

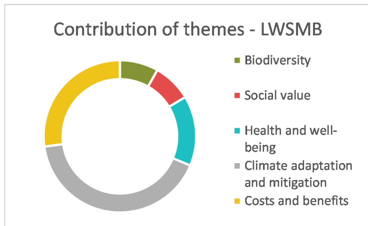


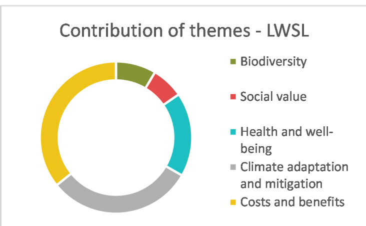










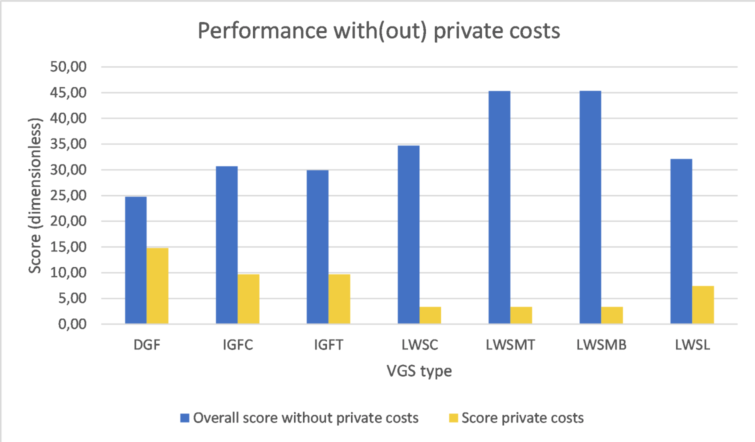


Note: Since themes have some overlapping criteria, the contribution diagrams do not add up to the total performance.

Performance with(out) private costs

When all criteria are of equal priority, the overall performance with(out) private costs is:

VGS type	DGF	IGFC	IGFT	LWSC	LWSMT	LWSMB	LWSL
Score without private costs	24,76	30,69	29,89	34,71	45,32	45,35	32,10
Score private costs costs	14,80	9,69	9,69	3,36	3,36	3,36	7,41

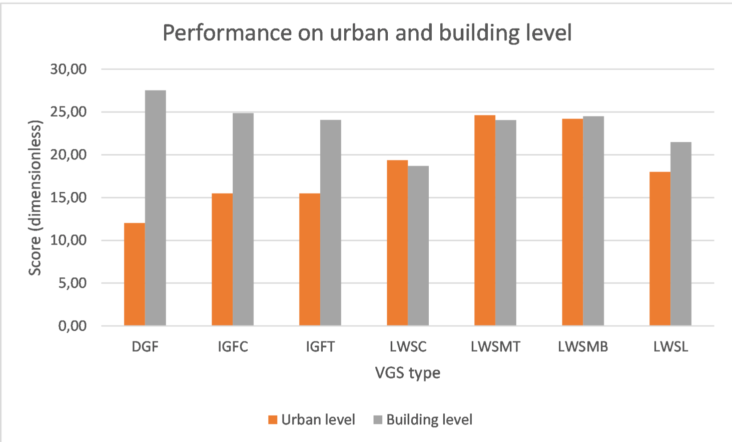


Note
Overall score without private costs: includes environmental burdens (good = small) and private benefits
A high score on private costs indicates relatively low costs

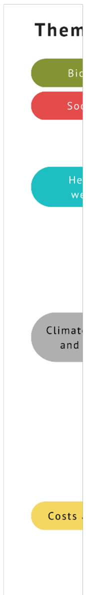
Performance on building and urban level

When all criteria are of equal priority (mean weighting for w_P), the aggregated performance on urban and building level is:

VGS type	DGF	IGFC	IGFT	LWSC	LWSMT	LWSMB	LWSL
Performance on urban level	12,02	15,50	15,50	24,08	24,63	24,21	18,01
Performance on building level	27,53	24,87	24,08	18,70	24,06	24,50	21,49



Explanation
See value tree on the right for which criteria affect urban or building level.



Appendices: example projects: input and results

Appendix: Education building: Echo

Project-specific input

To achieve project-specific results, please fill in the green boxes. The blue boxes are values that are fixed and cannot be changed.

1. Project description

Instruction: Describe the building project by filling in the green boxes.

Variable	Description	Range/scope	Value/result	Unit	Formula		Explanation
Name	Echo TU Delft						
Adress	Van Mourik Broekmanweg 5	The Netherlands					Format: Street and number, city
Client	TU Delft - Campus and Real Estate						

2. Potential: Environmental conditions

Instruction: Provide environmental conditions that will affect the scoring on some criteria. Click on the link to access the different websites.

Variable	Description	Range/scope	Value/result	Unit	Formula	Link	Explanation
H	Average building height in street, estimation		23	m		Webmapper	Retrieve from Webmapper; estimate average of buildings in 500 m radius around building
W	Average street width (facade to facade), estimation		34	m		Google Maps	Retrieve from Google Maps > 'Terrein' > 'Afstand meten' ; estimate average of buildings in 500 m radius aroun
H/W	Street aspect ratio	0-5	0,7	-	H/W		
$C_{district}$	Facade vegetation coverage in district, estimation	0-100	1	%		Google Earth	Retrieve from Google Earth or field observations, estimate for radius of 500 m around building
Climate	Climate type in Köppen-Geiger classification	Cfb	Cfb	-			(Further development: include more climate types)
Urbanity	Degree of urbanity of the neighbourhood		Sterk stedelijk	-		Atlas Leefomgeving	Retrieve value from Atlas Leefomgeving > Search for address, retrieve 'Mate van stedelijkheid van de buurt'

3. Relevance weighting

Instruction: How relevant are criteria to the location and project? Select or provide variables that affect the weighting.

Retrieve values from Atlas Leefomgeving.

Variable	Description	Range/scope	Value/result	Unit	Formula	Link	Explanation
PM2,5	Particulate matter (PM2,5) in air (2020)		9	µg/m3		Atlas Leefomgeving	Retrieve value from Atlas Leefomgeving > Search for address, retrieve 'Fijnstof in de lucht (2020)'
Noise	Noise in the environment (Lden)		57	dB		Atlas Leefomgeving	Retrieve value from Atlas Leefomgeving > Search for address, retrieve 'Geluid in de omgeving'
Green space	Percentage area of green space within a circle with a radius of 500 m		48	%		Atlas Leefomgeving	Retrieve value from Atlas Leefomgeving > Search for address, retrieve 'Groen binnen 500 meter'
Heat island	Average ambient air temperature difference, relative to rural area		1,4	˚C		Atlas Leefomgeving	Retrieve value from Atlas Leefomgeving > Search for address, retrieve 'Zomerhitte in de stad'

Retrieve values from Klimaateffectatlas.

Variable	Description	Range/scope	Value/result	Unit	Formula	Link	Explanation
Heat stress	Severely lonely elderly over 75 (2020)		< 10	#/km2		Klimaateffectatlas	Retrieve value from Klimaateffectatlas > Select 'Ernstig eenzame 75+ers', then search for adress
Rainfall	Yearly precipitation (2016)		>900	mm		Klimaateffectatlas	Retrieve value from Klimaateffectatlas > Select 'Jaarlijkse neerslag', then search for adress

Select the (planned) inclusion of cooling and heating systems.

Variable	Description	Range/scope	Value/result	Unit	Formula	Comment	Explanation
Cooling system	Presence of active cooling system (such as air conditioning or heat cold storage)		Yes			***Possible comment***	If a cooling system that consumes any energy is present, select 'yes'. If not known yet, select 'yes' .
Heating system	Presence of active heating system		Yes				(Further development: include 'no' option for heating system)

4. Priority weighting

What criteria have most priority? In cooperation with the client, allocate weights to the different criteria.
First, allocate a value of 10 to the least important criterion, using the drop-down menu. Then, allocate a multiple of 10 to the other criteria. This indicates their relative importance.
Allocate the highest values to the most important criteria, and lower values to less important criteria. Several criteria can have the same value, indicating that they are equally important.
The 'rank' list on the right shows the resulting ranking of criteria, according to the assigned 'priority' weights.

