URBAN VERTICAL GREEN

The need and potential of vertical greenery systems in dense urban areas

Daan Helmerhorst
MSc Thesis Metropolitan Analysis Design & Engineering
Advanced Metropolitan Solutions
Amsterdam, 25-11-2022

AMSTERDAM INSTITUTE FOR
ADVANCED METROPOLITAN SOLUTIONS

Author
Daan Helmerhorst
daan.helmerhorst@wur.nl

Supervisors
Martijn Lugten (TU Delft)
martijn.lugten@ams-institute.org

Corné Vreugdenhil (WUR)
corne.vreugdenhil@wur.nl

Summary/Abstract

Urban population is on the rise, and therefore the demand for liveable cities keeps increasing. To achieve this, cities need to become greener. But in a lot of cities, the spatial density prevents conventional horizontal forms of greening. Therefore, alternative ways of greening, such as vertical greenery systems, become necessary for the integration of greenery into dense parts of the city. This study presents an GIS based multi criteria analysis that indicates which areas need greenery the most. Amsterdam is taken as the case study. The multi criteria analysis has shown that the historic centre of Amsterdam needs greenery the most. The suitability for vertical greening in these locations was analysed, leading to certain facades. A case study of the most suitable façade and its local conditions showed what types of vertical greenery systems and plant species could be applied. This provided an initial selection of possible systems and plant species. Based on the preferences of the stakeholders, a direct green façade made of Ivy was deemed as most suitable. Further research on how dense, urban, and possibly historic areas can be greened is necessary to broaden the possibilities in which this can be done.

Preface

During a former course, my group developed a product called 'Green Paint' which was essentially paint with moss spores in it which causes moss to grow on the painted surface. This idea stuck with me, and I hoped I would be able to incorporate it somewhere in a following course. There seemed no option for that. During another course I did work on finding the most suitable places for planting tree seedlings in Amsterdam. It turned out that there was little to no room in the dense centre of Amsterdam for additional trees. This was because of the high spatial density. This led me to the question: how can these areas be greened? The answer seemed obvious; by vertically greening them. But how? Why aren't these areas already vertically greened? What are the obstacles in the way of vertically greening dense urban areas? And what form or type of vertical green should be proposed for these areas? This thesis came into existence to answer these questions.

I want to thank my supervisors Martijn Lugten (TUD) and Corné Vreugdenhil (WUR) for their guidance, advice, and motivation throughout the course of the project. I also want to thank my friends and family for their support.

List of Acronyms

BGI	Blue Green Infrastructure
FSI	Floor Space Index
GSI	Ground Space Index
GIS	Geo Information Systems
VGS	Vertical Greenery System
MCA	Multi Criteria Analysis

Contents

1. Introduction

1.1 Urban vertical nature

The urban usage of vertical greenery has been around since one of the first civilizations. The famous hanging gardens of Babylon used to be just a mystery of the orient but are now seen as one of the seven wonders of the ancient world. The story is told that one of the kings of Babylon, *Nebuchadnezzar*, had given the gardens as a present to his wife *Amyitis* who was homesick for mountain scenery. (Reade, 2009) This was a wonderful gift, but not a cheap one. Only kings could collect exotic plants, which required the luxury of watering. Nowadays, vertical greening has become more accessible, but still is a luxury. Historians are not certain if Babylon's hanging gardens actually existed or have been glamourized and mystified. The historian Dalley coined the theory that the gardens were in Nineveh and not in Babylon, where the river Tigris was near enough to provide sufficient water for the plants.

Whatever the specific location of the hanging gardens was, they have always sparked the imagination of people across the world. The integration of nature into the built environment has since then only developed. Gardens were not only popular in the ancient empires of the Middle East, but also in Hellenic cultures and later the Roman Empire (Foster, 2004). Narrow back gardens covered in vines were some of the earliest forms of vertical gardens. It provided shade, cooling and even had economic value because of the fruits that could be consumed by the people living there. These vertical gardening practices developed over the centuries. Around the year 1500, in Central Europe, woody vines were the most popular climbing plants (Köhler, 2008). In 19^{th}-century Europe, traditional climbers and balcony decoration was used to green facades. This kept on developing, especially in Germany, research regarding green facades was flourishing (Köhler, 2008).

Nowadays, the connection between cities and nature is becoming more prevalent. There is renewed interest in greenery. Especially integrating greenery in the urban environment is a part of the agenda of cities and can significantly help to mitigating climate change (Wolfram et al., 2019). Some countries and cities have a clearer connection to nature, in Florence, there is a contest called 'Fiori a Fiorenza' Flowers in Florence. In this competition, judges will score who has the most beautiful balcony in terms of plants and flowers. This leads to beautiful balconies across all Florence which enhances the aesthetical value of the city but also improves biodiversity. The interest in urban greenery is however not solely a European affair. Affluent cities in the Global South adopt similar strategies. In Singapore, which actively promotes and develops vertical greening techniques, more than one million square metre of grey surface is covered with green (Verhorst, 2019).

If people don't green their city, eventually green will take over the city by itself. Greenery always finds its way back through the most devastated cities on earth. Even in a site like Chernobyl, which had been abandoned 36 years ago, plants have slowly reclaimed the poisoned land. So instead of waiting for plants to take over cities, we might as well integrate the greenery in our environment ourselves.

1.2 Necessity of vertical green in dense areas

The process of urbanisation relies on the destruction, alteration or degradation of natural environment (Tassicker et al., 2016). And when the urbanisation has taken over the land, the reduced or completely removed vegetation is almost never compensated in the city or at other urban developments (Feitosa & Wilkinson, 2018). The incorporation of greenery into urbanised areas becomes more and more challenging as population grows, cities densify, and the competition for space and land intensifies (Bustami et al., 2018; Croeser, 2016; Lin et al., 2015). But even dense urban areas can be made more resilient and liveable; by integrating vertical greenery. Vertical greenery systems can be very adaptive. By taking advantage of existing walls the competition for space is minimalized. Which could enable the reincorporation of vegetation in cities (Bustami et al., 2018; Feitosa & Wilkinson, 2018).

Climate change influences the liveability of numerous urban areas all over the world. The broad scope of attributes that vertical greenery can possess leads to a multitude of possibilities to mitigate or adapt to climate change (Demuzere et al., 2014). These climate benefits span from indoor (Parhizkar et al., 2017) and outdoor air purification (Dahanayake & Chow, 2015), water purification (Aterlier GROENBLAUW, 2020), additional runoff potential (Hachoumi et al., 2021), sound (Tang et al., 2021) and thermal insulation (Schettini et al., 2016), urban heat stress mitigation (Koch et al., 2020), microclimate regulation (Tavares et al., 2015), biodiversity conservation and improvement (Mayrand & Clergeau, 2018) and human health (Sheweka & Magdy, 2011) and psychological benefits (Başdoğan & Çiğ, 2016).

Almost all the aforementioned benefits are tied to urban problems which require mitigation. Air pollution, water pollution, noise nuisance, urban heat island effect, low runoff potential, decrease in biodiversity, and a decline in human (mental) health, all emphasize the need for greenery in urban environments. Unfortunately, urban densification limits the available space for greenery. One of the most prominent criticisms of urban densification focuses precisely on the lack of urban green space and the removal of green space in the urban densification process (Madureira & Monteiro, 2021). In fact, densification policies may strive to increase the amount of green space on a regional level, but they actually reduce the amount of green space within urban areas (Haaland & van den Bosch, 2015).

Besides densification and the added benefits of greenery from an environmental perspective, vegetation also has a sheer financial side. Property developers prefer high densities, because of higher profits, and rarely prioritize the presence of greenery. But various studies show that vegetation does raise the economic value of an area. Access to parks is linked to increased residential property values (Nicholls & Crompton, 2005) and street-level greenery has a positive impact on residential value as well (Morancho, 2003). A recent study in New York has shown that street-level greenery adds financial value to not only residential property but to commercial buildings as well (Yang et al., 2021).

It is evident that greenery is a necessity for various stakeholders in cities. with horizontal space being a scarcity, the potential of vertical greenery is emphasized. The necessity and potential of vertical greening would suggest that vertical greening is already a common practice, but it isn’t. That leads to the next question; why isn’t vertical greening commonly being practiced yet?

1.3 Struggle of implementation

Vertical greening may seem like the ideal solution to the lack of green in cities, but vertical greenery systems have many negative connotations. Complaints frequently concern how time expensive vertical greenery is: maintenance issues, the amount necessary cuts, dead leaves, obstructed gutters and problems with the restoration of the greenery (Köhler, 2008). Vertical greenery can also become a financial burden if the maintenance cannot be performed by the owner. But also damage to the façade, an increase in amount of insects and a decrease in the amount of daylight are possible disadvantages. Wong et al., (2010) state that a lot of these problems stem from a lack of knowledge regarding the environmental and technological aspects which leads to uncertainties in the installation and design of vertical greenery systems. To be able to realize vertical greenery an innovative and creative approach is required which is based on integrated transdisciplinary design and proper knowledge of the plants within their environmental context and the construction of the system (Rakhshandehroo et al., 2016). Therefore, one of the main struggles of implementation is the uncertainty about the implementation of vertical greenery systems.

Another obstacle is the urban compactness of cities. Although this is a reason for the necessity of vertical green, it also an obstacle for implementing some types of vertical green. Some types of vertical greening systems rely on soil. But there are numerous obstacles that could be present such as cables, pipes, and rocks. Tian et al., (2012) has stated that an urban soil, which is characterized as 'stony' or 'sandy', with a poor structure, heavy compaction and plenty of rubble is not suitable for plants and that urban compactness has been verified to play the most important role in restricting plant growth in cities.

Furthermore, finding locations where vertical green can be implemented is also a challenge. Because urban land is a 'mosaic of private, shared, and public property' (Scott & Storper, 2015), it is hard for a government to decide which locations should be greened. The government also does not have the resources to do it all on their own. The only way vertical green can be realistically implemented is by cooperating with all relevant stakeholders. Which are, the municipality, developers, citizens, architects, botanists, and property owners. They all function and act in networks on various scales and levels (Van den Biesen, 2018). These networks do not necessarily interact with each other, or use different approaches, leading to a lack of information to decide on where and how to apply vertical greenery. The challenge becomes to align the views of the stakeholders (Verhorst, 2019).

But aligning stakeholder views and information will not automatically mean that a vertical garden can or will be implemented. Construction and maintenance costs might be high, making investors or property owners wary. Also, the image of vertical greenery as an expensive, corporate, and figurative façade for businesses might cause resistance from local communities. Green initiatives can cause property value fluctuation, which leads to the influx of wealthier residents. This often triggers the fragmentation of the existing neighbourhood communities and the dislocation of local citizens (Ling et al., 2020). Hence, the implementation of vertical greenery does not only lead to benefits, but also comes with several risks and liabilities.

1.4 Problem statement

The previous section mentioned several problems concerning vertical greenery systems (VGS). The problem that this study focusses on is the uncertainty surrounding the potential benefits of VGS on a city level, and the implementation of VGS on a facade level. Such uncertainty can make it difficult for decision makers to decide where and what type of VGS should be implemented. This means that there is a need for research that helps to give more of an overview. Some of the aspects also have overlapping causes and effects. The connections, correlations and possible mitigations between these aspects are shown in Figure 1. This figure is based on my initial perception of the relevant aspects and their connections.

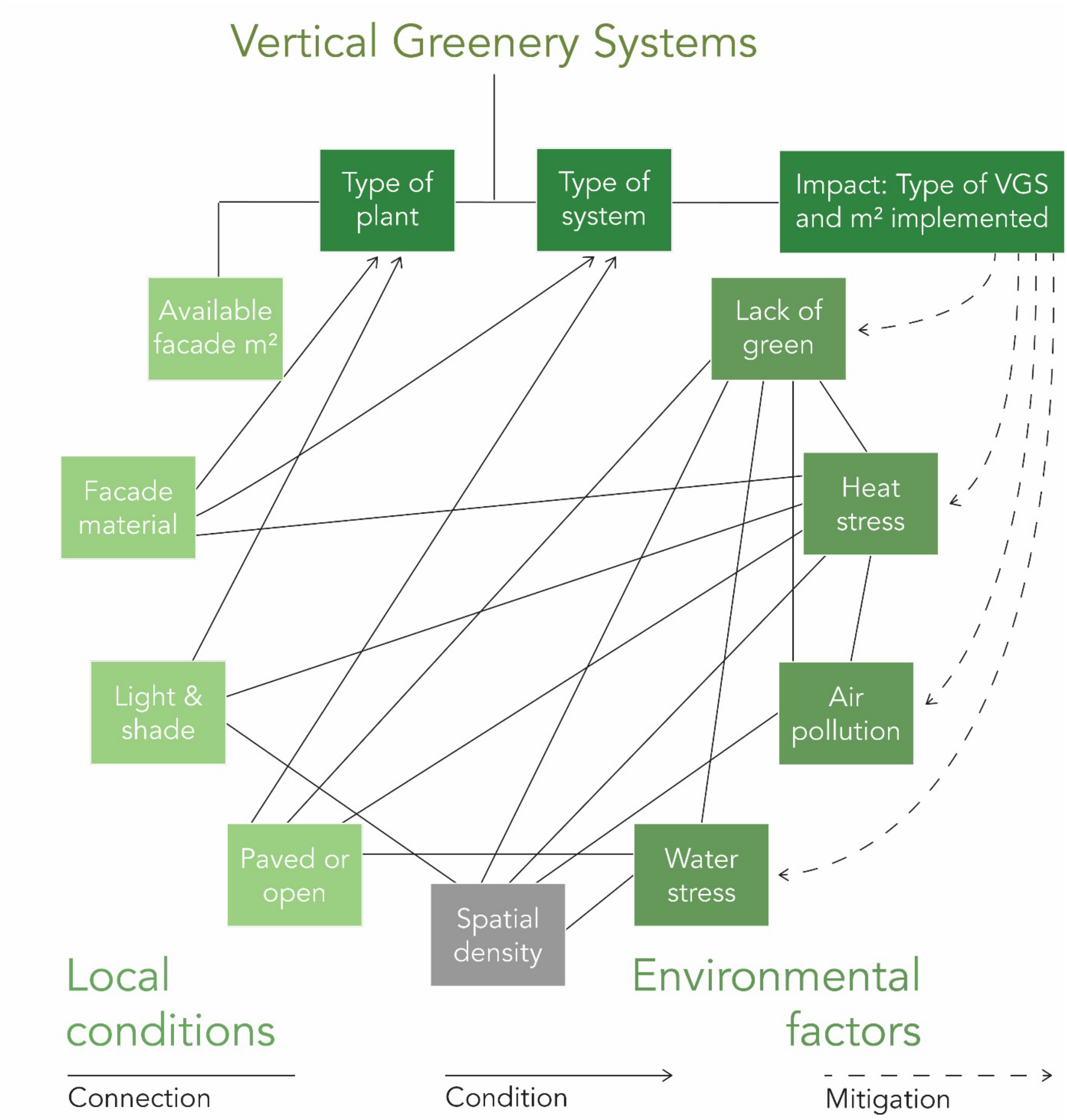


Figure 1 Hypothetical network of connections / framework / overview of system

Research objective

Complex situations can be clarified by researching the components of the process and mapping aspects at play. But because there are a lot of aspects, dividing them into smaller sections is necessary to get a clear picture of the situation. By putting these parts into a framework (Figure 2), an overview of the situation can be made. This allows the aspects to be considered in steps, instead of all at once. The following is to collect the data about these aspects. And fortunately, municipal wide geo-data on a lot of the relevant aspects is available in Amsterdam. These aspects can be mapped and brought together in GIS (Geo Information System). With GIS, spatial data can be combined, maps can be created and used for communication with stakeholders. Therefore, the research objective is to identify where on the city scale vertical greenery can mitigate environmental problems the most, and which type of system and species should be allocated on a façade scale. The research objective will be worked towards by answering research questions divided into four parts.

1.5 Research questions and methods

There are four research questions. The first one is introductory, which helps with understanding the subject that is to be implemented, which are vertical greenery systems. It is therefore a contribution to my personal knowledge and is only discussed in the literature study. The three last questions are the main research questions that will be answered throughout the results that will be presented. These research questions are all tied to a spatial scale, which goes from municipal, to local, to façade. This creates the connection between the need for greenery on a large scale, and the possibilities for it on smaller scales.

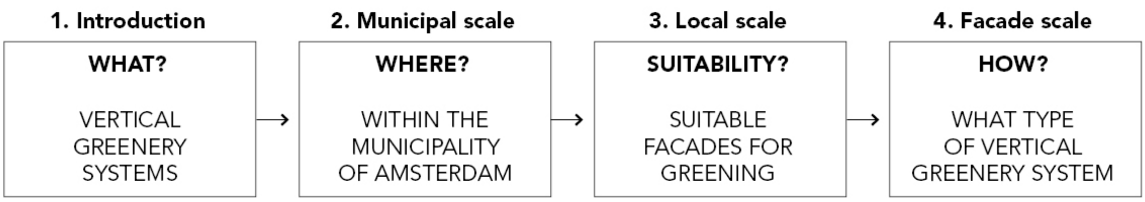


Figure 2: Abstract theoretical framework

- ***1. Introduction: What?***
  What are VGS and what urban problems do they mitigate?
  This question is asked to become familiar with the different types of VGS and their attributes. Especially their mitigation possibilities and potential benefits are identified which is necessary for the next question. Methods used to answer this question are **Literature Study** and **Desk Research**.

- ***2. Municipal scale: Where?***
  How can data on environmental factors be analysed to find out where vertical greening is most necessary?
  Urban problems that can be mitigated by VGS should be mapped to get a clear picture of where in Amsterdam VGS would be of most value. These problems consist of overlapping environmental aspects and spatial density. This leads to target locations, or 'areas in need of VGS' that will be identified. The method used to answer this question is **Spatial Analysis**.

- ***3. Local scale: Suitability?***
  How to assess the suitability of facades for vertical greening?
  Every façade could possibly be greened, but not all façades are as easy or ideal to green. Therefore, the suitability of vertically greening all the facades in an 'area in need' should be checked. The suitability of a facade is mostly determined by physical conditions but also by the ownership of the building or the monumental value. The methods used to answer this question are **Literature Study** and **Spatial Analysis**.

- ***4. Facade scale: How?***
  How can the right type of VGS and plant species be allocated to a facade?
  Lastly, the fitting type of vertical greenery systems (VGS) is allocated to a façade. This is because local conditions may vary, which require specific types of VGS. Next to the local conditions, the stakeholders of a façade need to be considered during this last research question. The methods used to answer this question are **Interviewing**, **Literature Study** and **Spatial Analysis**.

1.6 Readers Guide

After the introduction, an overview of the relevant theory on VGS is given in chapter 2*,* which contains the literature study and a subsequential theoretical framework. The literature study addresses vertical greening, dense greening and spatial analysis. The theoretical framework is based on the literature study and continues the research questions asked in the previous section. This is followed by chapter *3*, which addresses the context in which the study is performed and what methods are used to perform the collection, processing, and analysis of the data. Also, the case study interviews that have been conducted are elaborated. The following chapter is *4*, in which the results of the research questions are given. The case study location is decided upon, its potential is assessed and possible types of VGS are given. Also, the final interviews with stakeholders in the case study area are presented. After that, the discussion and conclusion are presented.

2. Theory

As shown for each research question, they all require specific methods to be able to provide an answer for them. Most of them require literature study. In this second chapter of the thesis report the literature study is conducted, and the theoretical framework is proposed. The first subchapter is the literature study. Second is the theoretical framework which is replicable and is not bound to the case study used in this study.

2.1 Literature study

Literature is written about varying stages and aspects of the vertical greening process. There is a lot of research on VGS, but it is mostly on specific aspects. Comprehensive multidisciplinary studies covering the entire VGS domain have rarely been conducted (Ahsan et al., 2022). During this literature study, broad and specific literature is both consulted. Initial literature was found by searching on *'vertical'*, *'green, 'urban'* and *'dense'* in differing combinations on Scopus. This provides an overview of the available literature. The literature search on Scopus resulted in eight documents. This led to other studies and research mentioned in the found literature. Literature on specific characteristics or benefits of vertical greenery systems was found by searching on those specific terms. Ultimately, literature was collected on technical aspects of VGS, climate benefits of VGS, dense urban greening and spatial analysis of urban green(ing). Policy documents and additional information about the municipality of Amsterdam are added to become familiar with the goals and regulations of the municipality. Lastly, two thesis reports from former students of Wageningen University regarding relevant subjects are added as well. Their work also led to a lot of resourceful studies. The literature study is divided in three topics, which are: vertical greenery systems, dense urban greening, and spatial analysis. Firstly, vertical greenery systems will be discussed.

2.1.1 Vertical Greenery Systems

The first research question is: *"What are VGS and what urban problems do they mitigate?"* This is answered by first looking at vertical greening and its attributes in general. Secondly, the different types of systems are listed and considered for urban usage. And lastly, the available plant species for vertical greening are researched.

VGS in general

The first modern vertical greenery system was an *"architectonic structure of any buildable size, shape or height, whose visible or exposed surfaces may present a permanently growing covering of vegetation"* (Hindle, 2012) developed and patented by Stanley Hart White in 1938. Since then, vertical greenery systems have been developed but the basis features have hardly changed. A vertical greenery system is a system which enables vegetation to cover a vertical surface. In this section, the general attributes of vertical greenery systems will be listed.

In section *1.2*, the benefits of vertical greenery systems have already been listed, but their attributes will be emphasized in this section. In 2022 a review of research progress into VGS has been published. In there, a current sum of the attributes of VGS is given. VGS lowers the temperature inside buildings during the summer, and acts as an insulator during the winter, which reduces the heat loss of the building, which reduces energy consumption. The temperature of air between buildings can also be reduced which can contribute to controlling humidity. Also, the article notes that VGS can have acoustic isolation properties which mitigates noise pollution. They can improve air quality, remove pollutants, and increase biodiversity. It also has the ability to improve the aesthetical appearance of a building and has a positive psychological effect on humans. (Ahsan et al., 2022) Additionally, green facades have potential to increase runoff (Roehr et al., 2009). All vertical greenery systems could generate these benefits, but the context in which they are placed determines how much of this potential can be reached.

These properties can be linked to urban problems which can be mitigated by VGS. The thermal properties of VGS can mitigate the urban heat island effect (UHI). Noise pollution can be reduced by the acoustic properties of VGS. Air quality can be improved by the purifying properties of VGS. The soil in VGS reduces water stress by increasing the runoff potential. The presence of greenery also increases biodiversity. It can also help with improving the physical and mental health of citizens living near the greenery. These properties and the problems they can mitigate will be further discussed in section 2.2.1 . To summarize; the climate related problems VGS can mitigate are **heat** and **water stress**, **noise** and **air pollution,** and increase **biodiversity**. These five climate related aspects are the urban problems that will be used in this study. Their connection to spatial density is discussed in chapter 2.1.2.

Type of system

Vertical greenery systems conveniently provide a developed and technologically established method of greening vertical surfaces. The most common distinction between types is the 'Green facade' and the 'Living wall'. The main difference between them is that living walls are more of an architecture and gardening technique that places soil and water delivery mechanisms into a wall to grow vegetation. (Spacey, 2019) In green facades, the plants grow from planters in or on the ground, direct or indirectly connected to the façade. Figu re 3 shows a basic distinction between the types of vertical greening systems.

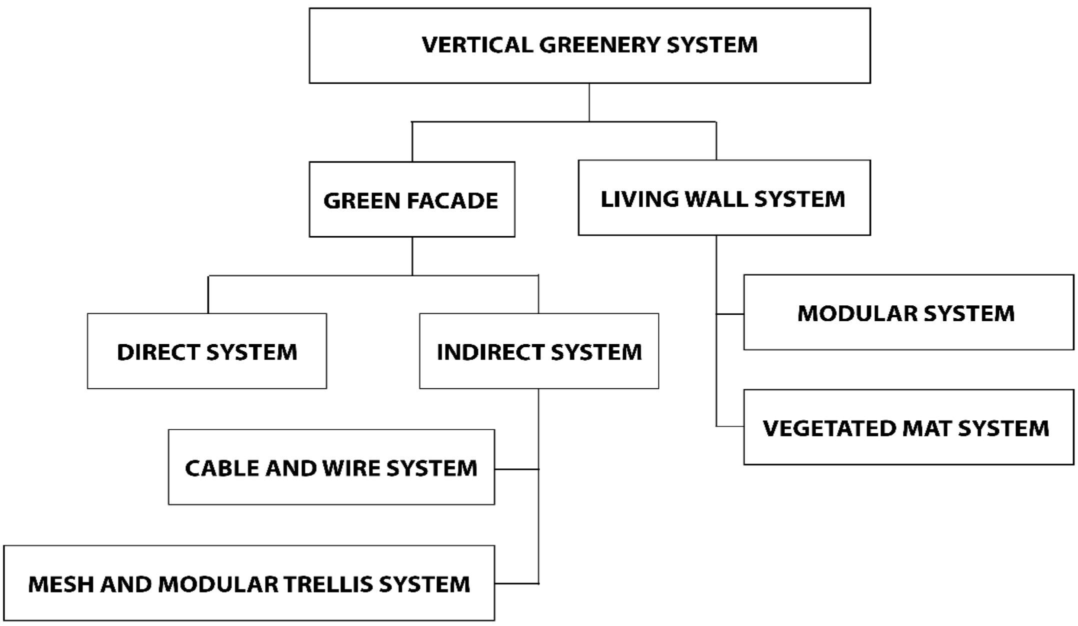


Figure 3. Edited from VGS Classification in (Čekić et al., 2020)

As mentioned, the main distinction made between VGS types is between living walls and green facades. Green facades require less maintenance due to the low amount of materials needed and are more environmentally and economically friendly (Rajak et al., 2022). On the other hand, the aesthetic potential of living walls is higher because they allow the combination of varying species. Another benefit of living walls is that they obtain environmental benefits right after they have been installed (Fernández-Cañero et al., 2018). Compared to living walls, green facades are simpler and cheaper. Because living walls are, in general, quite expensive, they are not an ideal fit for large-scale urban application but rather for individual walls. Living walls are generally more expensive to create but also to maintain. (Lundegren, 2016) This makes them less attractive for institutions such as municipalities and housing corporations. Because of significant building loads some LWS are also less sustainable. The LWS based on felt layers has the highest environmental burden of all the VGS (Ottelé et al., 2011).

Conditions of a façade and or its environment may prevent the possibility of implementing certain types of systems. Some facades may have too little load-bearing capacity and therefore can't carry the weight of a living wall. But in most cases, many different systems could be installed on a façade. The decision about what type of system to choose is mainly based on what goal one hopes to achieve by installing the system. This can be environmental, financial, aesthetical or all the above. The type of system is also often decided upon after the plant species is selected. Some plant species require certain support systems, and if selected therefore dictate which system should be installed.

Plant species

Living walls can host many different types of plant species, green facades are more restricted in specie selection. The design of the supporting system is herein important, as not all species can climb up on their own. Depending on the plant species, plants will grow upward, or grow in all directions. This means that some species need more support and manual fixation to support systems to cover a wall (Fernández-Cañero et al., 2018). For example, green facades require climbing plants that can bind to supporting structures or facades. The fixation methods of climbing species vary, and it determines what species is suitable for a type of supporting structure. Some of the plant species use the growth and tropisms of a plant such as tendrils, twining or adventitious roots (Fernández-Cañero et al., 2018). Another common distinction is made between evergreen and deciduous species.

Qualities, characteristics, and disadvantages of plant species are remarkably complex. The choice of plant species influences the performance of VGS in terms of energy savings, air quality improvement depending on their evaporation capacity and wall coverage. For example, when comparing plant species in green facades, ivy provides the largest cooling effect due to its density of foliage which casts shadows, with indoor temperature differences up to 3 °C (Pérez et al., 2011). Research has also shown that the capacity of particulate matter that can be collected by VGS depends on plant species (Ottelé et al., 2010). Varying conditions in locations limit and dictate the species that could be selected. Plant selection is determined by multiple factors including climatic conditions and the amount of exposure to sunlight (Fernández-Cañero et al., 2018). Next to that, the type of soil, characteristics of the container, requirement of water and nutrients and the neighbouring plant species all influence the plant species selection. Also notable is that is it overall best to prioritise native plant species as they are better suited to survive in their local climate (X. Wang et al., 2020).

2.1.2 Dense Urban Greening

Although there is no research question about the importance of vertical greening in dense urban areas, the significance of spatial density should not be overlooked. Spatial density can be seen as the original source from which all the research questions derive. The environmental factors listed in the previous section are in a way all caused by urban density. The higher building density is on a location, the lower the amount of green space becomes. This effect influences heat stress and water runoff potential. Air and noise pollution are also influenced by how many people live in a location, which is also correlated with building density. Urban density also increases the sound diffraction caused by the higher densities of roofs and façades (Ismail, 2010). All chosen environmental factors that can be mitigated by vertical greening are connected to building density. Therefore, density is seen as playing a significant role in the origin of all these problems. Therefore, spatial density should be researched properly to find out what current strategies are available to green dense areas. Spatial density can be measured in multiple ways, these are discussed in the section: Density.

As mentioned in section 1.3, the spatial density is a problem for the implementation of greenery in general but is also the reason why vertical greenery is necessary. And that in fact, densification policies may increase the amount of green space on a regional level but they actually reduce the amount of green space within urban areas (Haaland & van den Bosch, 2015). Density also leads to problems with infrastructure, housing, food and water supply, and sewage treatment (Cunningham, W. P., & Cunningham, 2017). Next to that, increasing urban densification is also connected to social inequality due to higher cost of land, lower neighbourhood satisfaction and air pollution (Madureira & Monteiro, 2021). Summing up these disadvantages may make it seem that urban densification is a bad thing, but simultaneously, urban densification helps with saving thermal energy, but also by reducing traffic costs because citizens don’t have to travel far for their daily agenda (Neuman, 2005). It is also claimed that urban density promotes community-orientated social patterns (Katz, 1994).

This dilemma of simultaneously promoting urban densification and promoting urban liveability has been given the name of *‘The Compact City Paradox’*. This is seen as paradox because urban densification is often seen as one of the most promising strategies for responding to climate change, but on the other hand, urban greening is also seen as the most feasible strategy to reach the climate adaptation goals (Madureira & Monteiro, 2021). To solve this some approaches to plan a both dense and green city have been proposed but there is a consensus about the lack of integrative concepts for the dense and simultaneously green city. This is the way how cities can respond to the environmental, social, and economic challenges that are posed by urban development (Madureira & Monteiro, 2021). Commonly a green belt is suggested to separate the city and its surrounding area to achieve a sustainable urban form (Frey, 2000). This is seen in big European metropoles such as Berlin, London, Budapest, Moscow, Prague and Copenhagen (Jongman et al., 2004). Green centres or ‘green hearts’ have also been proposed by post-modern planners (Burke, 1966). This model is characterized by a patchwork structure with disintegration and fragmentation (Tian et al., 2012). The most recent strategy is by creating an ecological network which exists out of small green patches, lines and corridors spread throughout the city (Pungetti, 2004).

Fortunately, we are not bound to the two-dimensional horizontal planes of our cities and vertical vegetation can successfully incorporate greenery into the urban scape without using all the limited available horizontal space. Therefore, there should be a focus on vertical greenery in dense cities.

2.1.3 Spatial Analysis

Lastly, similar methods of analysing the lack of green in urban areas in GIS have been developed and used. In Ljubljana, GIS was used to create a GI (Green Infrastructure) deficit index (Gantar et al., 2022). This deficit index is the base of the decision support system they developed to identify the potential areas in the city where additional green space would be most favourable. The study examines the need and opportunities to implement vertical green in Ljubljana as a case of a medium-sized and relatively green European city. The study focusses on the execution of implementation by presenting semi-structured interviews and workshops. They took inventory of all public vertical greenery systems in Ljubljana, which were also used to substantiate the GI deficit index. A remarkable note is that only 10% of all VGS cases in Ljubljana turned out to be living wall systems. The study concluded that there are lots of potential locations for implementation; however, this seemed to be hindered by economic issues and management.

In Amsterdam locations in need of GI were targeted as well. But in this study, the focus was on Blue Green Infrastructure (BGI) and the locations were also analysed to determine the allocation of the proper type of green infrastructure (Opstal, 2022). Opstal edited his framework from a suitability framework designed by Martijn Kuller. The framework was edited for it to work for the allocation of blue green infrastructure instead of green urban stormwater infrastructure. Those subjects are quite similar, therefore little adaptation was necessary. The framework exists out of two parts: the needs and the opportunities. The first part focusses on identifying priority areas within a larger case study area based on problems that could be mitigated by BGI implementation. This is done by performing a multi criteria analysis in GIS. Once the priority area is determined, the opportunity side of the framework maps the suitability of different BGI measures. The results of his research had shown that the method was able to locate priority areas and allocate a fitting BGI measure. The measurement allocation could be based on one of the problems, or multiple at once. By focussing on a single problem, the benefits for that specific problem are larger and when multiple problems are considered, the benefits are divided. Opstal concluded that his method has advantages over comparable methods because it operates from the perspective of a location and not from a specific measure perspective. The disadvantage that Opstal mentioned about his method is that the GIS-based multi criteria analysis takes longer to process than other methods.

A study in Vienna assessed the potential of 'greenable' area in the urban building stock by estimating the green retrofit potential of roofs and facades (Stangl et al., 2019). The research group Urbane GmbA explored a new methodological approach, based on publicly available geo-data, and applied it at two study sites in high-density urban quarters in Vienna. The combination of a GIS-based analysis with digital and on-site photos allowed for the creation of a Level of Detail 2 (LOD2) 3D-model. In the case of Amsterdam, these LOD2 3D models are already available without additional on-site data. It is argued that "*in the context of establishing green infrastructure in cities, urban retrofit has presumably larger area potential than ground-based green. To support the large-scale advancement of urban green, the assessment of greenable potential plots in the building stock, both on horizontal and on vertical scale, provides first indispensable indications for decision-making*" (Stangl et al., 2019).

A study in Australia investigated the suitability of retrofitting vertical greenery on facades. The study compared facades in multiple cities and their overall suitability. If the wall's height was greater than three metres, only the wall area from the ground level up to three metres was assessed. The suitability was tested by first excluding facades based on a list of conditions. These were: glazed facades of 50% or more, walls with no ground access, driveways/garage doors, heritage listed front facades, and (street)art. If any of these features is present, the façades are excluded from the following step. Secondly, several questions were asked about the wall's immediate surroundings and physical characteristics to determine its retrofit suitability. If answered with yes, the facades gain plus one point, if answered with no, the facades gain zero points. This analysis leads to a score between zero and six that provides a representation of the suitability for green wall implementation (Douglas et al., 2021). The list of questions asked about the facades regard more regulatory and structural circumstances that do not make the location completely non-viable, but only less suitable for the implementation of vertical greenery.