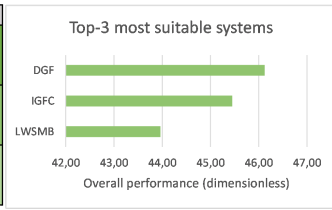
Criterion	Description	Range/scope	Weight	Unit	Rank	Explanation
BD	Biodiversity	10-100	10	-	8	Potential to provide plant species variety and density, as well as a habitat for birds, snails, insects, beetles and
AV	Aesthetic value	10-100	30	-	5	Potential for aesthetic appeal to citizens.
PM	Particulate matter removal	10-100	10	-	8	Potential to remove particulate matter, one of the major outdoor air pollutants.
TN	Traffic noise reduction	10-100	10	-	8	Potential to reduce traffic noise pollution on street level.
RE	Relaxation effects	10-100	10	-	8	Potential to bring psychological and physical relaxation, i.e., stress reduction, to citizens.
HS	Indoor heat stress reduction	10-100	60	-	2	Potential to reduce indoor heat stress by lowering indoor temperatures during summer heat waves.
UHI	Urban heat islands reduction	10-100	10	-	8	Potential to reduce outdoor air temperatures to combat the urban heat island effect (temperature rises in citi
RC	Rainfall runoff control	10-100	10	-	8	Potential for rainfall flow retention and reduction.
EB	Environmental burdens	10-100	80	-	1	Environmental burdens, e.g. from materials, maintenance and water use.
CS	Carbon sequestration	10-100	10	-	8	Potential to sequester carbon dioxide from the air.
GW	Greywater treatment	10-100	10	-	8	Potential to remove pollutants from greywater (e.g. from kitchen, shower) for irrigation of vertical greening sy
CE	Cooling energy savings	10-100	60	-	2	Potential to lower cooling costs in summer because of the insulation and shading by the vertical greening syst
HE	Heating energy savings	10-100	60	-	2	Potential to lower heating costs in winter because of the insulation by the vertical greening system.
PC-I	Private costs - Installation costs	10-100	30	-	5	Costs for design, materials, irrigation system and installation.
PC-MO	Private costs - Maintenance and operation costs	10-100	30	-	5	Annual costs for pruning, irrigation and replacements.
PC-DC	Private costs - Disposal costs	10-100	10	-	8	Costs for disposal of system at the end of the lifetime.
PB-PR	Private benefits - Plaster renovation saving	10-100	10	-	8	Savings from less building facade maintenance because of protection of building facade by vertical greening sy
PB-VI	Private benefits - Real estate value increase	10-100	10	-	8	Increase of the economic property value because of the vertical greening system.

Factsheet key results

This factsheets presents the most suitable VGS systems for the specific project. More elaborate results can be found below.

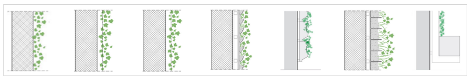
Rank	System	Overall performance	Average installation costs (€/m2)
1	DGF	46,12	44
2	IGFC	45,45	214
3	LWSMB	43,96	409

Dimensionless performance that includes costs

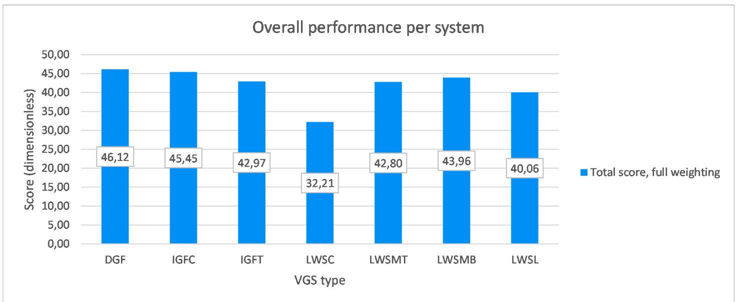


Overall performance

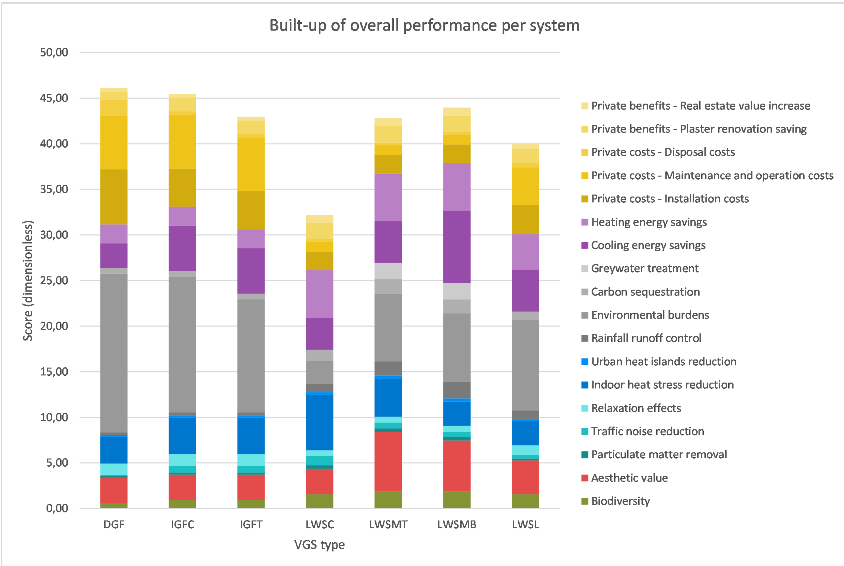
Given the project-specificity and priorities, the overall performance on the suitability of the different VGS types is:



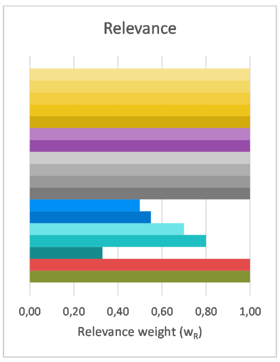
VGS type	DGF	IGFC	IGFT	LWSC	LWSMT	LWSMB	LWSL
Overall performance	46,12	45,45	42,97	32,21	42,80	43,96	40,06
Ranking	1	2	4	7	5	3	6

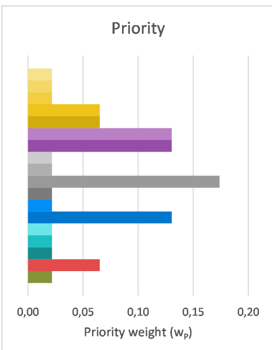


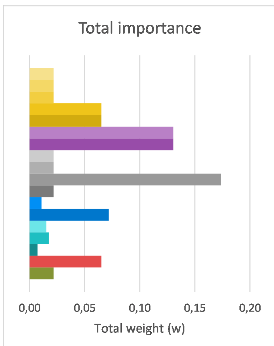
The overall performance is the sum of weighted scores, as shown below. Hover over a bar to see numerical values.



Weighting takes places based on both relevance (objective) and priority (subjective). The multiplication of both results in the total importance.