The studies in Ljubljana, Vienna, and Australia all focus on a specific step or aspect within the proposed process of this study. In Amsterdam, the location and allocation of BGI is based on needs and opportunities. But it focusses on BGI instead of VGS. In Ljubljana, locations for vertical greenery systems are based on a 'green deficit index'. The studies in Vienna and Australia are comparable to each other because they both evaluate the suitability of vertically greening facades. The study in Vienna focuses more on the potential of the entire greenable building stock, which also includes roofs, and the study in Australia specifically targets the current suitability of walls in cities. In Amsterdam, the location and allocation of BGI is based on needs and opportunities. All these studies focus on a part of the proposed research in this study or contain a method which is similar. Therefore, they are valuable research to base this study on. Identifying the different methods used throughout the literature gives insight into where the knowledge gap is. A lot of the individual aspects regarding vertical greening have been researched, but they have not been combined into a single study yet.

Because all the studies focus on a specific step, they are very resourceful to consult during parts of the research that are similar to their studies. The framework used in the study of Opstal will be used as a basis for the theoretical framework developed in this study. This is because that framework uses needs and opportunities as a method to find out, step-by-step, what is needed where. It also connected to scale. The first question; *where?* is asked on a large scale, considering a part of, or an entire city. The answer to this question leads to a specific location. The next step zooms in on that location, and thus considers a smaller scale. This is a practical way of approaching a city-wide problem and looking for a solution on a local scale. Some adaptations will have to be made when developing the theoretical framework for this study, but essentially, the method of first finding out where greenery is needed, and subsequently allocate a fitting VGS measure at that location, will be the core of the method used in this study.

2.2 Theoretical framework

Based on the literature study in the previous section of this study, the initial abstract theoretical framework (Figure 2) is amended. The framework is adapted from the frameworks of Kuller and Opstal discussed in 2.1.3 Spatial Analysis. The approach of the research differs, this is because Opstal developed his tool for urban planners. This study is rather focussed on stakeholders instead of designers. This is because vertical greenery is less dependent on professional designers than the blue green infrastructures which are considered in the study of Opstal. The three final steps and their aspects are elaborated in the following section. The first step of the framework is discussed in section 2.1.1.

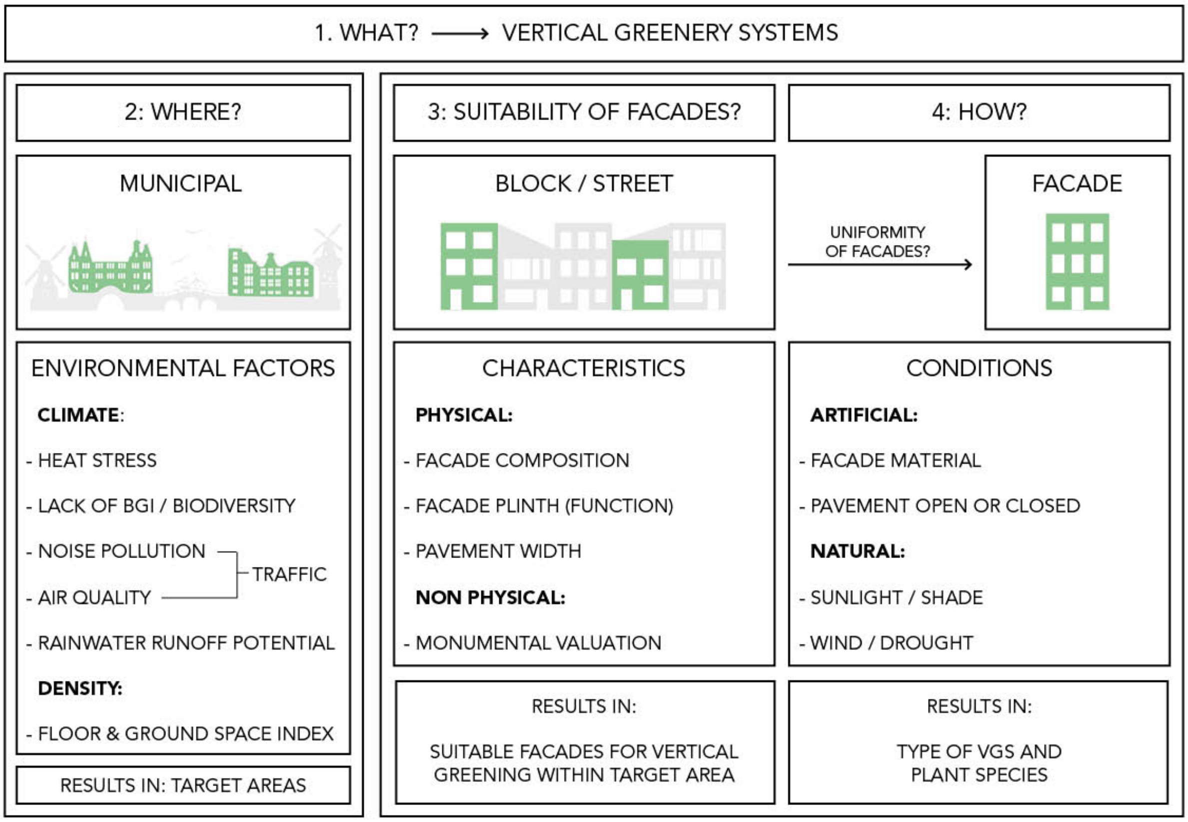


Figure 4: Suitability framework adapted from Kuller et al. (2019). The second step represents the 'Needs' and the third and fourth step represent the 'Opportunities' from the original framework.

2.2.1 Where?

To find out where VGS is most needed, the environmental factors related to urban problems that can be mitigated by VGS should be mapped. This will lead to target areas and subsequently a case study location. These urban problems are listed in a previous section: VGS in general. How they can be mitigated by VGS, how they can be represented with geo-data and why they are the most important criteria to base the location specification on is elaborated in this section. Next to these climate related aspects, the spatial density is also mapped. Why and in what form density is integrated is elaborated in its own section. Finally, all aspects are summarized, and clarification is given for why certain aspects are left out.

Biodiversity

In cities, biodiversity occurs in smaller fragmented and isolated patches of green (Fuller, R. A., & Gaston, 2009). To enhance the level of biodiversity, a connection between the fragmented patches of green should be made (Shanahan et al., 2011). This connection can be established by greening the areas in between the disconnected patches of green. This can be done by implementing vertical greenery. Vertical greenery systems have demonstrated to be a habitat that can support biodiversity. In contrast to stone walls and masonry walls where flora is only spontaneous, vertical greenery systems leave many possible microhabitats for differing types of species (Mayrand & Clergeau, 2018).

But the conditions in which a vertical green is implemented influences its impact on biodiversity improvement. The vertical green can function as steppingstones within the urban area to enhance the connectivity of greenery in the city. The dispersal of several species in urban climates relies on scattered habitats across the city. Current low levels of fauna in vertical green have been shown to be connected to the landscape surrounding the vertical greenery, but only for species with low dispersal capabilities, such as beetles (Madre et al., 2015). Therefore, planning green corridors can be a critical way to facilitate dispersal of species within urban environments (Ahern, 2013).

The first environmental aspect in the theoretical framework is the general lack of green and low or decreasing biodiversity coming along with that. Lack of green and low levels of biodiversity are not the same but are connected. But to optimally increase biodiversity, decisions regarding the type of greenery should be based on the local ecosystem. Water should be included, because it also contributes to the biodiversity of areas. To conclude, biodiversity is much more than just the amount of green and blue area, but in this research the lack of green and blue area is considered as the lack of biodiversity.

Heat stress

Urban heat stress is a growing problem due to urbanisation and the global temperature that is slowly rising. Especially in dense urban areas this is a significant problem. A study estimated that annually, heat-related mortality will increase from *“the 32.1 per million recorded from 1986–2005 to 59.2–81.3 per million for the 2.0 ◦C warming”* (C. Wang et al., 2022). The cooling potential that vegetation has on buildings has been researched thoroughly in recent years. Vertical greenery has shown to be a flexible tool for decreasing the temperature in building walls, indoor air and ambient air temperatures which result in increased thermal comfort and a reduction in energy demand for cooling. There are four effects that contribute to the cooling capacity of vertical greenery, those are: insulation, ventilation, shading and evapotranspiration (Koch et al., 2020).

But not all types of vertical greenery systems have the same cooling effects or capacity. Comparing the different systems in terms of cooling capacity is often challenging due to the large diversity of vertical greenery systems. This is because the type of system, the plant species and substrate all influence the thermal properties. Overall, green walls have the largest cooling capacity because of the amount of substrate vertically spread throughout the wall and the wide range of plant species a green wall can carry (Čekić et al., 2020). If cooling an area is the top priority, differences in the cooling capacity of systems should be considered. The environmental conditions in which the cooling capacity of vertical greenery systems is measures is also significant. Studies conducted during summer show reductions of multiple degrees Celsius, while during autumn, there was hardly any difference measured (Perini et al., 2011).

Traffic: noise and pollution

Traffic plays a key role in the functionality of cities, but at the same time it can also decrease the liveability of the city. Cities have several sources of noise and air pollution; the significant and preventable sources arise from traffic and industry. The most important source for air pollution is motor traffic, especially in cities (Mayer, 1999). And that motor traffic is usually the single greatest contributor of noise in most cities as well (Bhatia, 2014). Overall, the other sources of noise and air pollution cannot be neglected, but in this study the focus lies on dense urban areas where often industrial sites are not present. Therefore, noise and air pollution are considered as two environmental factors caused by one aspect, which is traffic.

Studies have shown that vertical greenery systems have the potential of mitigating urban air pollution (Irga et al., 2015). The 'porous' nature of plants allows them to remove and dispose of air pollution (Escobedo & Nowak, 2009). Next to that, some of the innate processes of plants such as absorption, adsorption, detoxification and accumulation allows the plants to function as a 'living filter' without being harmed by it (Garbisu et al., 2002; Jim & Chen, 2008). The leaves of plants also accumulate particulate matter on their surfaces, which effectively filters the air (Shi et al., 2017). However, urban air pollution minimization is not equal for different plant species. Some species can even act as source of pollution (Curtis et al., 2014). Therefore, the selection of plant species requires careful consideration when designing in urban environments (Zupancic, 2015).

Vertical greenery systems are also able to function as passive acoustic insulation. Not only do vertical greenery systems reduce noise pollution, but they also minimalize the sound transmission from the environment onto the surrounding surfaces. The scattering and reflection of airborne sound on leaves, branches or trunks which further causes the attenuation of noise (Azkorra et al., 2015). The development of vertical greenery systems also causes the vegetation and substrate to change, which leads to the sound absorption capacity of vertical greenery systems to possibly increase (Ahsan et al., 2022).

Water stress

Another climate related aspect is the runoff potential of rainwater. Lack of this potential leads to flood risk. High amounts of paving can often cause a low runoff potential. Opening the pavement by taking out paving stones creates access to the soil for rainwater. This mitigates the potential of flood risk. Not all vertical greenery systems are rooted in opened paving, but green walls have their own way of controlling runoff. The green wall can retain water runoff from the roofs by covering the impervious surface of the facade with plants, soil or other planting medium (Sheweka & Magdy, 2011).

A study from 2008 in Vancouver showed that the addition of green roofs and green facades would reduce stormwater runoff up to 13%, from what 6% was caused by the green facades. This significant share of the green facades has shown great potential for reducing stormwater runoff, but further research on green facades is required to achieve more accurate data (Roehr et al., 2009). This significant share of runoff reduction of the green facades was caused by the amount of roof area being less than half of the façade area on their selected site. But this is not exclusive to Vancouver. Other high-density cities also have much more available façade area than roof or street area. This emphasizes the need for vertical greenery systems in dense urban areas.

Density

As mentioned in section 2.1.2, urban density or compactness is the spatial density of buildings. The more compact a city becomes; it risks becoming less liveable. This is mainly caused by the lack of space for urban green areas that should compromise the grey mass. Higher density does lead to energy savings but also leads to more frequent and significant heat stress. Urban density has a lot of advantages but for almost every positive, there is also a negative connected to it. It has also shown that density is connected to all the previously mentioned aspects. Therefore, density is incorporated in the theoretical framework as an individual aspect.

Densities are usually measured in dwellings per hectare in Dutch spatial planning practice. This unit measures the number of dwellings on a given surface area and is therefore interesting for the housing market, but it only gives an indication of spatial density: a dwelling may be very small or very large, and non-residential buildings, such as offices, schools, and shops, are not included. Non-residential buildings are included in the CBS environmental address density (OAD), but the surface area of an address can also vary enormously. After all, an address can be a few square metres - for a bridge operator's house - or 160,000 m2 - for a building like "De Rotterdam". A further limitation of the OAD is that it is available at neighbourhood and district level, but not at building block level. (Harbers et al., 2019)

Another frequently used density indicator is the number of inhabitants per square kilometre, possibly combined with the number of employees or visitors. This gives a picture of the intensity of use of an area but is not a physical indicator of building density. By using the Floor Space Index (FSI) as a unit of density, these limitations are overcome with a unit that does justice to the physical-spatial appearance of an area. The FSI shows how the floor area (the area of all the floors together) relates to the land area, regardless of the function and regardless of the intensity of use. The GSI (Ground Space Index) represents the part of a site that is built up and gives insight into the percentage of open land compared to buildings. The FSI and GSI are both relevant in the case of vertical greening. The GSI shows how much horizontal space there is left, if this number is very low, vertical greening is favoured. The FSI approximates the heights of the buildings around the open space based on the number of layers a building has. This indicates the vertical potential of an area. If there is a high FSI, there are multiple stories which could be greened. (In some cases, i.e., warehouses sometimes have only one or very few layers but are still tall buildings. But those are rarely present in dense urban areas.)

Sum of aspects

To conclude, biodiversity, heat stress, noise pollution, air pollution and water stress are the environmental aspects that have the most potential to be mitigated by VGS. Building density has shown to be connected to all of them and is used as a stand-alone aspect. Summing up all these aspects will show where in the municipality these aspects are most prominent and thus where the addition of vertical green is of most importance.

There are some other aspects that are relevant to vertical greening as well but will not be included in further steps of this research. These are aesthetic value and the physical and mental well-being of citizens. This does not rule out the potential mitigation of these problems if they are present in a chosen target location. If in another case, one of these aspects is a priority, they could be integrated in the research.

2.2.2 Suitability of facades?

After a case study location has been appointed in the previous step, the third research question must be answered, which is: *How to assess the suitability of facades for vertical greening?*

As discussed in 2.1.3 Spatial Analysis, different parameters can be considered when assessing the suitability of a façade for vertical greening. Especially the study of Douglas et al., (2021) has performed a very similar process. In their study, elimination traits were used to determine which facades where most suitable for vertical greening. The difference is that the questions they ask expect field work to be performed and cannot be answered by obtaining geo-data about the facades. The goal of this study is to find out how much information can be obtained through desk research.

Other than the discussed study, there isn't any literature on other methods for analysing facades. Some specific information in the form of the geo-data is lacking. And some aspects that require field work must be included because they are too significant to exclude from the process. Therefore, an enhanced cadastre would be extremely helpful for the suitability assessment of facades and prioritisation of green infrastructure development in general (Stangl et al., 2019). In the following section the aspects that are chosen to base the suitability assessment on are listed. The aspects are chosen based on literature. Each aspect is individually elaborated and substantiated.

Facade composition

The composition of a facade is where and how the windows, doors and other parts of a facade are divided over the entire surface of the facade. This can vary a lot in just one block, but in some cases, it is repeated throughout entire streets. To obtain data about façade composition, a quite detailed 3D model is required. Windows and doors are only included in models from Level of Detail (LoD) 3.1 and up (Arroyo Ohori et al., 2022). If this is not available, field work is required to obtain the data about this aspect.

Figure 5: Different types of façade compositions

Plinth accessibility

As the previous variable, the accessibility of the plinth of a facade can be very defining for the vertical greening possibilities. Some buildings have an open facade plinth, most stores for example. This often drastically reduces the practicality of vertically greening the remaining upper part of the facade. So, mapping the function of a building can be an indication but does not definitely tell whether the plinth of a facade blocks the vertical greening potential. Other features such as fire exits, garage doors and storage for bins can also decrease the suitability of a façade. In the study of Douglas et al., (2021), immediate surroundings and physical characteristics of facades are individually questioned.

Pavement width

The width of the pavement is another variable that influences the possibilities of vertical greening the facade connected to the pavement. If a pavement is very narrow, little to no space is left for pot and soil based vertical greenery system. The municipal draft policy framework 'Space for the pedestrian' stipulates that the free passage space on pavements must be at least 1.8m (Gemeente Amsterdam, 2020a).

Again, in practice, a narrow pavement does not exclude all possibilities. Hanging greenery systems could still be applied, but a lot of the climbing systems, especially the indirect systems, become very unpractical when there is little pavement space available. In the study about *'Greenable Area in the Urban Building Stock'*, from Stangl et al., (2019) the pavement width is taken as an important parameter in their GIS-based survey of the green facade retrofit potential.

Monumental valuation

Lastly, the monumental value of a building also has an influence on the greening possibilities. The study conducted in Australia (Douglas et al., 2021) also used the monumental value of a façade as one of the elimination features. But especially in the historic centre of Amsterdam, a lot of the buildings have a monumental value, and most interventions are not allowed. There is a difference between monuments owned by the state and monuments owned by the municipality. The municipality already has taken the initiative to assess the potential of vertically greening their own property.