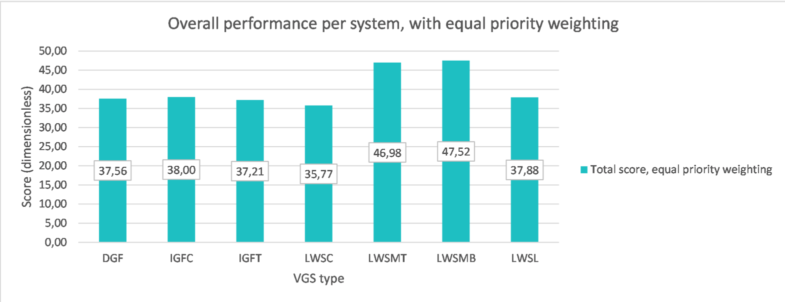




Overall performance for equal priority

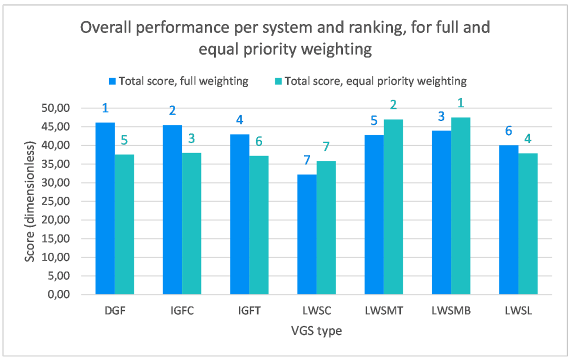
When all criteria are of equal priority (mean weighting for w_P), the overall performance on the suitability of the different VGS types is:

VGS type	DGF	IGFC	IGFT	LWSC	LWSMT	LWSMB	LWSL
Overall performance	37,56	38,00	37,21	35,77	46,98	47,52	37,88
Ranking	5	3	6	7	2	1	4



Comparing the performance for full weighting and equal priority weighting, the ranking might be different for the two scenarios:

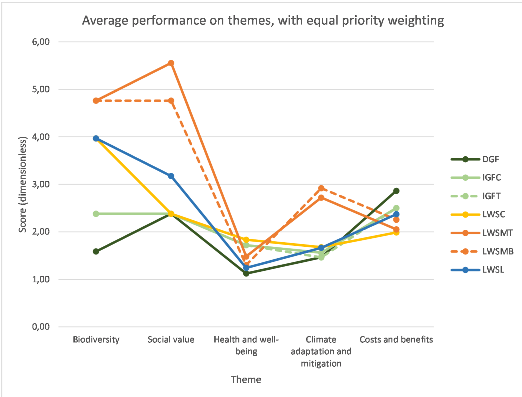
VGS type	DGF	IGFC	IGFT	LWSC	LWSMT	LWSMB	LWSL
Overall performance (full weighting)	46,12	45,45	42,97	32,21	42,80	43,96	40,06
Ranking (full weighting)	1	2	4	7	5	3	6
Overall performance (equal priority weig	37,56	38,00	37,21	35,77	46,98	47,52	37,88
Ranking (equal priority weighting)	5	3	6	7	2	1	4

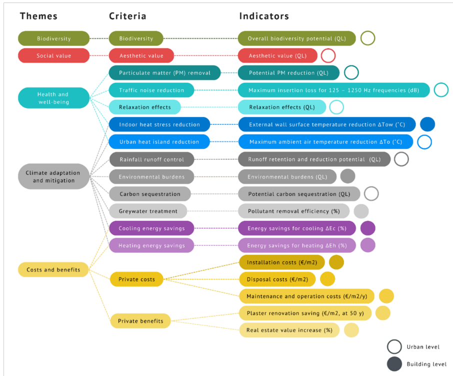


Performance on themes

When all criteria are of equal priority (mean weighting for w_p), the average performance per theme is:

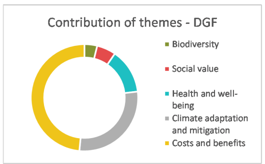
VGS type	DGF	IGFC	IGFT	LWSC	LWSMT	LWSMB	LWSL
Biodiversity	1,59	2,38	2,38	3,97	4,76	4,76	3,97
Social value	2,38	2,38	2,38	2,38	5,56	4,76	3,17
Health and well-being	1,12	1,72	1,72	1,83	1,48	1,30	1,24
Climate adaptation and mitigation	1,47	1,56	1,46	1,68	2,72	2,92	1,66
Costs and benefits	2,86	2,50	2,50	1,99	2,05	2,26	2,37

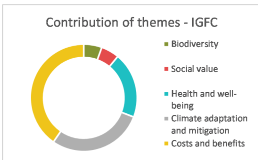


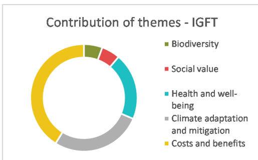


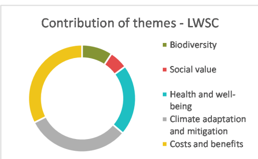
Explanation
See value tree on the right to see which criteria fall under what theme.

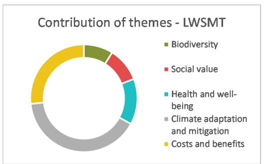
The following diagrams show the total contribution per theme to the performance with equal priority:

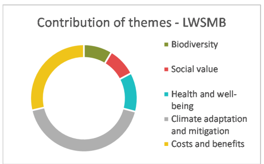


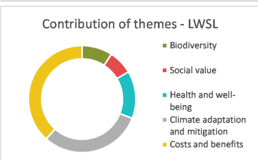










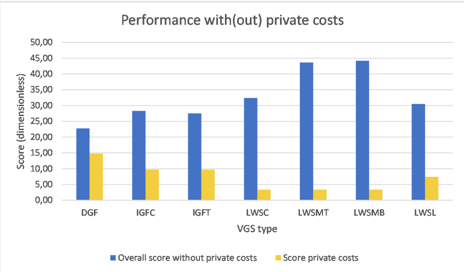


Note: Since themes have some overlapping criteria, the contribution diagrams do not add up to the total performance.

Performance with(out) private costs

When all criteria are of equal priority, the overall performance with(out) private costs is:

VGS type	DGF	IGFC	IGFT	LWSC	LWSMT	LWSMB	LWSL
Score without private costs	22,77	28,32	27,52	32,41	43,62	44,16	30,47
Score private costs costs	14,80	9,69	9,69	3,36	3,36	3,36	7,41

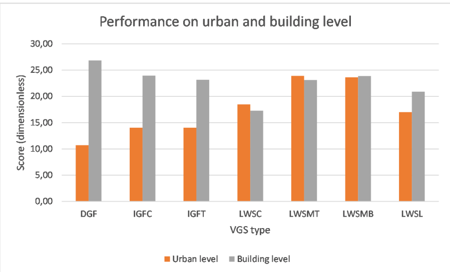


Note
Overall score without private costs: includes environmental burdens (good = small) and private benefits
A high score on private costs indicates relatively low costs

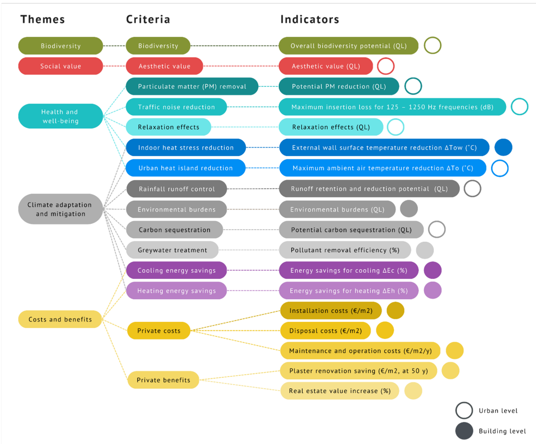
Performance on building and urban level

When all criteria are of equal priority (mean weighting for w_p), the aggregated performance on urban and building level is:

VGS type	DGF	IGFC	IGFT	LWSC	LWSMT	LWSMB	LWSL
Performance on urban level	10,71	14,05	14,05	23,16	23,89	23,63	17,00
Performance on building level	26,85	23,95	23,16	17,29	23,09	23,89	20,88



Explanation
See value tree on the right for which criteria affect urban or building level.



Appendix: Data centre: AMS11

Project-specific input

To achieve project-specific results, please fill in the green boxes. The blue boxes are values that are fixed and cannot be changed.

1. Project description

Instruction: Describe the building project by filling in the green boxes.

Variable	Description	Range/scope	Value/result	Unit	Formula		Explanation
Name	AMS11 Data centre						
Adress	Koolhavenlaan 93, Schiphol-Rijk	The Netherlands					Format: Street and number, city
Client	Digital Realty						

2. Potential: Environmental conditions

Instruction: Provide environmental conditions that will affect the scoring on some criteria. Click on the link to access the different websites.