Most of the time, interventions proposed for a monumental facade are restricted. Fortunately, the development in indirect green facade technology possibly opens the option of vertically greening monumental facades. Indirect greenery systems, with little connection to the facade, can become a valid option of greening those monumental facades. Currently all systems need to be anchored in some type of way to the facade, therefore damage is done to the monument. Direct green facades are completely disregarded because of the damage self-climbing or -adhesive species can do to a façade. Therefore, the current possibilities of vertically greening monumental facades are very slim.

2.2.3 How?

When it is decided which facades are suitable for vertical greening, the final research question is asked, which is; *How can the right type of VGS and plant species be allocated to a facade?*

Which type of VGS can be applied to a façade depends on a few aspects. This leads to a decision between a green façade or green wall. Specifying fitting plant species is more complex. Fortunately, botanists can precisely specify what type of species or even sub-species would fit best on a certain location. In this research, only a general estimation will be made about what type of species would fit best. That general estimation is based on two aspects discussed in this section. They are chosen based on literature and contact with botanists. As seen in the figure below, the type of plant and system are directly influenced by the local conditions but are also tied to the aspects discussed in the previous sections.

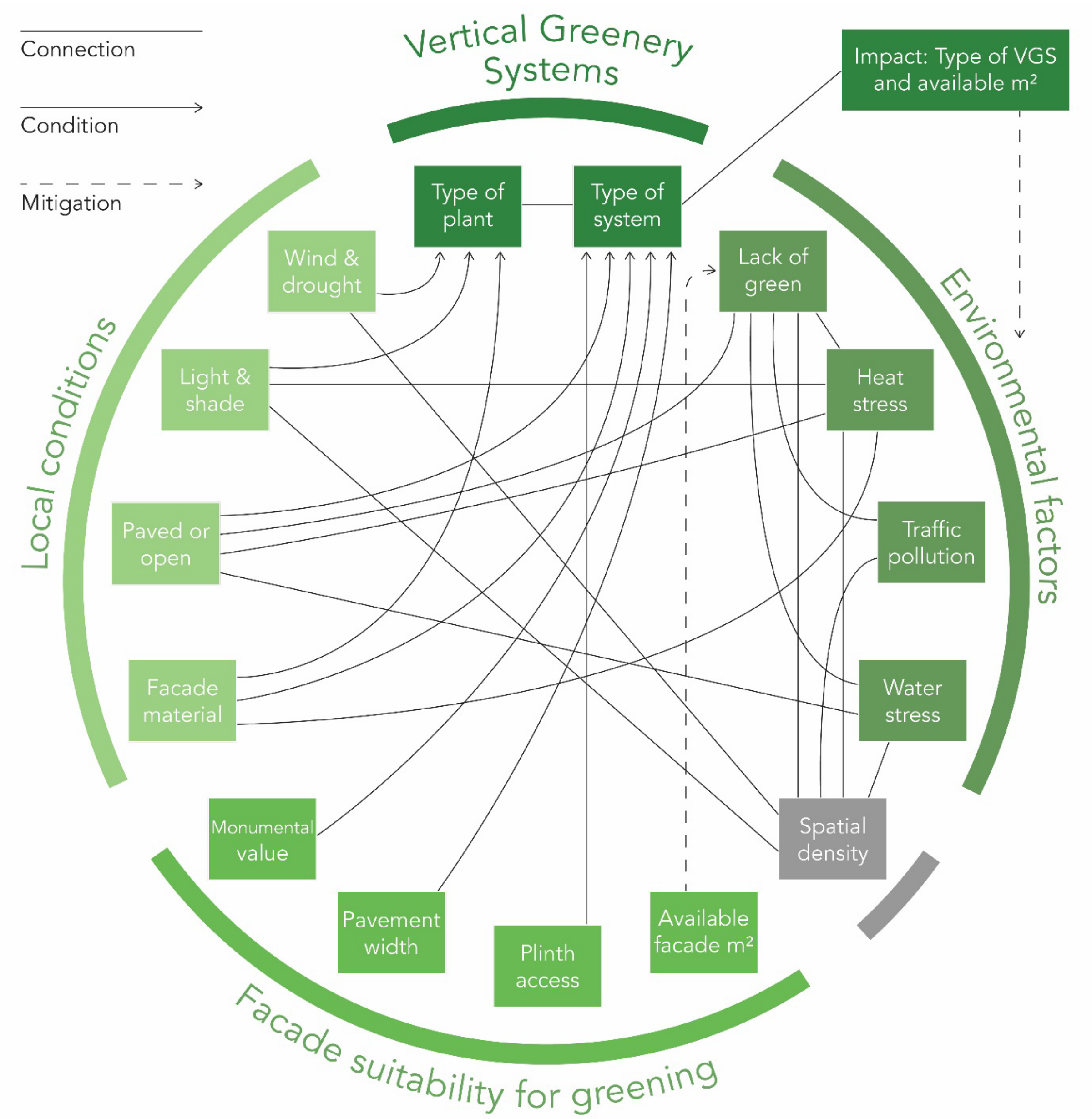


Figure 6: Completed network of connections

Facade material

The material of a facade dictates the possibilities for the anchoring method of the greenery system. Different materials allow different ways of anchoring, and some materials allow little or no ways of anchoring. In that case, only hanging or self-supporting vertical greening is applicable. Also, different facade materials have different thermo-dynamic properties, and thus influences the choice of plant species that is best for the facade. Aesthetic value can also be considered. Facades with unattractive materials could be prioritised for vertical greening. In this study, only material is considered.

Additionally, the state of the material should be considered. If the material is poorly maintained, direct green facades should not be applied to the façade. This is because climbing plants directly connected to the façade will slowly root in any available crack. This will decrease the load-bearing structure of the façade. This also dictates which vertical greenery systems can be applied to the façade. Therefore, the year of construction and state of material should be considered.

Ground / Pavement open or closed

If the pavement is closed, and the ground is solid, greenery systems in pots become most feasible. In some cases, pavement can be opened. But to assess the potential of this, the quality of the soil is important to consider. If for example the soil exists completely out of sand, it is hard for plants to root properly. If the pavement is opened, and there is a direct connection to usable soil underneath, soil-based systems are most beneficial and practical. But the available space in the soil must be checked as well. Pipes and cables often restrict the possibility of letting plants freely root in the soil. To check the presence of pipes and cables, a *klic-melding* must be requested at *Kadaster*, which is a government-maintained public register of registered property. (Too much method?)

Sunlight and shade

The most significant variable for deciding plant species is the sunlight and shade that shines or is casted on the facade in question. Facades that do not get any sunlight throughout the day can still be greened, but only by using species that survive those circumstances. For example, moss walls thrive in shaded areas and do not survive in direct sunlight. If the facade does receive sunlight, the amount of sunlight is still a variable that should be looked at. All the botanists I spoke with see this as the main variable to look at when deciding the right species for vertical greening. Usually, a distinction is made between full, half and no sunlight. 'Full' is when a façade faces south, 'half' when facing east and west and 'no' when facing north.

Wind and drought

Next to sunlight and shade, other natural conditions influence plant species selection as well. Mainly wind is seen as a significant parameter. The wind itself can be detrimental to certain plant species when plants are exposed to too much wind. Therefore, it can exclude the possibility of using certain species on windy locations. Next to that, wind direction influences the way rain falls. Because in Amsterdam the wind generally comes from the South-West, the North-East side of buildings are usually the driest. This is less of an obstacle because watering can be manually increased.

3. Methods

Throughout this study several methods are used. The method used to answer the second research question is a GIS-based multi-criteria analysis of chosen environmental factors in. From this, the case study locations derive, and one of them is used during the third and fourth research questions. The method used to answer the third research question is a more detailed exploration of the local situation present at the case study locations. During that method, the selected relevant aspects are assessed to see if they allow vertical greening in general. The last research question is answered not only based on data but also by consulting experts and the relevant stakeholders present in the case study location. These three questions and methods make up the three steps that can also be seen in the theoretical framework. To work with these methods, other preparative steps are required. The data necessary to execute the methods needs to be collected and edited before it can be processed and analysed. The stakeholder interviews are elaborated in the end of this section.

3.1 Vertical greening in Amsterdam

The research takes Amsterdam as the municipal case study. This is because of multiple reasons; foremost because I live and study in Amsterdam and am therefore familiar with the city. The municipality of Amsterdam also has a lot of data available. Next to that, the dense urban fabric of the centre of Amsterdam makes for an ideal case study. Furthermore, vertical greening corresponds with the climate agenda of Amsterdam. For that reason, policy documents on relevant subjects should be studied to know what the goals of the municipality are and what initiatives and practises are already in place. Problems that the municipality addresses as urgent will be used to substantiate the necessity of the proposed method of greening.

A municipal goal of Amsterdam is that in 2050; buildings have roofs with plants, vertical gardens, green facades with climbing plants and they are attractive to insects, bats, and birds. The greenery on plots and buildings helps to reduce the temperature in the city on hot days and reduces the burden on the sewers during heavy rainfall. Especially in places in the city that are paved and where there is little shade, we encourage greening of facades, roofs, and gardens. In this way, cooling can be provided naturally. Rainwater can be collected in the courtyard gardens, front gardens and facade gardens and used for gardening (Gemeente Amsterdam, 2020).

The municipality aims to set a good example by paying attention to nature inclusiveness in the development, design, and management of municipal real estate. Renovations and new buildings are carried out in a nature-inclusive manner. For example, by constructing green roofs, facades, or courtyards, or by making alterations to a building that benefit its biodiversity.

An initiative that should start setting this good example is a motion that was submitted by the PvdD (Party for the Animals). The motion proposes the greening of the façades of some 135 buildings belonging to the municipality of Amsterdam. This can yield in total more than 33,000 m2 of extra green. To test it out, a pilot for 10 facades has already started.

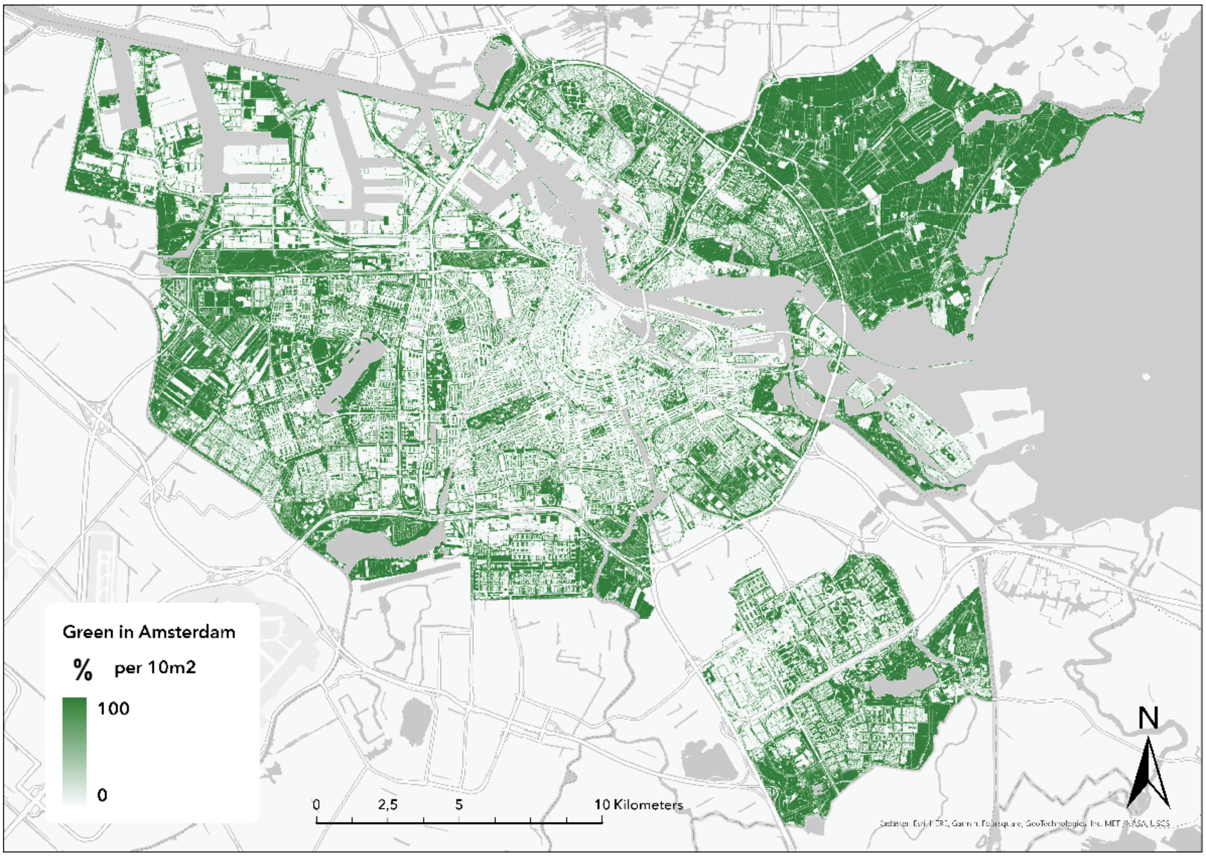


Figure 7: Map of green in Amsterdam on 10m2 resolution

Overall, there is a lot of green in Amsterdam. But as can be seen in Figure 7 the amount of green quickly reduces as building density grows towards the centre. There are some green facades already present in the city, but unfortunately, they aren't mapped. Therefore, that cannot be used as input for the green deficiency index, which could indicate where green facades are most necessary. The municipality does map the presence of façade plants, which are present a lot on the quay walls.

The figure does not show what the ratio is between public and private green. This may be quite misleading, because a large part of the green area present, especially in the centre of Amsterdam, is part of private gardens. This is due to the morphology of the buildings in the centre. The building blocks results in small green spaces that are private and disconnected from other green areas. As a result, the chopped green patches and sequestered on the ground level, while on aerial level it may seem like there is an green network present in the centre (Mumm et al., 2022). To create connections between these green areas, facades and roofs should be greened in between them.

3.2 Data collection

For the multi criteria analysis method to be applied, a variety of geo data about environmental, spatial and other aspects in Amsterdam must be collected. This will mainly be done through the open data from the municipality of Amsterdam. But additional sources have been used as well in order to collect specific data. Table 2 shows all the data used and from where it has been collected. Gathering the data is divided in the same three sections used in the theoretical framework (Figure 4); *where?, suitability of facades?*, and *how?.*

Where?

The data collected for *Where*? is used as the input for the data-driven case study selection process. This is retrieved from the municipality, the National Institute of Public Health and the Environment (RIVM), Open Street Map (OSM), the Climate Effect Atlas (KEA) and the Netherlands Environmental Assessment Agency (PBL). Only the data about water depth on streets after heavy rainfall had to be requested, all the other data was open to download. Data about the additional aspects is retrieved from the municipality. Data to substantiate the case study selected is also retrieved from the municipality. Data about property owned by housing corporations is publicly available to download on the site of the municipality. Data about the municipal owned property had to be requested at the real estate management department of the municipality.

Material	*Category*	*Step*	*Purpose*	*Source*
Borders	*Shapefile*	*-*	*Is used as input for the spatial constraint*	*maps.amsterdam.nl*
Heat stress	*Raster data* *10M Res*	*Where?*	*Is used as input for the urbanisation related pressures*	*RIVM*
Noise	*Shapefile*	*Where?*	*Is used as input for the urbanisation related pressures*	*maps.amsterdam.nl*
Verkeers-prognose	*Polyline data*	*Where?*	*Is used as input for the urbanisation related pressures*	*maps.amsterdam.nl*
Water depth after heavy rainfall	*Shapefile*	*Where?*	*Is used as input for the urbanisation related pressures*	*KEA*
Greenspace	*Raster data* *10M Res*	*Where?*	*Is used as input for the green aspect of the BGI*	*RIVM*

Water	*Shapefile*	*Where?*	*Is used as input for the blue aspect of the BGI*	*OSM*
Density	*Shapefile*	*Where?*	*Is used as input for GSI and FSI values*	*PBL*
Municipal property	*Shapefile*	*Where? / Additional Indicator*	*Is used as additional data to base case study selection on*	*Private data*
Housing Corporations	*Shapefile*	*Where? / Additional Indicator*	*Is used to determine the presence of property owned by housing corporations*	*maps.amsterdam.nl*
Monumenta l valuation	*Points*	*Suitability of facades?*	*Is used to determine the monumental value of a building*	*maps.amsterdam.nl*
Facade composition	*-*	*Suitability of facades?*	*Is used to determine how much surface of the façade is greenable*	*Field Work*
Plinth accessibility	*Shapefile*	*Suitability of facades?*	*Is used to determine the function of a building*	*Field Work/ maps.amsterdam.nl*
Pavement width	*Polylines*	*Suitability of facades?*	*Is used to determine which type of VGS is suitable*	*maps.amsterdam.nl*
(State of) Facade material	*-*	*How?*	*Is used to determine what type of VGS can be applied*	*Field Work / maps.amsterdam.nl*
Ground material	*Shapefile*	*How?*	*Is used to determine possibility of soil-based greenery systems*	*Field Work*
Sunlight / shade	*Solar Radiation Toolset*	*How?*	*Is used to measure amount of sun irradiation and shade*	*Cardinal direction / Field Work*
Wind/ drought	*Raster*	*How?*	*Is used to determine what type of plant should be applied*	*Global Wind Atlas / Cardinal direction*

Table 1: Data used in study

Density

Data about spatial density is collected from the research done by Habers et al., (2019) on '*Spatial densities and function mixing in the Netherlands'*. In this research information on all types of spatial densities has been collected and made public for usage. The dataset is called 'RUDIFUN' which is an abbreviation for the research title in Dutch. The data provides data on density with multiple ways of scale measurement. Bruto and netto values are given for block, neighbourhood (buurt), wijk (area) and district. The scales are levels of detail. The difference between bruto and netto is that netto only takes the building parcel as floor area. Bruto density data is collected for the processing. Bruto takes the surrounding street and pavement into account as well. Which results in an average spatial density of an area instead of the building parcel. This is necessary because this study focusses on the public space that can be enhanced by green, not the building itself. And the spatial density surrounding that public space needs to be incorporated.