Variable	Description	Range/scope	Value/result	Unit	Formula	Link	Explanation
H	Average building height in street, estimation		15	m		Webmapper	Retrieve from Webmapper; estimate average of buildings in 500 m radius around building
W	Average street width (facade to facade), estimation		52	m		Google Maps	Retrieve from Google Maps > 'Terrein' > 'Afstand meten' ; estimate average of buildings in 500 m radius aroun
H/W	Street aspect ratio	0-5	0,3	-	H/W		
$C_{district}$	Facade vegetation coverage in district, estimation	0-100	0	%		Google Earth	Retrieve from Google Earth or field observations, estimate for radius of 500 m around building
Climate	Climate type in Köppen-Geiger classification	Cfb	Cfb	-			(Further development: include more climate types)
Urbanity	Degree of urbanity of the neighbourhood		Niet stedelijk	-		Atlas Leefomgeving	Retrieve value from Atlas Leefomgeving > Search for address, retrieve 'Mate van stedelijkheid van de buurt'

3. Relevance weighting

Instruction: How relevant are criteria to the location and project? Select or provide variables that affect the weighting.

Retrieve values from Atlas Leefomgeving.

Variable	Description	Range/scope	Value/result	Unit	Formula	Link	Explanation
PM2,5	Particulate matter (PM2,5) in air (2020)		7	µg/m3		Atlas Leefomgeving	Retrieve value from Atlas Leefomgeving > Search for address, retrieve 'Fijnstof in de lucht (2020)'
Noise	Noise in the environment (Lden)		70	dB		Atlas Leefomgeving	Retrieve value from Atlas Leefomgeving > Search for address, retrieve 'Geluid in de omgeving'
Green space	Percentage area of green space within a circle with a radius of 500 m		36	%		Atlas Leefomgeving	Retrieve value from Atlas Leefomgeving > Search for address, retrieve 'Groen binnen 500 meter'
Heat island	Average ambient air temperature difference, relative to rural area		1,0	˚C		Atlas Leefomgeving	Retrieve value from Atlas Leefomgeving > Search for address, retrieve 'Zomerhitte in de stad'

Retrieve values from Klimaateffectatlas.

Variable	Description	Range/scope	Value/result	Unit	Formula	Link	Explanation
Heat stress	Severely lonely elderly over 75 (2020)		< 10	#/km2		Klimaateffectatlas	Retrieve value from Klimaateffectatlas > Select 'Ernstig eenzame 75+ers', then search for adress
Rainfall	Yearly precipitation (2016)		800-900	mm		Klimaateffectatlas	Retrieve value from Klimaateffectatlas > Select 'Jaarlijkse neerslag', then search for adress

Select the (planned) inclusion of cooling and heating systems.

Variable	Description	Range/scope	Value/result	Unit	Formula	Comment	Explanation
Cooling system	Presence of active cooling system (such as air conditioning or heat cold storage)		Yes			***Possible comment***	If a cooling system that consumes any energy is present, select 'yes'. If not known yet, select 'yes' .
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4. Priority weighting

What criteria have most priority? In cooperation with the client, allocate weights to the different criteria.
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The 'rank' list on the right shows the resulting ranking of criteria, according to the assigned 'priority' weights.

Criterion	Description	Range/scope	Weight	Unit	Rank		Explanation
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AV	Aesthetic value	10-100	50	-	4		Potential for aesthetic appeal to citizens.
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Factsheet key results

This factsheets presents the most suitable VGS systems for the specific project. More elaborate results can be found below.

Rank	System	Overall performance	Average installation costs (€/m2)
1	DGF	52,27	44
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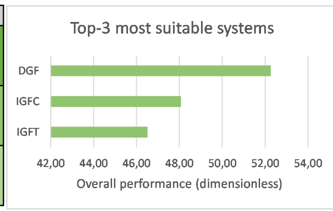
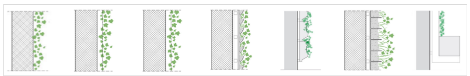
3	IGFT	46,52	214
		Dimensionless performance that includes costs	

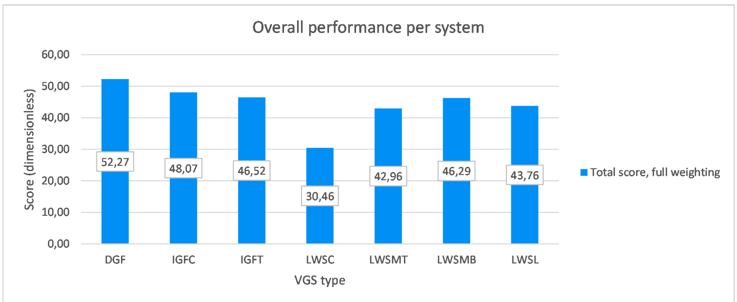


Overall performance

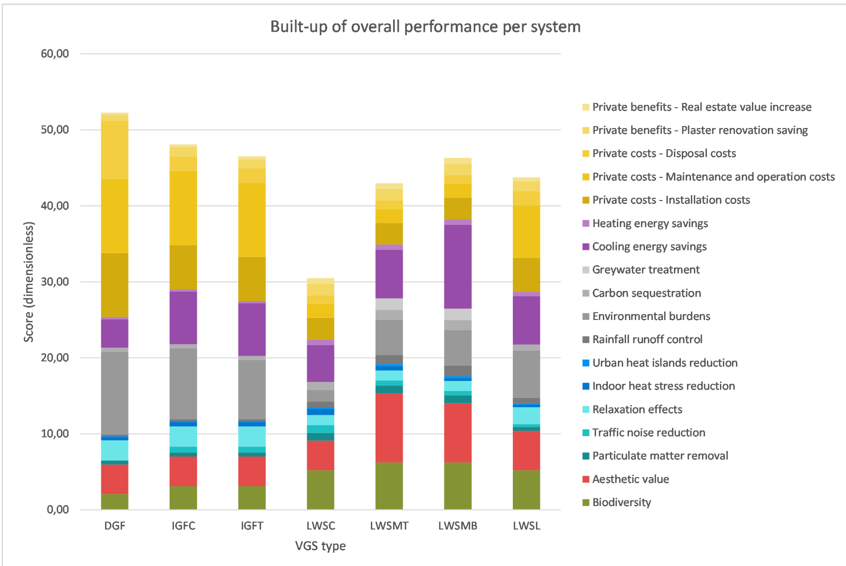
Given the project-specificity and priorities, the overall performance on the suitability of the different VGS types is:



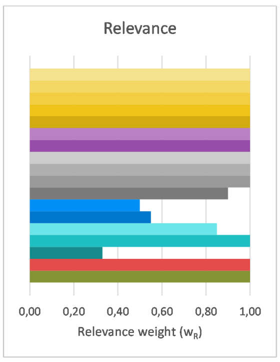
VGS type	DGF	IGFC	IGFT	LWSC	LWSMT	LWSMB	LWSL
Overall performance	52,27	48,07	46,52	30,46	42,96	46,29	43,76
Ranking	1	2	3	7	6	4	5

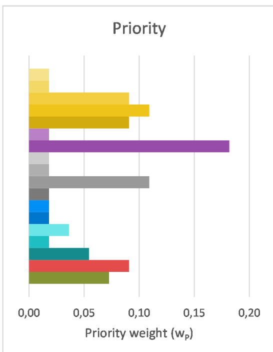


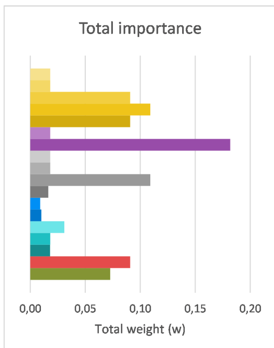
The overall performance is the sum of weighted scores, as shown below. Hover over a bar to see numerical values.