Case Study Data

Secondly, data about the suitability shows the general potential for vertically greening the facades present in the chosen target locations. This section is called '*Suitability of facades?'*. The data about the suitability was retrieved from the municipality, except for the façade composition. This is the first three-dimensional variable, and the first variable for which currently no data is available and therefore requires field work to obtain the data. In total five aspects: facade composition, plinth and material, ground material and sunlight/shade require field work. Municipal data about the function in the plinth of buildings gives an indication about the accessibility of the plinth. But does has to be verified with field work. When a case study location is chosen, and the suitable facades have been determined, a field trip is made to examine the facades at hand and collect necessary data.

Lastly, data about the local conditions of the suitable facades is collected. Data about the façade and ground material are collected through field work. Data about the year of construction, which gives an indication of the state of the material, is retrieved from the municipality. The sunlight/shade and wind/drought are both mainly dictated by the cardinal direction in which the façade is facing, and therefore require no data collection. Field work is required to find out if there any obstacles which cast shade on the façade, such as trees. Additional data on wind speed is retrieved from the Global Wind Atlas.

3.3 Data processing

3.3.1 Where?

To find the target locations, the data that has been collected about the environmental factors has to be processed in order to be able to combine the data. An overview of the processing steps can be found in Appendix 2.

Some of the data covers not only Amsterdam but additional areas as well. To make future processing easier, all datasets that contains information outside of Amsterdam are clipped (A1). All data on the selected aspects needs to be transformed to raster data (B1) if it was not acquired in that format. This is because strictly raster data can be used as input value for the 'Zonal Statistics' (C1) operation which is performed later. The output cell size of the rasters is set to 1 because only then it is detailed enough to be translated properly later in the process. Setting the output cell size any lower would have no additional value because there are no datasets provided with a finer grid size.

Traffic

The data used about noise and air pollution are based on traffic data, the two have been merged to compromise their influence on the combined indicator map. This is because both datasets represent the same source, which is the traffic. They have been combined by adjusting the maximum value of the aspect in a later step (D1). Before that, the datasets are both transformed to raster data. The traffic prognosis is done on streets, and therefore the data is presented as polylines. This is done by 'Feature to Raster' (B1). The output cell size of the raster is set to 1 for the traffic prognosis data. A cell size of 1 is necessary because it must match the detail of the other rasters which are going to be used as input. The same is done for the noise pollution data. This is a polygon instead of a polyline but is can also be transformed by the 'Feature to Raster' tool (B1). The output cell size is set to 1 as well.

Biodiversity

Data about green space shows only where green space is, and the density of it. A lot of places do not contain any green at all, and therefore are not included in the raster. These places are the places that should specifically be included in the process, because they lack green the most. To use this, a process that will convert 'NoData' to a value will be executed later (C5). Also, water is a space that lacks green but does not suffer similar climate stress as the areas on land. In fact, the presence of water supports cooling and biodiversity and therefore decreases the need for additional greening. If data about water is not added, water will be registered the same as land without green. Therefore, water surface data is added to the green space raster.

Water is added by converting water polygon data to a raster (B1). Secondly, the water raster must be merged with the green raster. The green raster is valued from 0 to 100. When the water is merged, it should receive a numeric value of 100 and not just any other value. Water is present or not, and not rated based on its density. Therefore, all water should be assigned a constant value. This is done by transforming the given values in the 'Raster Calculator' with the 'Con' tool (C1). Next, the green and water data are merged by 'Mosaic to New Raster' (C2). The greenspace raster and water grid (edited in the previous step) are used as input rasters. A cell size of, once again, 1 is selected. The number of bands is also set to 1. The mosaic operator is set to 'last' so the water data, which was added last as input data, is what becomes the value where the rasters overlap.

Density

First, both the FSI and GSI datasets are clipped (A1) because they contain the entirety of North-Holland. There were some errors in the FSI dataset, some of the values were unrealistically high. Some fields had values of over a thousand. Such a value implies that there is a thousand story building present in Amsterdam. To make sure I was not unaware of any new high rise, I checked the strange values. This was done by sorting the FSI values in a descending order, showing the highest values on top. When zooming in on these values, it shows that they are all little circles with out of proportion high values. Because this study focusses on the dense centre of Amsterdam, high rise surrounding the city with very high FSI values do not have to be considered. To filter this, all values above 5 are given the value of 5. This is a minor adaptation because only 0,01% of the dataset exceeds a FSI value of 5. It is done by selecting all rows in the FSI table that exceed a value of 5 and changing their value in the attributes pane. The GSI data required no adaptations. Both datasets are transformed into raster data (B1).

Extent

Not all the datasets have the same extent, i.e., the extent of the data provided by the RIVM spreads over the entirety of the Netherlands. Datasets that are too big can easily be clipped. Datasets that only contain information is a specific part of the municipality require another approach. When finally combining the rasters in the final step, cells that have 'NoData' as value in one of the rasters are excluded in the combination process. This results in a map that only shows the raster cells of the smallest dataset, which is the traffic prognosis, which only includes streets. So, the following step is to take out empty values. This can be done by the processing tools 'IsNull' (C4), which finds the 'NoData' values and 'Con' (C5) which changes them to a numeric value of zero. By doing this, the final combined indicator map shows the sum of all values in every part of the grid. An important note is that the processing extent of 'IsNull' must be set to the desired target area. It is automatically set to the extent of the input raster. Which is no problem in this case because the dense urban areas are the focus so areas on the border of the municipality can be neglected.

Normalization

After that, the rasters should be normalised, this is done through the 'Rescale by Function' (D1) tool. Rescaling changes the minimum and maximum value of a raster to zero and ten, instead of whatever it was before. This is done so that the indictors can be combined and all score from 0 to 10. The transformation function is set to 'Linear'. During this step, weighting can be assigned to aspects. This is done by scoring aspects for half as much, which in this case leads to a maximum value of 5, instead of 10. This certain weight is based on the indicator being combined with another indicator, which is also representative of the same source. Because the source needs to be represented as a full indicator, scoring both combined indicator's half produces a full score for the combined indicator. This is for traffic, existing out of noise pollution and traffic prognosis, and spatial density, which is made up of GSI and FSI. Only FSI is not rescaled because it already had a maximum value of 5.

After being rescaled, the BGI data needs to be adapted before it is eligible for the final step. An inversion is needed: originally, the value in the dataset goes up as the density of green increases. For the data to work as an indication of the lack of green, the values need to be inverted. So that the value goes up as the amount of green decreases. This can be done through the 'Raster Calculator' (D2). The formula written to get this result is*: (("Rasterlayer" - Max_value) * -1) + Min_value*, which is my case is: *((“Rescaled_BGI" -10) * -1) + 0.*

Zonal statistics

Finally, the data will be transformed into a hexagonal grid. The input grid is produced by the tool 'Generate Tesselation' (E1). It creates a grid, optionally hexagonal, which can be further used to transform data with. Hexagons are chosen because their circularity allows them to represent curved patterns better than square grids (ArcGIS Pro, 2007). The surface area set for one hexagon in the grid is 1000 square metres. This means that each side of the hexagon is 19.5 metres long. Such detail is necessary to be able to see variation in values within different parts of a street. The hexagon grid will be used to define the zones during 'Zonal Statistics as Table'(E2). The values of the input rasters are calculated for each hexagon cell, which have a GRID_ID assigned to them. The statistics type used in the Zonal Statistics as Table is 'mean'. This means that the average of all cells in the value raster that belong to the same zone as the output cell will be calculated.

The tables that are the output of the previous step are combined by joining them all with the attribute table of the hexagon grid layer. This is done by 'Join Field', which joins specified fields from tables. The 'mean' field of every output table is transferred to the hexagon grid table based on the common GRID_ID. These individual mean scores can be summed up in the 'Calculate Field' tool which adds the sum as a new column in the attribute table of the grid layer.

Target areas

These steps results in a map showing all the aspects combined. There are five aspects (two combined aspects) which results in a maximum value of 50. The output map gives insight into which locations in Amsterdam endure the combined highest value of the chosen aspects. These locations are seen as target areas, because they are the areas that would benefit the most from vertical greening. Based on this and additional aspects, case study locations are selected. These methods are further elaborated in the following section.

3.3.2 Case study selection

The initial case study area is the entire municipality of Amsterdam. The research objective considers dense built areas. These are often located in, or directly around, the historic centre of cities but are not confined to the centre. Therefore, data has been collected for the entire municipality. This is because the spatial density of areas is incorporated as an aspect in the multi criteria analysis, which produces the target areas.

Stakeholders

A great percentage of property in Amsterdam is privately owned. Almost sixty percent is privately owned or rented out. Especially in the centre, only 25% is owned by housing corporations (Nul20, 2022). It will therefore be a very restricting filter to apply to the case study selection. But despite this, the stakeholders that this study will be focussing on are non-private owners. This is done because it is harder to get in contact private stakeholders, especially if the case study contains property of multiple different owners The two main public institutions that own the largest amount of property in Amsterdam are housing corporations and the municipality. These institutions will be targeted because they are easier to get in contact with and interview than private owners. Data about housing corporations can be retrieved from the municipality of Amsterdam. Oddly enough, data about municipal owned property cannot be publicly retrieved from the municipality. This is retrieved through getting in contact with the municipality.

Selection process

The case study selection will be based on a combination of the results of the multi criteria analysis which shows where in the city vertical greening is most necessary and the locations of property owned by the municipality and housing corporations. Ideally, property owned by these institutions is present in one of the highest scoring areas. If not, municipal or housing corporation property that scores highest will be selected. Several other aspects could be taken into consideration when selecting a case study. For example, the initiative from the municipality of Amsterdam, mentioned in 3.1 Vertical greening in Amsterdam, has used the condition and aesthetical value of buildings as well to base their selection on.

When the case study location is chosen, the second step of the data-acquisition and processing begins. Aspects regarding the suitability and conditions of facades should not be considered beforehand. This could lead to confirmation bias because of the will to find vertical surfaces that have the most potential for vertical greening. To get a realistic picture of central Amsterdam's potential for vertically greening, facades that may not be fitting for VGS at all, are incorporated in the research as well.

3.3.3 Suitability of facades?

The second data processing step further investigates the chosen case study locations. Characteristics of the facades in that area give insight into the potential for vertically greening the area. This is done by evaluating the suitability of the facades for vertical greening based on those characteristics. Practically every façade could be greened, but this study focusses on the suitability for vertical greening, not the possibility. Four aspects are selected that indicate whether a facade has the possibility to be vertically greened. These aspects are elaborated and substantiated in section 2.2.2. In this section, the methods for collecting the data and analysing the aspects in GIS are explained. For every aspect, values are picked that divide the aspects into two options: suitable or unsuitable. In some cases, this distinction depends on the type of system that is to be installed. For example, if the pavement width in front of a façade is very narrow, there is no space available for a green façade, but a living wall could be applied.

Monumental valuation

The municipality of Amsterdam has a database which consists of all buildings that are monuments in the city. The monuments are divided into ownership, there are municipal and state-owned monuments, but in this study, this division is not considered. If a building has a monumental value, it is eliminated from the process. The data only must be imported into ArcGIS. No further processing is required.

Pavement width

The municipality also has a dataset about pavement width available. It does not include the entire centre of Amsterdam but a very large part of it. The width is classified in seven classes: smaller than 0.6m, 0.6 to 0.9m, 0.9m to 1.8m, 1.8m to 2.2m, 2.2m to 2.9m, 2.9m to 3.6m, and 3.6m or wider. Because the municipality stipulated that the free passage space on the pavement must be at least 1.8m, every pavement wider than 1.8m is included. Again, no processing is necessary after importing the dataset.

Plinth accessibility

There is no specific data about the plinth of a facade available. Therefore, on-site analysis is required for accurate data about this variable. The initial suitability of this aspect is based on the function of the plinth. This dataset does not require processing as well. Additionally, if there is a fire exit, garage door, glazed surface or storage for bins that prevent vertically greening the façade, it is listed as not suitable. Data on those possible obstacles is retrieved through field work.

Façade composition

The façade composition is one of the trickiest aspects in this step. Unfortunately, there is currently no data available about this aspect. This is because such detail is still too complicated for 3D models to be automatically generated. The level of detail that is currently available for buildings in Amsterdam goes up to 2.3. And as discussed, the level of detail that contains data about the façade composition is only included from 3.1 and up. Thus, field work is required to obtain data about the surface area of windows and doors on a façade. The areas of the surfaces are measured on pictures taken on the case study location. There are two significant aspects within a facade composition, these are the amount of window surface and the depth of a facade. A completely flat facade makes most forms of vertical greening a lot easier. If a facade is filled with ornaments and curving surfaces, vertical greening becomes harder. Next to that, if a facade almost entirely exists out of windows, there is little surface area left to green. Therefore, if a façade is covered in glass for more than 75%, it is classified as unsuitable. This percentage isn't based on any literature but is taken as a test value.

If it turns out that this value is too high or too low, it can be adapted in further studies. Only if a facade is reasonably flat and has less than 75% window coverage, the façade is classified as suitable.

When all data is imported into ArcGIS, each aspect of every façade is listed in a table containing all case study facades. If all aspects are found to be suitable, the façade is chosen and used in the last processing step. The suitability of the aspects is assessed through the mentioned yes or no distinction made for each aspect. When the data is imported into ArcGIS, it is immediately in place. Therefore, no processing is needed, the data just needs to be analysed for each façade. The monumental value is visualized as a dot on a building, if there isn't any dot, the building is suitable. The pavement width is visualized as a coloured line, the colour of the line represents the classification of the pavement width. If it exceeds 1.8m, the adjacent façade is labelled as suitable. Plinth accessibility is initially represented by the function of the building. Field work shows the actual accessibility of the plinth. If one the mentioned characteristics is present, the aspect is labelled as unsuitable. The façade composition is measured as described in the previous paragraph. The table and figure underneath give an example of how the selection process looks like.

Building	Monumental value	Pavement width	Plinth accessibility	Facade composition	Suitability
Street name	Y / N	< 1,8M = Y > 1,8M = N	Y / N	Y / N	Y / N

Table 2: Example of facade selection process

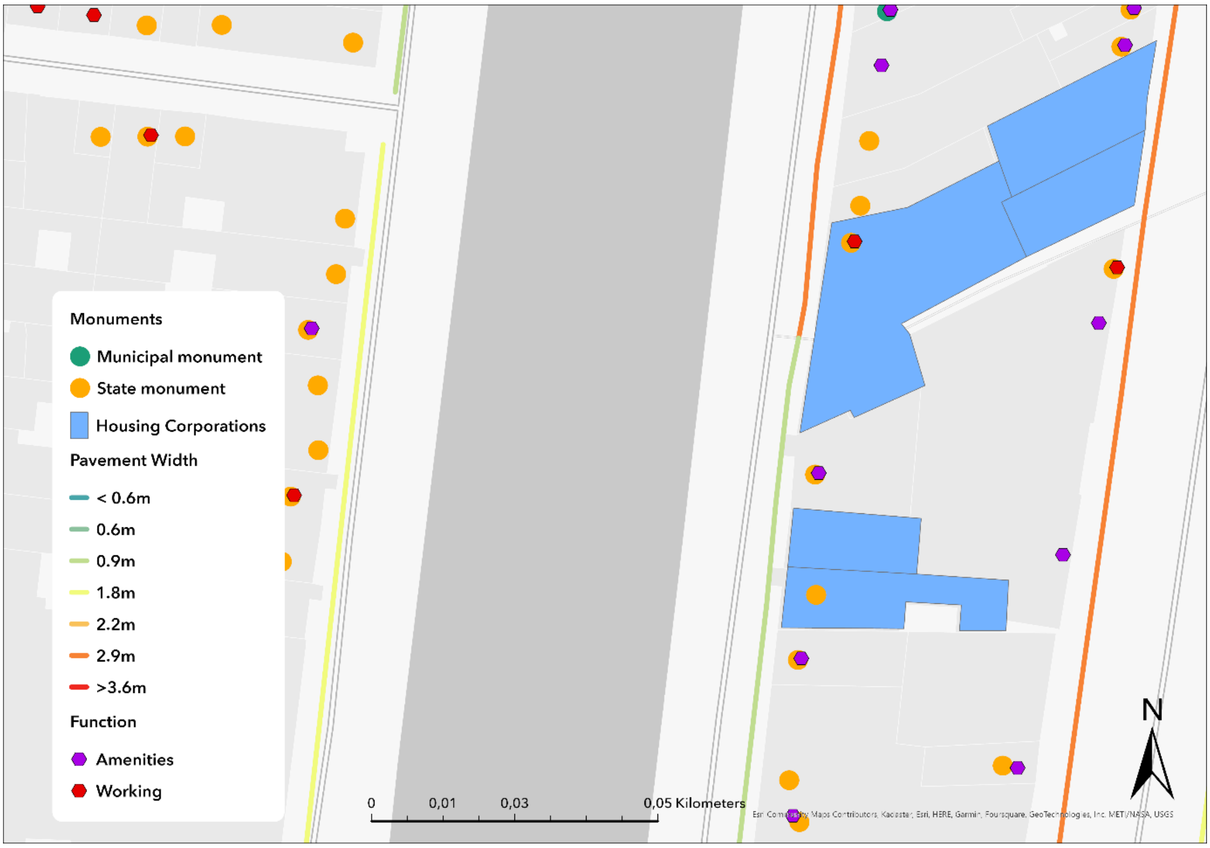


Figure 8: Example of aspects in an area

3.3.4 How?

The third data processing step is applied to only the facades that are found to be suitable for vertical greening during the previous step. The final step examines the conditions of the façade and its environment. The façade and ground material indicate what type of mounting system is most suitable for application. This is done by looking at the aspects that have direct influence on the support system for the vertical greening system, which are the façade and ground material. These connections can be seen in Figure 6. Next to the mounting system, the plant species are also decided in this step. This decision is based on the two final aspects, which are: sunlight and shade, and wind and drought. These aspects mostly exclude species from the selection that are not able to grow in certain circumstances.