Weighting takes places based on both relevance (objective) and priority (subjective). The multiplication of both results in the total importance.



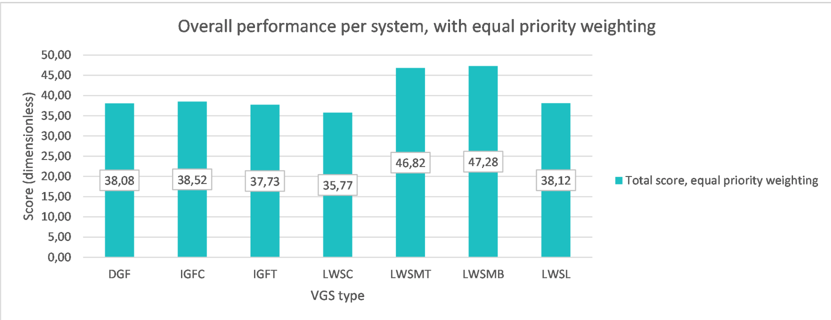




Overall performance for equal priority

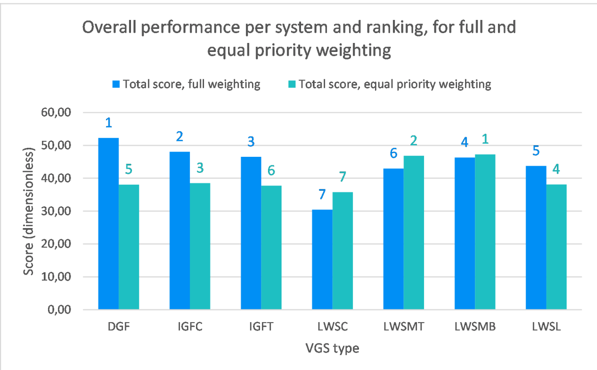
When all criteria are of equal priority (mean weighting for w_p), the overall performance on the suitability of the different VGS types is:

VGS type	DGF	IGFC	IGFT	LWSC	LWSMT	LWSMB	LWSL
Overall performance	38,08	38,52	37,73	35,77	46,82	47,28	38,12
Ranking	5	3	6	7	2	1	4



Comparing the performance for full weighting and equal priority weighting, the ranking might be different for the two scenarios:

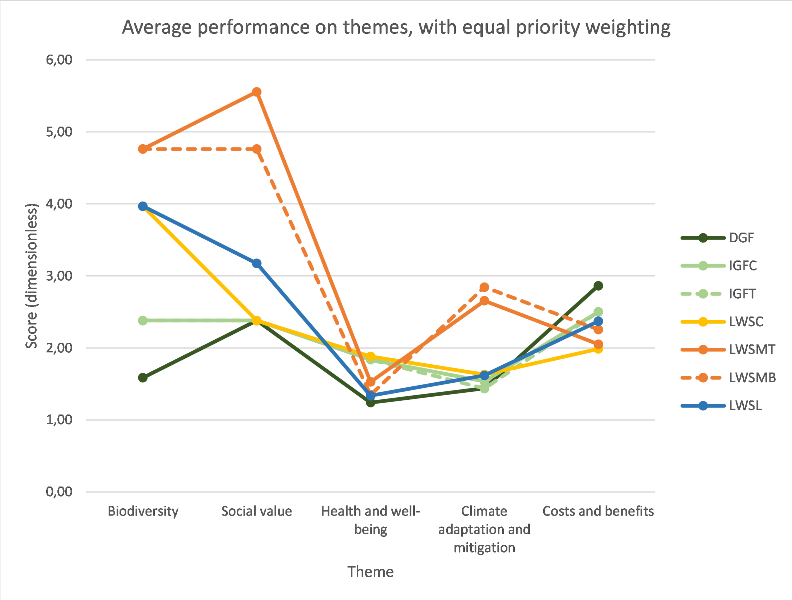
VGS type	DGF	IGFC	IGFT	LWSC	LWSMT	LWSMB	LWSL
Overall performance (full weighting)	52,27	48,07	46,52	30,46	42,96	46,29	43,76
Ranking (full weighting)	1	2	3	7	6	4	5
Overall performance (equal priority weig	38,08	38,52	37,73	35,77	46,82	47,28	38,12
Ranking (equal priority weighting)	5	3	6	7	2	1	4



Performance on themes

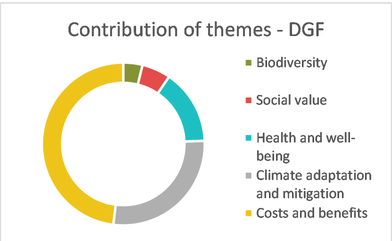
When all criteria are of equal priority (mean weighting for w_p), the average performance per theme is:

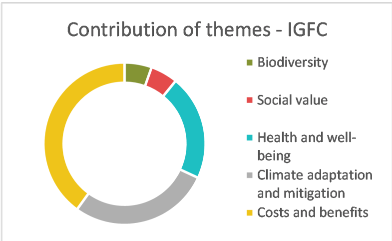
VGS type	DGF	IGFC	IGFT	LWSC	LWSMT	LWSMB	LWSL
Biodiversity	1,59	2,38	2,38	3,97	4,76	4,76	3,97
Social value	2,38	2,38	2,38	2,38	5,56	4,76	3,17
Health and well-being	1,24	1,84	1,84	1,88	1,53	1,35	1,34
Climate adaptation and mitigation	1,44	1,54	1,44	1,63	2,66	2,84	1,62
Costs and benefits	2,86	2,50	2,50	1,99	2,05	2,26	2,37

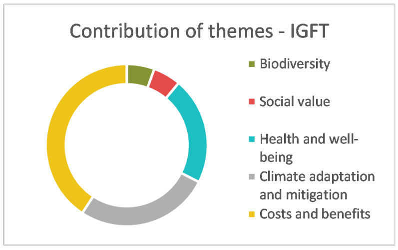


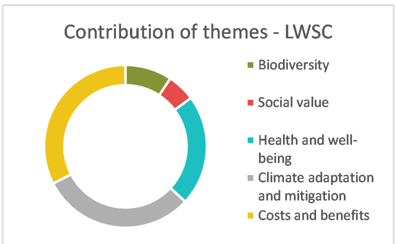
Explanation
See value tree on the right to see which criteria fall under what theme.

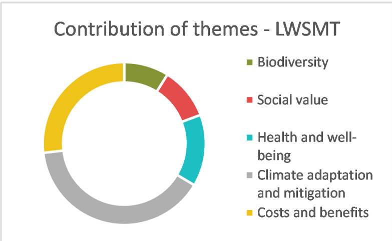
The following diagrams show the total contribution per theme to the performance with equal priority:

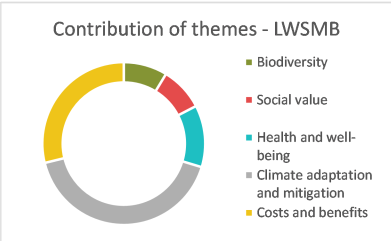


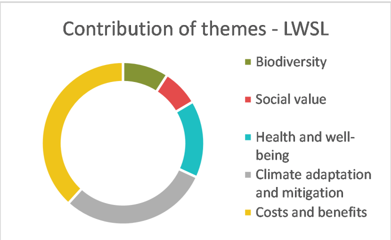










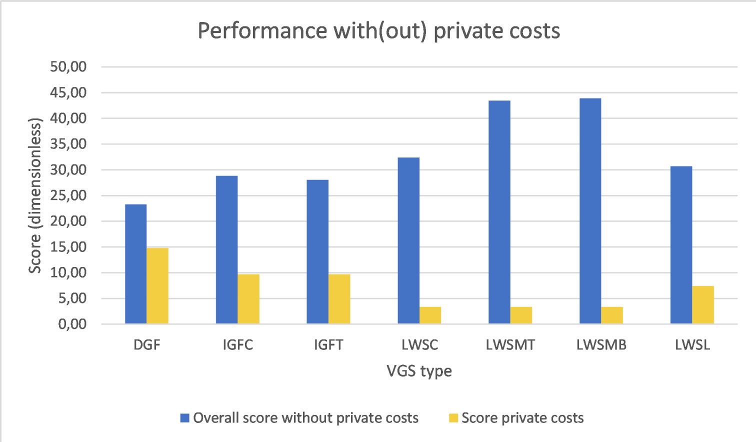


Note: Since themes have some overlapping criteria, the contribution diagrams do not add up to the total performance.