(State of) Façade Material

Most facades in the centre of Amsterdam are made from brick. Some of the newer buildings may differ in façade material but a lot of the newer architecture also uses brick to fit within the architectural context. Not only the general material is determined but also the state of the material. The year of construction is used to assess the weathering of the façade material, this is not certain because the maintenance performed on a façade varies. The façade material of the case study facades is detected trough field work, which also gives more insight about the state of the material. No processing of data is necessary.

Ground

The ground adjacent to the façade is also assessed during the field work. The result of this can be paved or open. Data about the soil material is not available. There is data available about soil quality, but it is not detailed. Requesting a *klic-melding* is possible but is not available for free. This leads to a low amount of accessible or available data on soil. Therefore, it is not possible to assess the suitability of the soil.

Sunlight and shade

The amount of sunlight a façade receives is mainly determined by its cardinal orientation. The distinction between south, east, west and north is made which leads to a façade receiving full (more than six hours), half (between three and six hours) or little (less than three hours) direct sunlight. Additionally, obstacles, such as trees can be present near facades which block the sunlight from shining on the façade. These should be considered as well to check the actual amount of sunlight a façade receives. The orientation of a façade can be obtained through desk research. The presence of obstacles is checked during the field work.

Wind and drought

The impact of wind on a façade is also partly determined by the cardinal direction the façade is facing. This is because wind direction influences the drought of a façade as well. This is determined by the direction the wind is blowing. In Amsterdam, wind usually blows towards the north-east, and therefore also causes north-east facing facades to be the driest. Next to this, the speed of wind that a façade endures can also be measured. This is mainly determined by the height of a building. Data about this is available to download from the Global Wind Atlas. It only provides data on a height of 10, 50, 100, 150, and 200 metres. Only the 10-metre height is usable due to the common building height in the centre of Amsterdam.

System selection

The first distinction to make is between a living wall and green façade. This is based on the state and material of the façade and adjacent ground. The type of structure and its load-bearing capacity can be restricting for the heavier types of systems. This can be assessed by the year of construction of a building, which gives an indication about the state of the material. The possibility of installing certain systems can be prevented if the state of the façade material is in bad condition. The decision about soil-based systems or planter boxes is based on the ground adjacent to the facade. If there is an opening in the paving, soil-based systems can be installed. A permit for removing tiles of the paving can be requested but, in this study, the current situation is considered.

There are sub-types within a system type. I.e., indirect green facades can consist of different types of support for the climbing plants used in the system. Because living walls are significantly more expensive, require more maintenance and space, they do not fit the type of application that is proposed in this study. Therefore, only direct, and indirect green facades are considered. The support systems indirect green facades have also come in a variety of forms and materials, there are mesh and modular trellis systems, wire and cable systems, timber supporting systems and hybrid systems. The usage of steel is commonly preferred over wood and plastic due to its strength, wind-resistance, strength, and easier maintenance. But the decision between these systems is mainly based on the plant species which they support. Therefore, the plant species is selected first and secondly a fitting support system is allocated.

Plant species selection

The selection of possible plant species is initially based on the last two aspects of the local condition: sunlight and wind/drought. These aspects eliminate a lot of possible species and therefore functions as a pre-selection of what general types of plant species can be used in a location. Because living walls are excluded from the selection, only climbing plants are considered. This also substantially reduces the number of available species. In tropical areas, there are between 300 and 500 usable climbing species, this is around ten times less in Europe (Köhler, 2008).

There are a lot of other aspects to consider when selecting plant species. The capacity to mitigate climate related urban problems varies between species. But the system in which the plants are placed can also influence its mitigation capacity i.e., insulation and cooling capacity are greatly affected by the type of system. Mainly living walls have significantly more cooling and insulation capacity than green facades, but since they are excluded from the selection, there is less deviation in the capacities of available systems.

Furthermore, the land of origin, contribution to biodiversity, if they are evergreen, if they produce edibles, and when and in which colour species bloom all varies. The maximum height the plant can grow to differs as well, and if an entire façade is to be greened, it should be considered. Planter boxes could be installed vertically along the façade which would enable smaller species to cover the entire façade as well, but this is more expensive and requires more maintenance. Native climber plants grow the best and produce the biggest amount of leaf surface area. The leaves of climber plants are mostly responsible for the environmental benefits these plants have. Information about these characteristics is collected for all species that could be applied. Which species are possible for application is dictated by the climate and market. In this study, the actual availability of species is not verified. A selection of suitable climber plants is taken from a local source to ensure the species are fit for the climate in which they are applied.

The municipality of Amsterdam has created a guide for creating a green façade with climbing plants. It provides a selection of 24 species that can be used in Amsterdam's' climate (Table 5). They are divided into four types of climbing plants, which are: twining, tendril, scrambling and clinging. The biggest difference between these is that the clinging species are self-adhesive and therefore don't require any support system at all. Further characteristics such as its land of origin, contribution to biodiversity, potential height and if the plant is evergreen are listed. Information about required watering, cooling, and filtering capacities are not listed. If this is to be taken into account, additional sources and input from botanists is required to substantiate such considerations.

Additionally, all plant species in the municipal guide contribute to biodiversity, but in differing ways. There are three significant ways in which a species can contribute to biodiversity based on the municipal climber plants guide. The species can produce food for insects (I), it can produce food for birds (B), or it can be suitable for birds to build nests (N). Which biodiversity traits species possess can be seen in Appendix 3. The preference of the residents regarding these aspects is asked during the interviews.

Finally, the residents of the selected case study are contacted to ask them if they are interested in a green façade and which type of plant species they would prefer and why. The main characteristics species can have will be listed and asked if they prefer that or not. Some people might like an increase in biodiversity, and some might not like the idea of more insects. The combined results of these questions will lead to a plant species that fits their preferences the most.

3.4 Case study interviews

To summarize the previous section; there are many ways in which a vertical greenery system can be realized. The goal one aims to achieve by installing such a system mostly dictates what form the VGS will take. Because the goals of the stakeholders often do not entirely match, all goals from different stakeholders should be considered when deciding on the form of VGS. The main stakeholders are usually the owner of the building, the resident, and the legislative organization, which can be the municipality or management of an area. When it is clear what the priorities, preferences and goals of the stakeholders are, they are analysed and compared. But to get these insights in the first place, interviews with these stakeholders must be conducted.

The interview with the owner concerns the interest of the owner in vertical greening, the feasibility of implementation and their reasoning. Non-private owners are targeted in this study, which can be contacted by using public contact details. Private owners may be harder to get in contact with. The legislative organisations are also public and therefore easy to reach out to. The interview with the municipality is about the municipality's agenda concerning vertical green in the centre of Amsterdam. And finally, interviews with the residents are about their possible interest in a green façade and their preferences regarding the characteristics and aesthetic of the vertical greening. The interviews with the residents are structured. This is done to be able to easily distribute the questions and compare the answers. A survey is made which the residents can fill out online or with my assistance in real life. The other two interviews are semi-structured. The results are presented in Appendix 7.

4. Results

4.1 Where?

To answer the question: *'Where in Amsterdam is vertical greening most necessary?'*, a multi criteria analysis was performed which includes the urban problems that can be mitigated by VGS listed in section 2.1.1. The output of this process is a map showing the total sum of all the aspects of these urban problems.

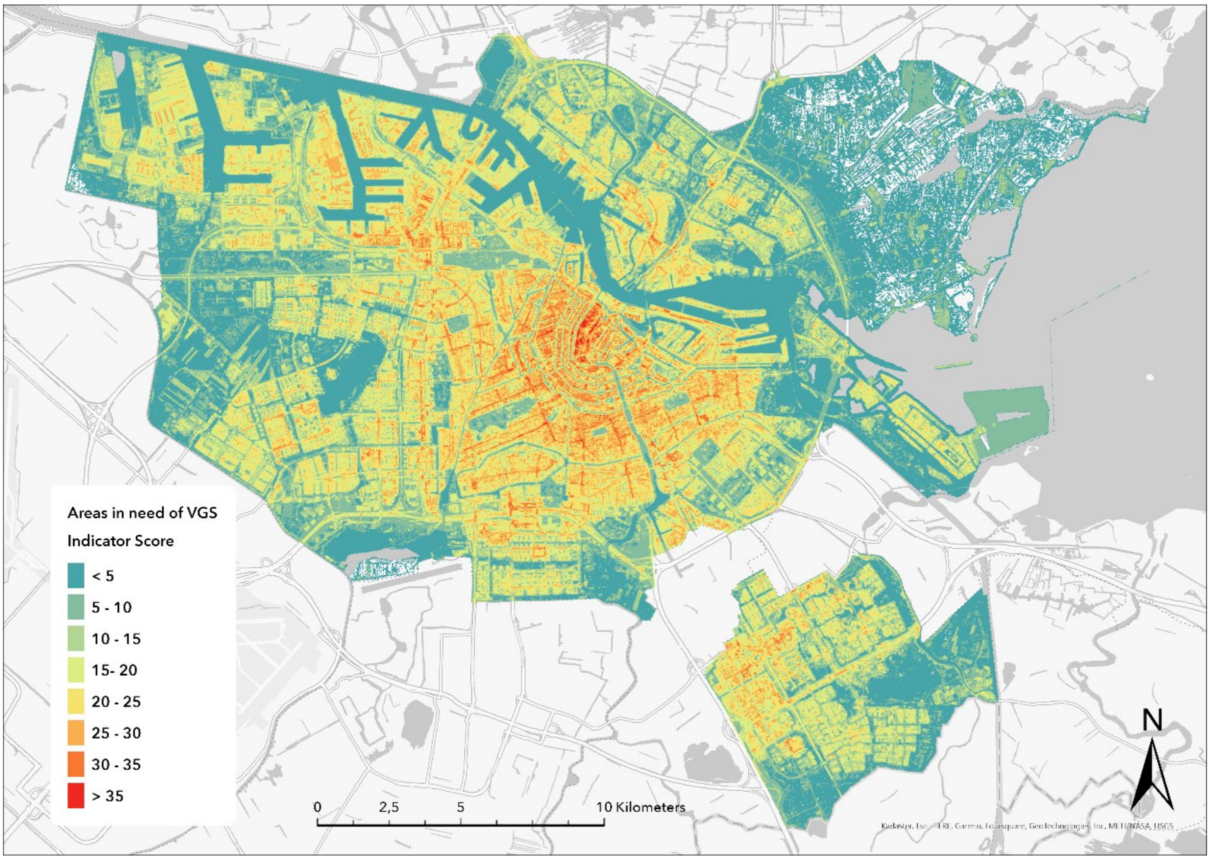


Figure 9: Areas in need of VGS map

The classification of the values is a custom division into 8 classes. In the map it is clearly seen that some of the environmental factors heavily influence the outcome of the map. The traffic prognosis and the noise pollution data both highlight some of the roads. The outline of building blocks and spatial density can also be recognized in the map. This is because the higher the spatial density is, the higher the heat stress and lack of green becomes. For these reasons, the streets surrounded by dense built areas can be seen standing out as the highest scoring locations. These highest scoring locations are the target areas and are used in the case study selection process.

The combined maximum value is 50, but there are no cells that contain a full value of all aspects. The actual maximum value is 40,3. Only two hexagon tiles score over forty, both are on the Damrak, a busy road from the Central Station to the Dam square. The Spuistraat and the Nieuwezijds Voorburgwal are the second and third highest scoring streets. Both close to the Damrak. This shows that the centre of Amsterdam is in the most need of VGS.

4.1.1 Case study selection

The case study area will be somewhere in the centre of Amsterdam because the areas that are in most of need of VGS are in the centre. Because the combined aspects scores are the highest in centre, the filter on the score can be raised. The values have been edited to only display values higher than 33,0. Additionally, the presence of property owned by housing corporations and the municipality is added to the map to see in which target areas within the centre they occur the most. There are 1466 buildings owned by housing corporations and 179 buildings owned by the municipality in the centre.

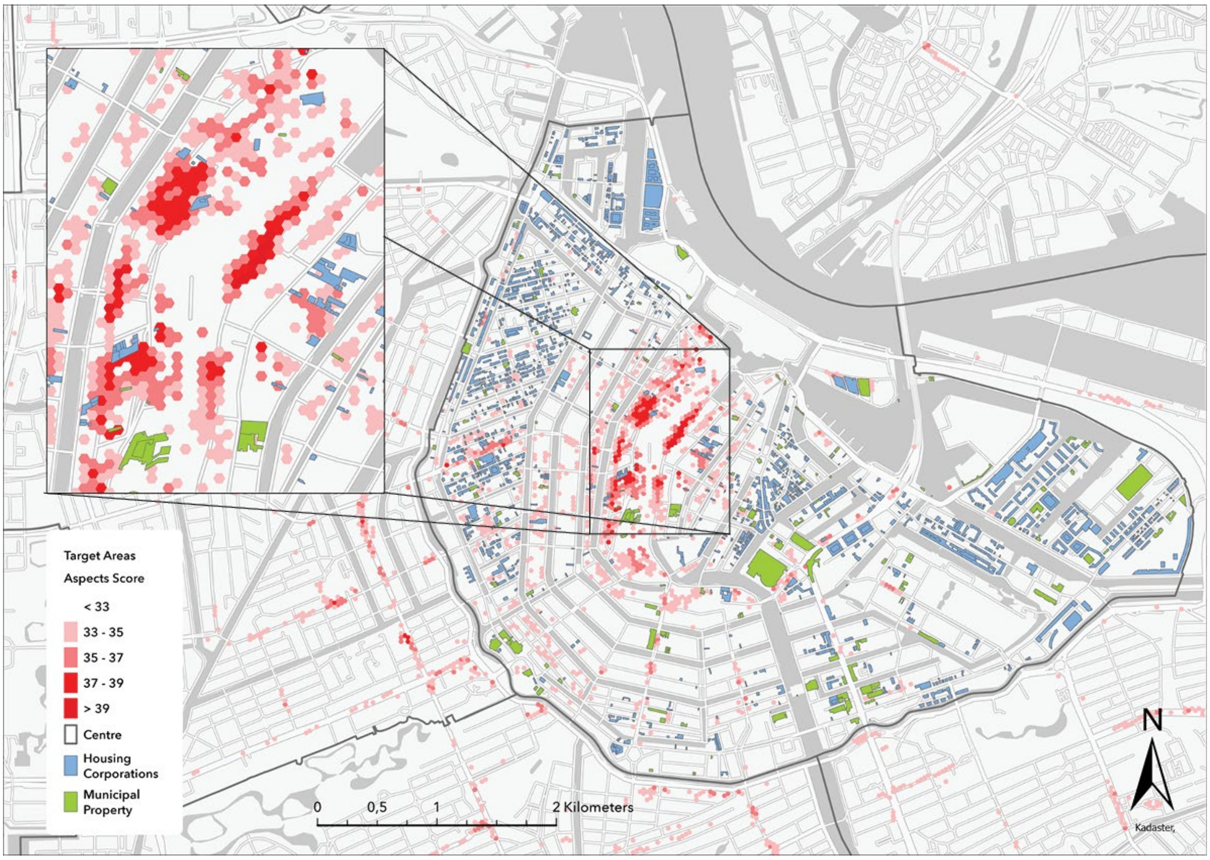


Figure 10: Target areas in centre of Amsterdam and non-private owned property

The target areas do not occur everywhere in the centre, but mostly around the main roads in the historic centre. Unfortunately, in this area very few buildings owned by housing corporations, or the municipality are present. To select the best locations, it is required to zoom in on the historic centre. If there is any property present within the target areas with the highest aspect score, that will become the case study. If that is not the case, the property most near to the highest aspect scores will be selected.

A large part of the Spuistraat is a target area and there is property present owned by housing corporations and the municipality. Compared to other target areas, quite a lot of non-private owned property is present in this area. Some property owned by Ymere borders these high scoring zones. Their property is located on both sides of the Spuistraat and the Nieuwezijds Voorburgwal. Next to that, some municipal owned property is near present at the Nieuwezijds Voorburgwal as well. This area can be seen as one target area. Not all facades are next to each other, but they do face the same streets. These buildings will be the case study. Only buildings with facades that are publicly accessible from these streets will be used in the case study. The buildings of Ymere on the Paleisstraat are left out because the street is a part of the target area. The same goes for the buildings located on the Singel. Lastly, there is a municipal owned stand within the target area which can be seen in Figure 13. Despite this being inside the target area, it is a small wooden stand with a little amount of façade surface. Therefore, it will not be included in the case study.

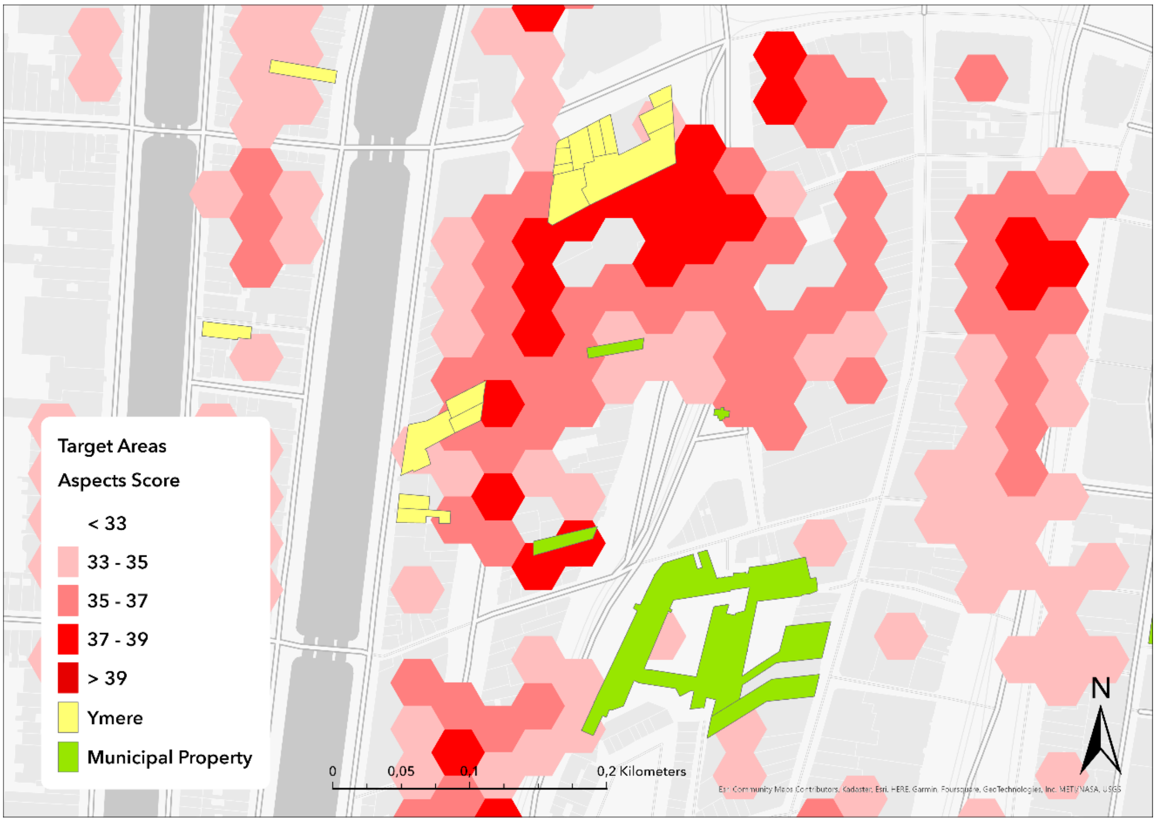


Figure 11: Target area at Spuistraat

Figure 12: Nieuwzijds Voorburgwal 277

Case Study: Ymere Property

Figure 13: Ymere Property

Figure 14: Spuistraat 131 – 137

Figure 15: Spuistraat 189

Figure 16: Nieuwezijds Voorburgwal 228 – 238

Figure 17: Spuistraat 236

Figure 18: Spuistraat 234

Case Study: Municipal Property

Figure 19: Municipal Property

Figure 20: Nwz Voorburgwal 270

Figure 21: Nwz Voorburgwal 296

Figure 22: Nwz Voorburgwal 357

4.2 Suitability of facades?

Data on suitability is collected to find out if facades have the possibility to be vertically greened. This is done for the selected case study. The case study area consists of one building block and two buildings further down and on the other side of the Spuistraat. The buildings are numbered in a table which lists their attributes as well. Field work is performed to obtain the data that could not be retrieved any other way. Pictures are taken to capture the data about the aspects. An overview of the results is shown in Table 3. Additional results per aspect are written out below.

Monumental valuation

Monuments are very common in the centre of Amsterdam. So, it is no surprise that a lot of the buildings in the case study area are monuments. There are a couple of the buildings that are no monument. 8 of the 14 buildings are monuments.

Pavement width

The municipal regulation for minimal width of a pavement is 1,8 metres. Therefore, if the width of a pavement is or is greater than 1,8 metres, it classifies as eligible for vertical greening. It does seem that some of the data is somewhat inconsistent. This is because there can be additional obstacles on the pavement that prevent the 1.8 metre free walking space. Based on the data, only 5 of the 14 buildings are adjacent to a pavement that is too narrow.

Plinth accessibility

A lot of the buildings are stores that have an open or even interactive plinth, which hinders the possibility of vertical greening. The restaurants, bars, and café's use the pavement in front of their store as a terrace. This does not completely exclude the possibility of vertical greening but does limit its potential. Some of the buildings are residential, most of them are suitable. One of the residential buildings has doors to storage units in its plinth, which makes it not suitable. The results show the function of the plinth and if it is accessible or not.

Facade composition

The facades of the case study buildings are quite uniform. Almost every building has a traditional Amsterdam style façade. There are a few exceptions. The buildings at the end of the *Spuistraat* (189, 234, 236) are newer, but do resemble the other facades. The only real exception is the building at *Nieuwezijds Voorburgwal* 238, which is an old printing company that is built in another style. This façade is also the only façade that has a lot of difference in depth. Therefore, although it may have less than 75% of window surface, still is listed as unsuitable. Four facades had more than 75% of window surface. This percentage could be adjusted when dealing with typologically different facades.

Suitable facades

Building	Monumental value	Pavement width	Plinth accessibility	Facade composition	Suitable?
Spuistraat 179	State monument	0.9m	Residential: accessible	< 75%	NO
Spuistraat 181	State monument	0.9m	Store: inaccessible	< 75%	NO
Spuistraat 183	State monument	0.9m	Store: inaccessible	> 75%	NO
Spuistraat 185	State monument	0.9m	Store: inaccessible	< 75%	NO
Spuistraat 189	No monument	0.9m	Café / Bar: inaccessible	< 75%	NO
Spuistraat 234	No monument	2.9m	Residential: inaccessible	< 75%	NO
Spuistraat 236	No monument	2.9m	Residential: accessible	< 75%	YES
Nieuwzijds Voorburgwal 228	State monument	2.9m	Café / Bar: inaccessible	< 75%	NO
Nieuwzijds Voorburgwal 230	State monument	2.9m	Residential: accessible	< 75%	NO
Nieuwzijds Voorburgwal 238	State monument	2.9m	Store: inaccessible	> 75%	NO
Nieuwzijds Voorburgwal 270	State monument	1.8m	Residential: accessible	> 75%	NO
Nieuwzijds Voorburgwal 296	State monument	1.8m	Residential: accessible	> 75%	NO
Nieuwzijds Voorburgwal 357	State monument	1.8m	Museum: accessible	< 75%	NO

Table 3: results of suitability analysis

4.3 How?

The selection process in the previous step has led to only one suitable facade. The building is located on the *Spuistraat* 236. The final aspects will be assessed considering this façade.

Figure 23: Most suitable façade

Building	Spuistraat 234
(State of) Façade Material	Well maintained brick
Ground Material	Open
Sunlight / shade	East: Half
Wind / drought	East: Dry
System:	Indirect green façade
Plant Species:	Drought resistant

Table 4: Results of 'How?'

(State of) Facade material

The facade consists of brick separated into columns with wooden window frames in between. The building has been constructed in 1900. The building seems to be maintained properly, no damage in the brick nor wooden parts of the façade can be detected. The façade anchors in the brick columns are small enough for greenery or a support system to pass.

Ground material

There is already some open soil with plants at the base of the façade. This is no guarantee that the soil can be used for climbing plants, but it is unknown how much space is available underground. Without a *klic-melding*, the possibility of soil-based systems is uncertain.

Sunlight and shade

The façade is facing east, and therefore receives sunlight for half a day. There are no additional obstacles near the façade that prevent any sunlight from reaching the façade.

Wind

The data about wind speed is divided into values going from one to eight. Almost the entire centre has a value of two, but the area around the case study building has a value of three. This is still very low and therefore does not exclude any plant species. The façade is orientated towards the east and is therefore listed as dry. This does influence the selection of plant species.

4.4 Proposed green facade

The case study façade is orientated towards the east, which causes the façade to receive three to six hours of sunlight, but also to be a generally dry façade. This amount of sunlight is regular and only excludes a few types of climbing plants, but it does permanently exclude species since this cannot be manually influenced. Only one of the 24 climber plants in the municipal guide is not suited for half-shaded areas. Therefore, there are still 23 different climber species available. The dry orientation of the façade does not definitely exclude species because the species that need more water are able to survive if they receive enough water through manual watering.

Because only one of the facades from the case study area is found to be suitable for vertical greening, the total amount of available surface area is not very high. The façade is about 9.5m wide and 14.5m high. The total surface area of the façade is about 140 m². The windows take up 65 m², the doorway takes up 14,5 m², and about 6 m² for the tiling on the plinth. This leaves 55 m² of available surface area. Which is 39% of the total surface area of the façade. There are some old anchors between the windows, but they are very small and do not prevent climber plants from climbing upwards. They also don't stick out far enough to hinder the application of an indirect green façade. Therefore, they do not form a problem for vertical greening. All the way at the top of the façade, there are some ornaments which are placed at the boundaries of the brick columns. The height of the façade dictates the possibility of using species with or without additional planter boxes along the vertical axis of the façade. Only three species of the available species reach up to 15 meters or higher. This leads to the decision to use one of these three species or use additional planter boxes to be able to cover the entire façade.

The interview with the housing corporation, municipality and residents has shown which certain systems and species are preferred by these stakeholders. To meet stakeholders demands, their preferences should be combined to ensure that all stakeholders are pleased with the outcome of the green façade.

The municipality has stated to prefer as much possible usage of Ivy throughout the city (Appendix 4). This is because this species has a lot of environmentally beneficial properties and can cover entire facades because it is capable to grow up to 30 meters high. Because this is a self-adhesive species, no climbing support would be required if this species is used. The housing corporation, Ymere does not necessarily prefer certain species, but prefer certain outcomes. The aesthetical value improvement, contribution to the liveability and biodiversity are the highest priorities on their list. Therefore, it is important to ensure that the species is evergreen, so that the façade remains green throughout the seasons and that the species has as many biodiversity improvement traits as possible. The only species that are evergreen and possess all three biodiversity traits in the municipal climber plant guide are Ivy and Evergreen Honeysuckle.

The responses of the residents have shown that evergreen species are preferred. The Ivy, Evergreen Honeysuckle, and Firethorn have the most votes of all the available species. But the Honeysuckle is not able to cover the façade without the usage of additional planter boxes along the façade. The same goes for the Firethorn, which reaches even lower heights than the Honeysuckle. Therefore, because of the ability to cover the entire façade on its own, being a preferred evergreen species and having a lot of environmental benefits, Ivy is proposed as the fitting climber plant species for the case study façade. No additional climbing support is required.

5. Discussion & Conclusion

5.1 Discussion

The discussion is separated into four sections: *Where?, Suitability of facades?, How?*, and *Interviews*. For each section, the results, and the impact of the method on the results, are discussed.

Where?

A multi criteria analysis has been performed to indicate where vertical greenery is most needed. Some of the environmental factors used as input are not necessarily most prominent in the centre, but when combined, the centre is shown to be most affected by all the environmental factors combined. But because spatial density, which is highest in the centre, was incorporated in the multi criteria analysis, this was somewhat of an ineluctable outcome. This is also because the spatial density is not a stand-alone aspect but is actually closely linked with all the other aspects used as input. Therefore, the results presented are heavily influenced by spatial density. The multi criteria analysis can also be performed while using only some of the aspects as input, which may lead to other results.

The case study area in this research was one of the highest scoring areas in the multi criteria analysis. The high score of the case study area was mainly based on three aspects, which are heat and water stress and the lack of biodiversity. All these aspects scored maximum, which already causes the area to score 30 of the 50 possible points. These aspects could be weighted lower, which would result in the remaining aspects to become more significant in the case study selection process. In some cases, where a specific aspect is prioritized, this would be a good method to obtain a result that is less influenced by the other aspects.

What also would be interesting is when performing the case study selection process, is to not consider the need for vertical greening, but rather the potential for it. This could be done by using the suitability aspects in the multi criteria analysis and assessing them in an area greater than just the case study area. This would result in a map which shows the suitability of vertical greening in the city, instead of the need for it. Combining this with the map of need for vertical greenery, would result in a map which offers an overview of where vertical greenery is most effective and practical. If both aspects are to be considered, it may be helpful to be able to assess them simultaneously.

Suitability of facades?

As for the previous step, specific choices have been made about which aspects to base the suitability on. Which resulted in a very low number of suitable facades. This number could become higher by tweaking the cut off range of aspects or disregarding certain aspects. The suitability of a façade is also not completely objective. In theory, every façade could be greened, but not every façade is as practical as the other. Therefore, the prioritization of certain aspects is a very significant component to consider. If it is important that a certain façade is vertically greened, aspects regarding its suitability can be disregarded. Required measures could be taken to, although its impracticality, still vertically green a façade. The current suitability assessment also overlooks the financial side of vertical greenery implementation. If it is clear what the stakeholders are trying to achieve by greening facades, the financial aspect could also be incorporated in the suitability assessment.

The low number of suitable facades found in this study was mainly caused by the monumental valuation of the facades. Only considering property of the municipality and housing corporations was also a limitation, but a lot of the private owned property in the centre are monuments as well. This causes the possibilities for vertical greening in the centre of Amsterdam to be little. Permission for any intervention on a monumental façade needs to be requested, and even then, chances are very slim. Any form of anchoring a support system in a monumental façade is currently not allowed. Therefore, if the centre is to be vertically greened on a large scale, the damage done to a façade by anchoring the support systems should be further reduced or the municipal and state regulations on greening the facades of monuments should be adjusted.

How?

Because only one façade had been found as suitable, little information was obtained about how facades in the centre could be greened. The facade results in a singular system and plant species that are concluded as most fitting for that façade. Results of other facades are necessary for comparison. There is no data available about the soil, and the data about the space in the soil costs money to obtain. This results in uncertainty about which system would be most fitting.

Only of the aspects used to determine which plant species are suitable is fixed, which is sunlight. This led to an initial pre-selection of species that can survive with the amount of sunlight that is casted on the façade. Further considerations about which plant species is most suitable are all dependent on what goal the stakeholders are trying to achieve with the vertical greenery and how much time and money they are willing to invest in the vertical greenery. In this study, living walls have been excluded because they are too expensive to install and maintain for the stakeholders. Other stakeholders may be more interested in living walls because they could be willing to invest more. It would be interesting to disregard the financial aspect in this last step and research the possibilities of living walls in the centre of Amsterdam. Because of this exclusion, only green facades, which use climber plants, were eligible for the case study facade. This greatly limited which plant species were possible to use, which leads to a limitation in what goals can be achieved with the vertical greenery.

Interviews

Because multiple stakeholders are present at the case study façade, they have been interviewed about their preferences and which goals they would like to achieve with vertical greenery. Only the interviews with the residents were structured and were held in the form of a survey. Because only three residents responded, it is not properly representative for all the residents. The survey was offered in person and a flyer was put in the mailbox of the people who were not present at the time. This may have led to the residents not engaging with the survey. Reaching out to the housing corporation to ask if they were willing to send the survey to the residents may have got the residents to engage more actively.

The interviews with the municipality and housing corporation were not structured. This caused deviations from the main subject during the interview and an unclear outcome of the interviews. Structured interviews would have led to more concrete answers which would be easier to use as input for the proposed green façade. But, although the interviews were unstructured, preferences about plant species and priorities were obtained. The preference of the municipality for using Ivy shows their environmental motivation (Appendix 5). The priority of the housing corporation was financial, but not by saving on energy costs, but rather by improving the aesthetic value and liveability of the façade and area surrounding it (Appendix 6). Therefore, the municipal preferred Ivy was also appealing for the housing corporation.

Proposed green facade

There is a catch to using Ivy for the case study facade, because the parts in between the brick columns in the façade are made of wood, and are therefore not fit for ivy, a self-adhesive species. Ivy can easily grow into joints in between wooden boards and damage the structure. This reduces the area that is usable with almost 12 square metres, which leaves 43 square metres instead of 55. Despite this reduction of usable area, ivy would remain as the proposed green façade because of its attributes and the stakeholders' preferences regarding it.

5.2 Conclusion

How can data on environmental factors be analysed to find out where vertical greening is most necessary?

Available geo-data on specific environmental factors that represent the need for vertical greenery can be used as input in a spatial multi criteria analysis. To do this, the data must be collected from varying sources and processed in a particular way depending on the format of the data. When the data is combined, specific locations show to be most affected by the environmental factors that can be mitigated by vertical greenery.

How to assess the suitability of facades for vertical greening?

The suitability of facades for vertical greening can be assessed by firstly determining which aspects influence the suitability. Subsequently, a range for every aspect should be created that divides an aspect into suitable or unsuitable. I.e., is the sidewalk wide enough to fit a vertical greenery system? By answering the questions for each aspect, the suitability of a façade for vertical greening can be assessed. This suitability is not absolute, the range used to determine suitability can be adjusted. And if the financial aspect is no burden, measures can be taken to install a type of vertical greenery system although a façade may have been deemed as unsuitable.

How can the right type of VGS and plant species be allocated to a facade?