Performance with(out) private costs

When all criteria are of equal priority, the overall performance with(out) private costs is:

VGS type	DGF	IGFC	IGFT	LWSC	LWSMT	LWSMB	LWSL
Score without private costs	23,28	28,83	28,04	32,41	43,46	43,92	30,71
Score private costs costs	14,80	9,69	9,69	3,36	3,36	3,36	7,41

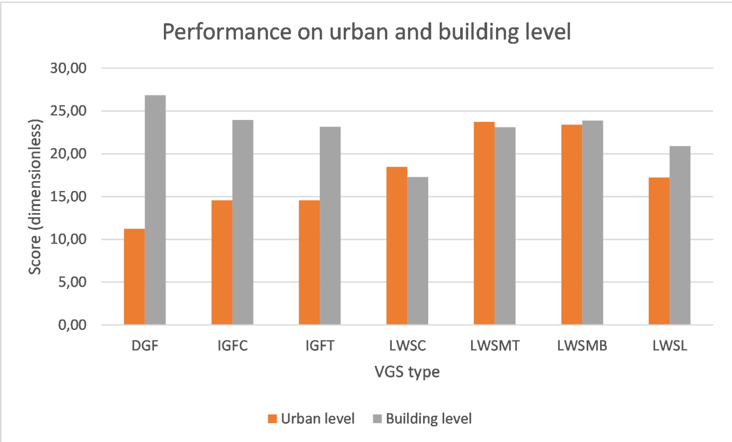


Note	
Overall score without private costs: includes environmental burdens (good = small) and private benefits	
A high score on private costs indicates relatively low costs	

Performance on building and urban level

When all criteria are of equal priority (mean weighting for w_P), the aggregated performance on urban and building level is:

VGS type	DGF	IGFC	IGFT	LWSC	LWSMT	LWSMB	LWSL
Performance on urban level	11,23	14,57	14,57	23,16	23,73	23,39	17,24
Performance on building level	26,85	23,95	23,16	17,29	23,09	23,89	20,88



Explanation	
See value tree on the right for which criteria affect urban or building level.	

Appendix: Residential project: Habitat Royale

Project-specific input

To achieve project-specific results, please fill in the green boxes. The blue boxes are values that are fixed and cannot be changed.

1. Project description

Instruction: Describe the building project by filling in the green boxes.

Variable	Description	Range/scope	Value/result	Unit	Formula		Explanation
Name	Residential project Habitat Royale						
Adress	Beethovenplein 2, Amsterdam	The Netherlands					Format: Street and number, city
Client	KondorWessels Vastgoed						

2. Potential: Environmental conditions

Instruction: Provide environmental conditions that will affect the scoring on some criteria. Click on the link to access the different websites.

Variable	Description	Range/scope	Value/result	Unit	Formula	Link	Explanation
H	Average building height in street, estimation		14	m		Webmapper	Retrieve from Webmapper; estimate average of buildings in 500 m radius around building
W	Average street width (facade to facade), estimation		55	m		Google Maps	Retrieve from Google Maps > 'Terrein' > 'Afstand meten' ; estimate average of buildings in 500 m radius aroun
H/W	Street aspect ratio	0-5	0,3	-	H/W		
$C_{district}$	Facade vegetation coverage in district, estimation	0-100	0	%		Google Earth	Retrieve from Google Earth or field observations, estimate for radius of 500 m around building
Climate	Climate type in Köppen-Geiger classification	Cfb	Cfb	-			(Further development: include more climate types)
Urbanity	Degree of urbanity of the neighbourhood		Zeer sterk stedelijk	-		Atlas Leefomgeving	Retrieve value from Atlas Leefomgeving > Search for address, retrieve 'Mate van stedelijkheid van de buurt'

3. Relevance weighting

Instruction: How relevant are criteria to the location and project? Select or provide variables that affect the weighting.

Retrieve values from Atlas Leefomgeving.

Variable	Description	Range/scope	Value/result	Unit	Formula	Link	Explanation
PM2,5	Particulate matter (PM2,5) in air (2020)		8	µg/m3		Atlas Leefomgeving	Retrieve value from Atlas Leefomgeving > Search for address, retrieve 'Fijnstof in de lucht (2020)'
Noise	Noise in the environment (Lden)		59	dB		Atlas Leefomgeving	Retrieve value from Atlas Leefomgeving > Search for address, retrieve 'Geluid in de omgeving'
Green space	Percentage area of green space within a circle with a radius of 500 m		54	%		Atlas Leefomgeving	Retrieve value from Atlas Leefomgeving > Search for address, retrieve 'Groen binnen 500 meter'
Heat island	Average ambient air temperature difference, relative to rural area		1,9	˚C		Atlas Leefomgeving	Retrieve value from Atlas Leefomgeving > Search for address, retrieve 'Zomerhitte in de stad'

Retrieve values from Klimaateffectatlas.

Variable	Description	Range/scope	Value/result	Unit	Formula	Link	Explanation
Heat stress	Severely lonely elderly over 75 (2020)		< 10	#/km2		Klimaateffectatlas	Retrieve value from Klimaateffectatlas > Select 'Ernstig eenzame 75+ers', then search for adress
Rainfall	Yearly precipitation (2016)		>900	mm		Klimaateffectatlas	Retrieve value from Klimaateffectatlas > Select 'Jaarlijkse neerslag', then search for adress

Select the (planned) inclusion of cooling and heating systems.

Variable	Description	Range/scope	Value/result	Unit	Formula	Comment	Explanation
Cooling system	Presence of active cooling system (such as air conditioning or heat cold storage)		No			***Possible comment***	If a cooling system that consumes any energy is present, select 'yes'. If not known yet, select 'yes' .
Heating system	Presence of active heating system		Yes				(Further development: include 'no' option for heating system)

4. Priority weighting

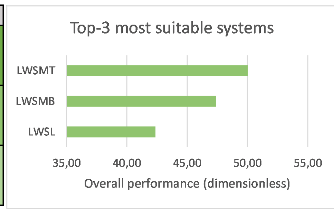
What criteria have most priority? In cooperation with the client, allocate weights to the different criteria.
First, allocate a value of 10 to the least important criterion, using the drop-down menu. Then, allocate a multiple of 10 to the other criteria. This indicates their relative importance.
Allocate the highest values to the most important criteria, and lower values to less important criteria. Several criteria can have the same value, indicating that they are equally important.
The 'rank' list on the right shows the resulting ranking of criteria, according to the assigned 'priority' weights.

Criterion	Description	Range/scope	Weight	Unit	Rank	Explanation
BD	Biodiversity	10-100	100	-	1	Potential to provide plant species variety and density, as well as a habitat for birds, snails, insects, beetles and
AV	Aesthetic value	10-100	60	-	2	Potential for aesthetic appeal to citizens.
PM	Particulate matter removal	10-100	10	-	12	Potential to remove particulate matter, one of the major outdoor air pollutants.
TN	Traffic noise reduction	10-100	30	-	6	Potential to reduce traffic noise pollution on street level.
RE	Relaxation effects	10-100	50	-	3	Potential to bring psychological and physical relaxation, i.e., stress reduction, to citizens.
HS	Indoor heat stress reduction	10-100	50	-	3	Potential to reduce indoor heat stress by lowering indoor temperatures during summer heat waves.
UHI	Urban heat islands reduction	10-100	10	-	12	Potential to reduce outdoor air temperatures to combat the urban heat island effect (temperature rises in citi
RC	Rainfall runoff control	10-100	10	-	12	Potential for rainfall flow retention and reduction.
EB	Environmental burdens	10-100	50	-	3	Environmental burdens, e.g. from materials, maintenance and water use.
CS	Carbon sequestration	10-100	10	-	12	Potential to sequester carbon dioxide from the air.
GW	Greywater treatment	10-100	10	-	12	Potential to remove pollutants from greywater (e.g. from kitchen, shower) for irrigation of vertical greening sy
CE	Cooling energy savings	10-100	30	-	6	Potential to lower cooling costs in summer because of the insulation and shading by the vertical greening syst
HE	Heating energy savings	10-100	30	-	6	Potential to lower heating costs in winter because of the insulation by the vertical greening system.
PC-I	Private costs - Installation costs	10-100	20	-	9	Costs for design, materials, irrigation system and installation.
PC-MO	Private costs - Maintenance and operation costs	10-100	20	-	9	Annual costs for pruning, irrigation and replacements.
PC-DC	Private costs - Disposal costs	10-100	20	-	9	Costs for disposal of system at the end of the lifetime.
PB-PR	Private benefits - Plaster renovation saving	10-100	10	-	12	Savings from less building facade maintenance because of protection of building facade by vertical greening sy
PB-VI	Private benefits - Real estate value increase	10-100	10	-	12	Increase of the economic property value because of the vertical greening system.

Factsheet key results

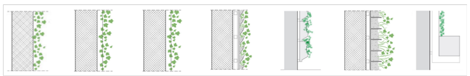
This factsheets presents the most suitable VGS systems for the specific project. More elaborate results can be found below.

Rank	System	Overall performance	Average installation costs (€/m2)
1	LWSMT	50,02	409
2	LWSMB	47,38	409
3	LWSL	42,37	302
		Dimensionless performance that includes costs	

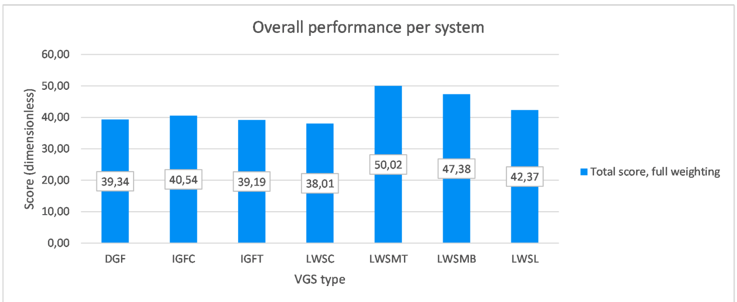


Overall performance

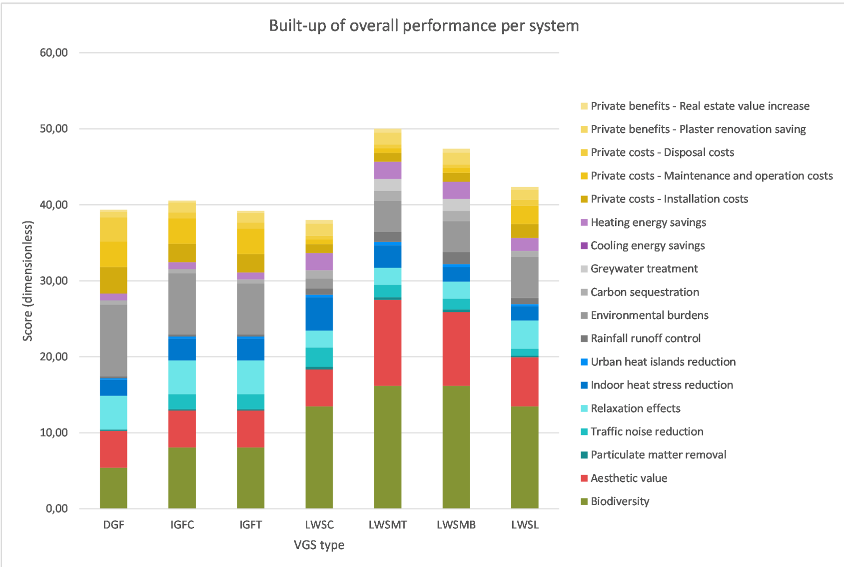
Given the project-specificity and priorities, the overall performance on the suitability of the different VGS types is:



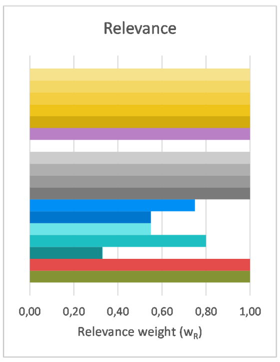
VGS type	DGF	IGFC	IGFT	LWSC	LWSMT	LWSMB	LWSL
Overall performance	39,34	40,54	39,19	38,01	50,02	47,38	42,37
Ranking	5	4	6	7	1	2	3

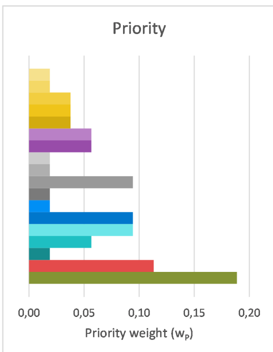


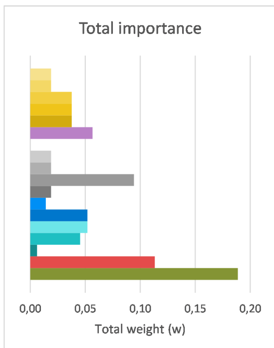
The overall performance is the sum of weighted scores, as shown below. Hover over a bar to see numerical values.



Weighting takes places based on both relevance (objective) and priority (subjective). The multiplication of both results in the total importance.



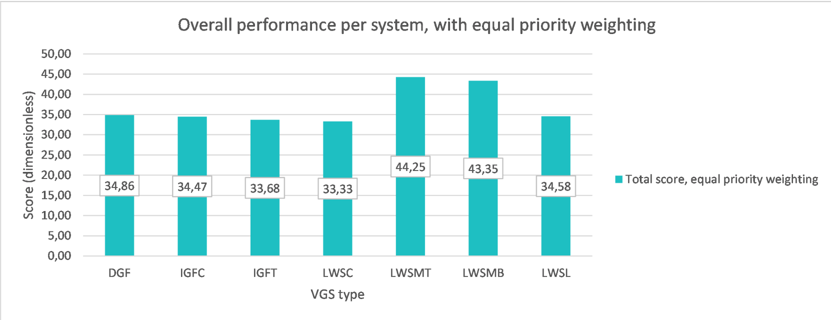




Overall performance for equal priority

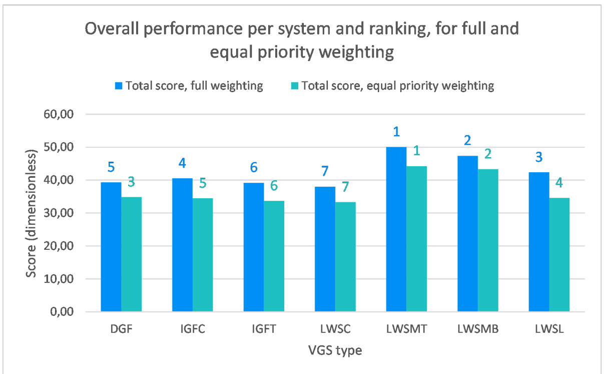
When all criteria are of equal priority (mean weighting for w_P), the overall performance on the suitability of the different VGS types is:

VGS type	DGF	IGFC	IGFT	LWSC	LWSMT	LWSMB	LWSL
Overall performance	34,86	34,47	33,68	33,33	44,25	43,35	34,58
Ranking	3	5	6	7	1	2	4



Comparing the performance for full weighting and equal priority weighting, the ranking might be different for the two scenarios:

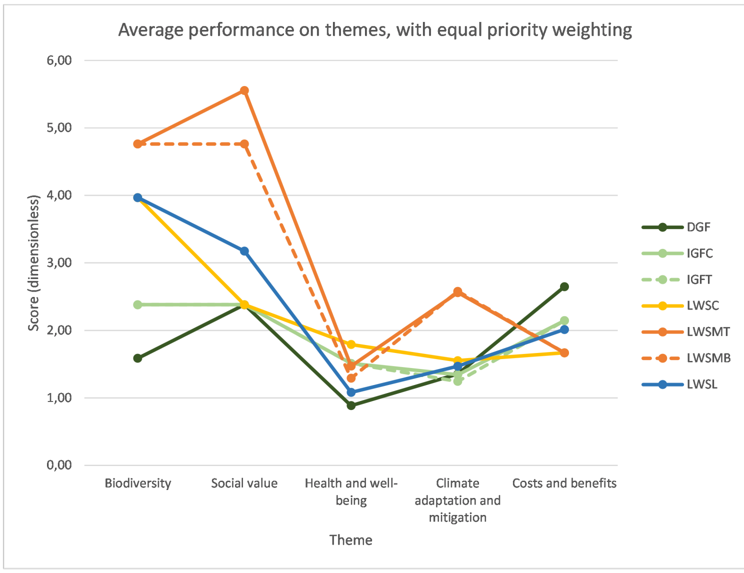
VGS type	DGF	IGFC	IGFT	LWSC	LWSMT	LWSMB	LWSL
Overall performance (full weighting)	39,34	40,54	39,19	38,01	50,02	47,38	42,37
Ranking (full weighting)	5	4	6	7	1	2	3
Overall performance (equal priority weig	34,86	34,47	33,68	33,33	44,25	43,35	34,58
Ranking (equal priority weighting)	3	5	6	7	1	2	4



Performance on themes

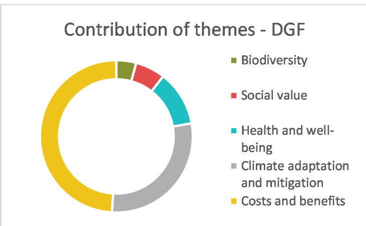
When all criteria are of equal priority (mean weighting for w_P), the average performance per theme is:

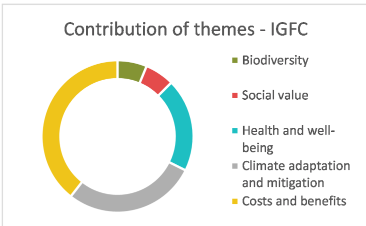
VGS type	DGF	IGFC	IGFT	LWSC	LWSMT	LWSMB	LWSL
Biodiversity	1,59	2,38	2,38	3,97	4,76	4,76	3,97
Social value	2,38	2,38	2,38	2,38	5,56	4,76	3,17
Health and well-being	0,89	1,51	1,51	1,79	1,47	1,29	1,08
Climate adaptation and mitigation	1,35	1,34	1,24	1,55	2,56	2,58	1,47
Costs and benefits	2,65	2,14	2,14	1,67	1,67	1,67	2,01

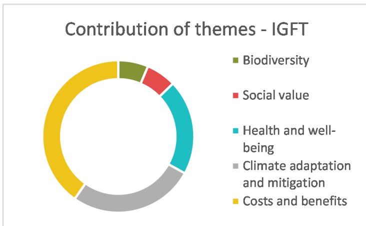


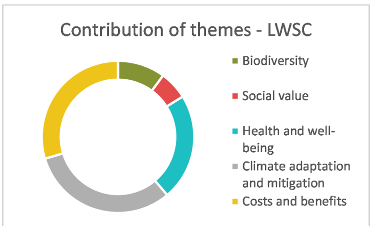
Explanation
See value tree on the right to see which criteria fall under what theme.

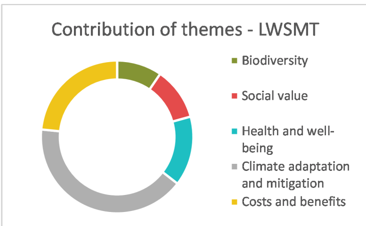
The following diagrams show the total contribution per theme to the performance with equal priority:

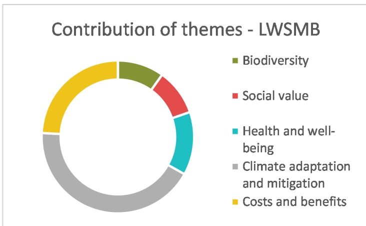


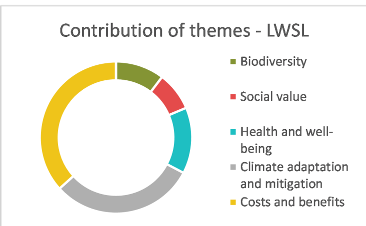










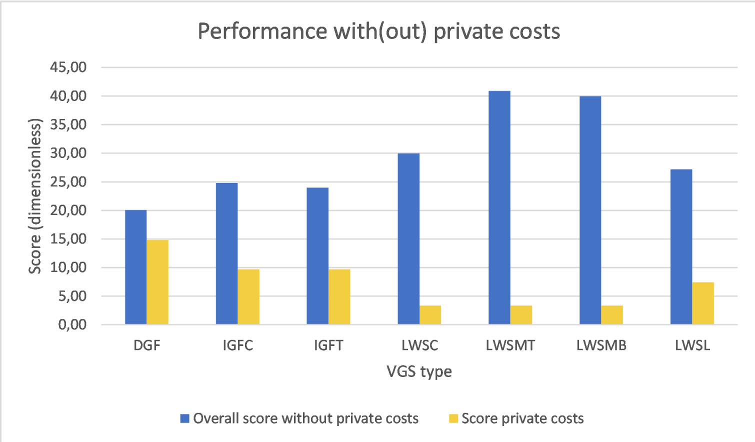


Note: Since themes have some overlapping criteria, the contribution diagrams do not add up to the total performance.

Performance with(out) private costs

When all criteria are of equal priority, the overall performance with(out) private costs is:

VGS type	DGF	IGFC	IGFT	LWSC	LWSMT	LWSMB	LWSL
Score without private costs	20,07	24,78	23,99	29,96	40,88	39,99	27,17
Score private costs costs	14,80	9,69	9,69	3,36	3,36	3,36	7,41

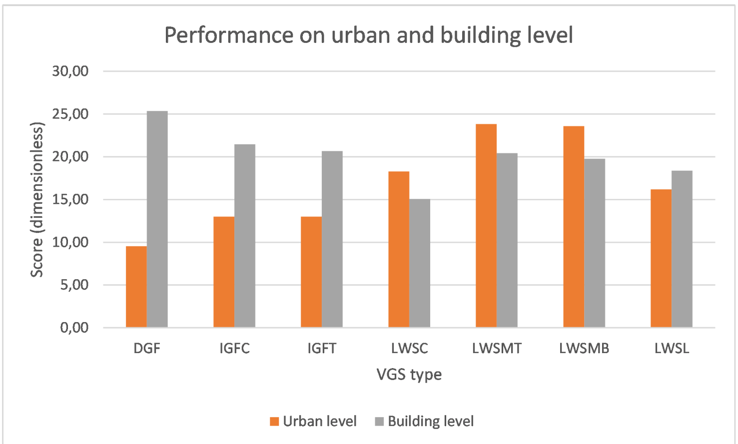


Note	
Overall score without private costs: includes environmental burdens (good = small) and private benefits	
A high score on private costs indicates relatively low costs	

Performance on building and urban level

When all criteria are of equal priority (mean weighting for w_P), the aggregated performance on urban and building level is:

VGS type	DGF	IGFC	IGFT	LWSC	LWSMT	LWSMB	LWSL
Performance on urban level	9,53	13,01	13,01	20,67	23,84	23,58	16,19
Performance on building level	25,33	21,46	20,67	15,06	20,41	19,77	18,38



Explanation	
See value tree on the right for which criteria affect urban or building level.	