How the right type of VGS and plant species can be allocated to a façade is harder to answer then the previous questions. This is because what is 'right' is dependent on the situation. The stakeholders of the façade decide what is right for them by stating what they want to achieve with the vertical greenery and how much they are willing to invest in it. Based on that, a fitting system and plant species can be allocated to the situation. This is done by first considering the local conditions of the façade, which leads to a pre-selection of possible plant species that are eligible for usage in a vertical greenery system on the façade. Secondly, the preferences of the stakeholders regarding the attributes of plant species are considered. These preferences are mainly divided into environmental, economic, aesthetical or all off the above. In this study, the combined preferences of multiple stakeholders led to the final selection. To conclude, local conditions determine which types of systems are most suitable and which plant species are eligible for usage. But the stakeholder preferences determine which type of system and plant species is right for their facade.

5.3 Recommendations

In this study, a multi criteria analysis was performed to find out where vertically greenery was most needed. What would improve this analysis is the addition of a green deficit index, which was used in other studies. Mapping the presence of green facades and green walls in the city, or in a specific district would be necessary to develop such an index.

The continuation of this research would be to use the suitability aspects in the multi criteria analysis to find out where vertical greenery is most suitable for application. In this study, the suitability of facades for the installation of vertical greenery has only been assessed in the case study area. Insight about where vertical greenery is most suitable in the centre could contribute to data driven decision making as well.

The monumental value facades in the centre are the main obstacle for the installation of vertical greenery in the centre. This restricted a lot of possibilities in this research. If there are no developments in the amount of damage anchoring an indirect green facade does to a façade or the monumental regulations are adapted, I recommend focussing on post-war constructed buildings in further research about vertical greenery the centre of Amsterdam. The aesthetic quality of those building is in my opinion often secondary to monumental property surrounding it. A green facade is a relatively simple way to improve the appearance of a building.

Areas around the centre, especially the bigger streets with a lot of traffic flow show also to be in need for vertical greenery. If traffic in the centre keeps on getting restricted more and more, these main streets around the centre will only become more polluted. Therefore, it is important to also prioritize these streets when looking for locations to implement vertical greenery.

A lot of climbing plant species are unable to grow as high to cover an entire façade. This leads to a little amount of the façade being covered, or the addition of planter boxes that need to be anchored in the façade. It would be interesting to investigate the possibility of using balconies along the façade to base planter boxes on, instead of anchoring them into the facade.

6. Appendices

Appendix 1. *Input Data Maps*

Urban Heat Stress

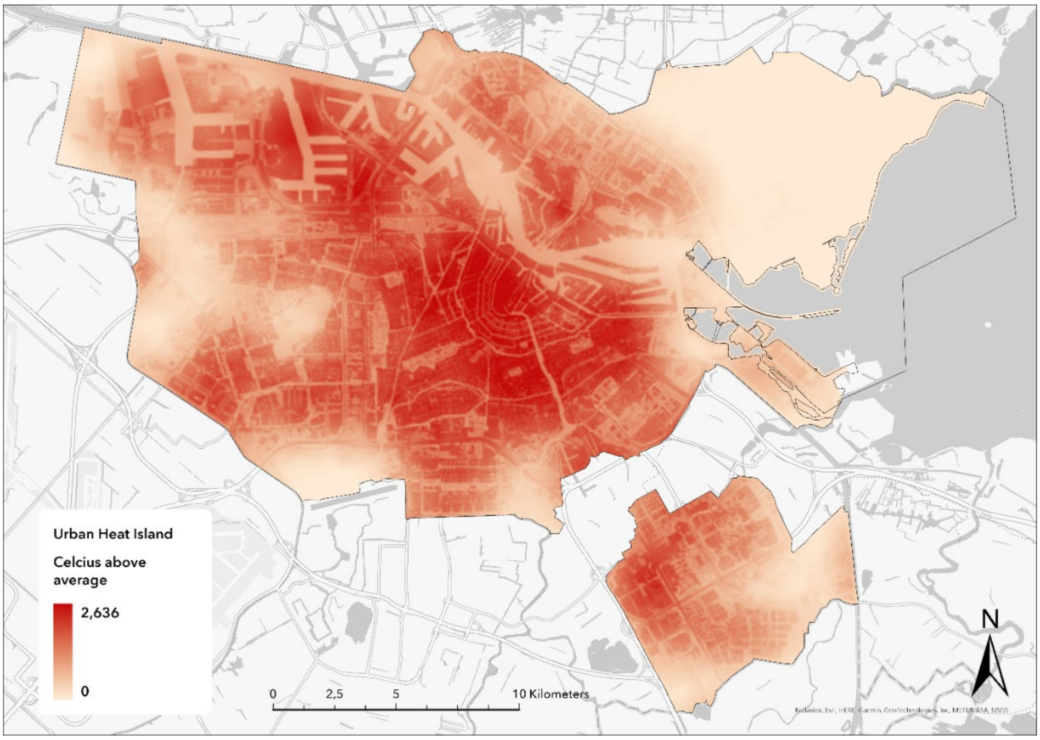


Figure 24: Urban Heat Island Map

Water Stress

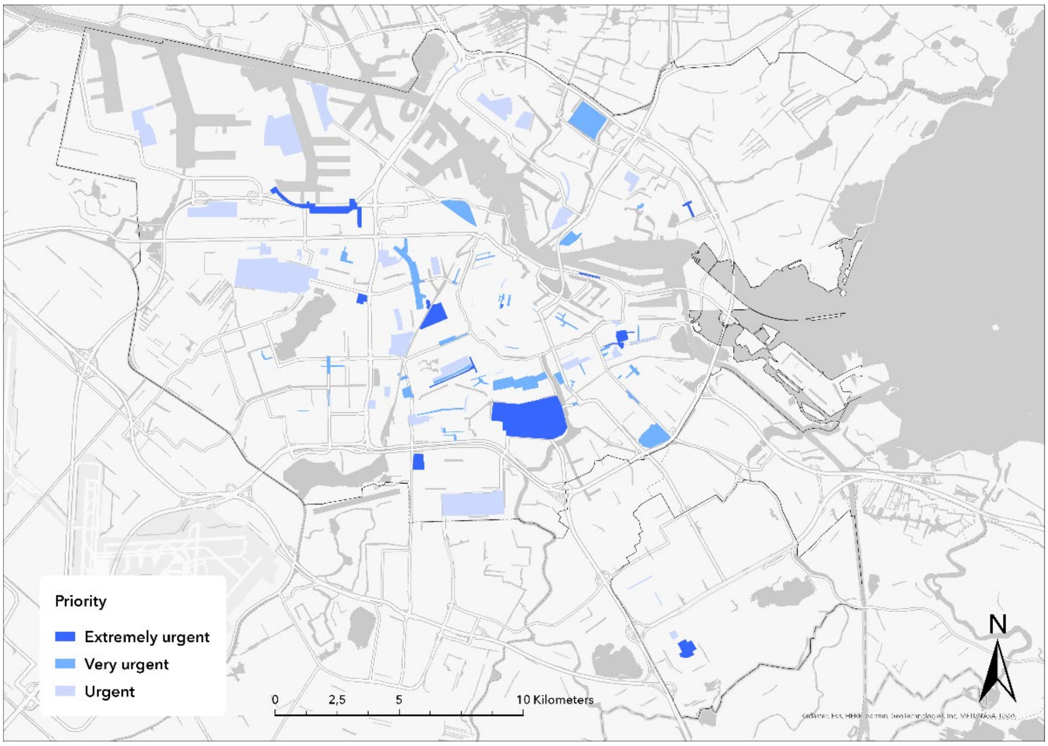


Figure 25: Water Stress Map

Noise Pollution

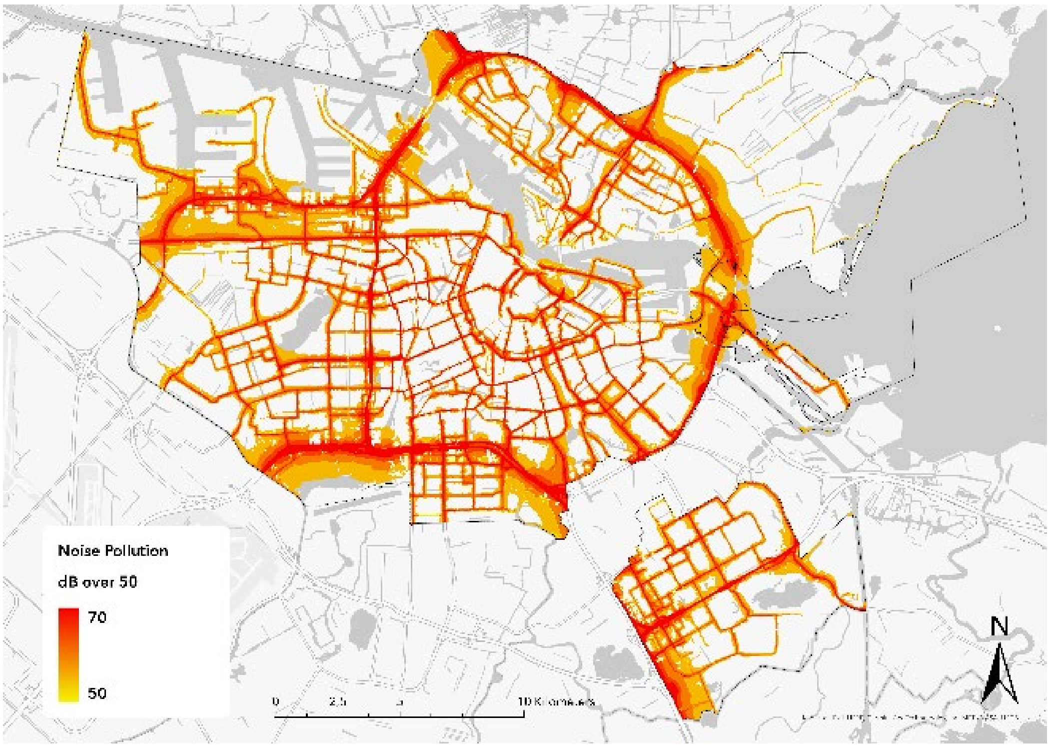


Figure 26: Noise Pollution Map

Traffic Prognosis

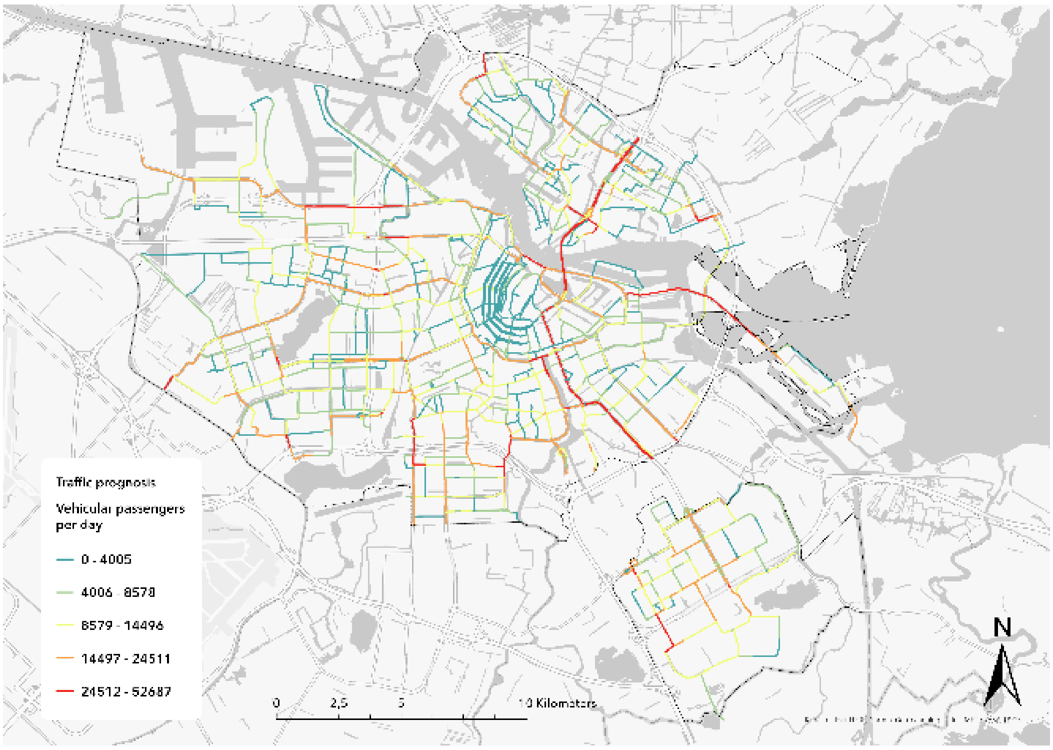


Figure 27: Traffic Prognosis Map

Ground Space Index

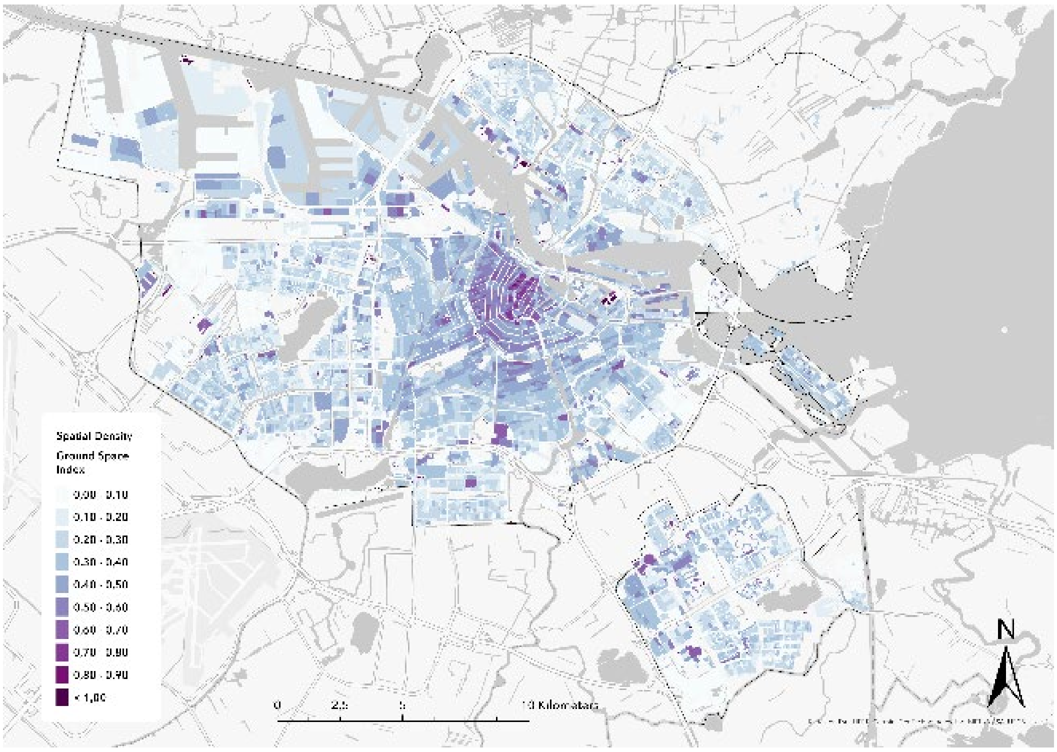


Figure 28: Ground Space Index Map

Floor Space Index

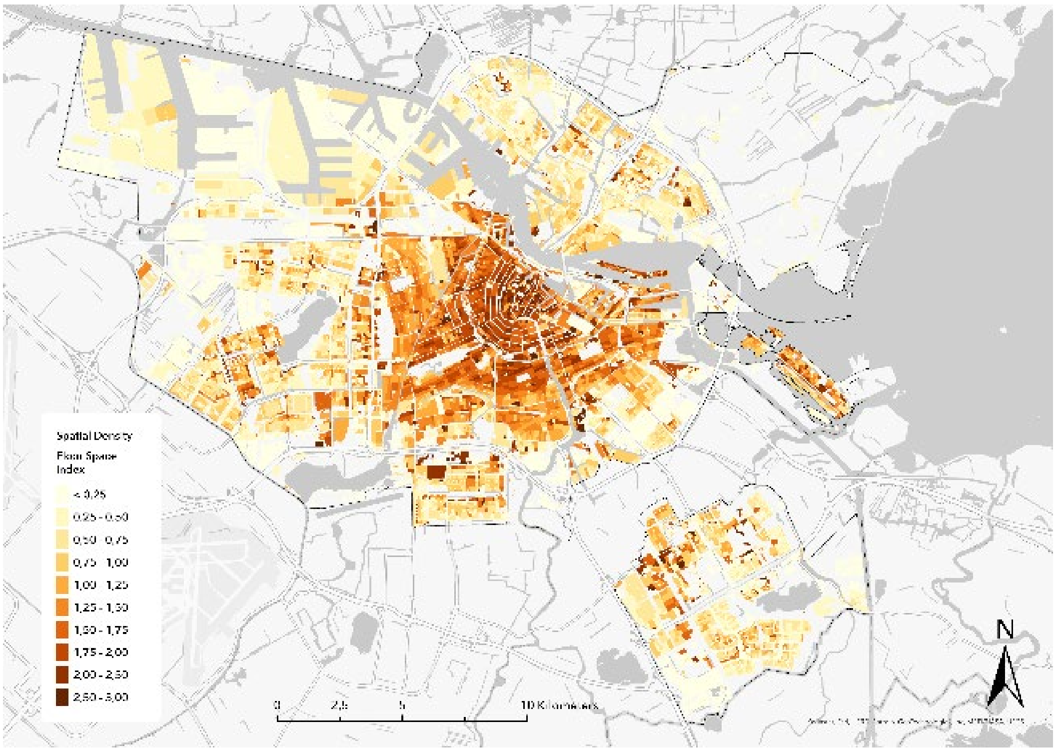
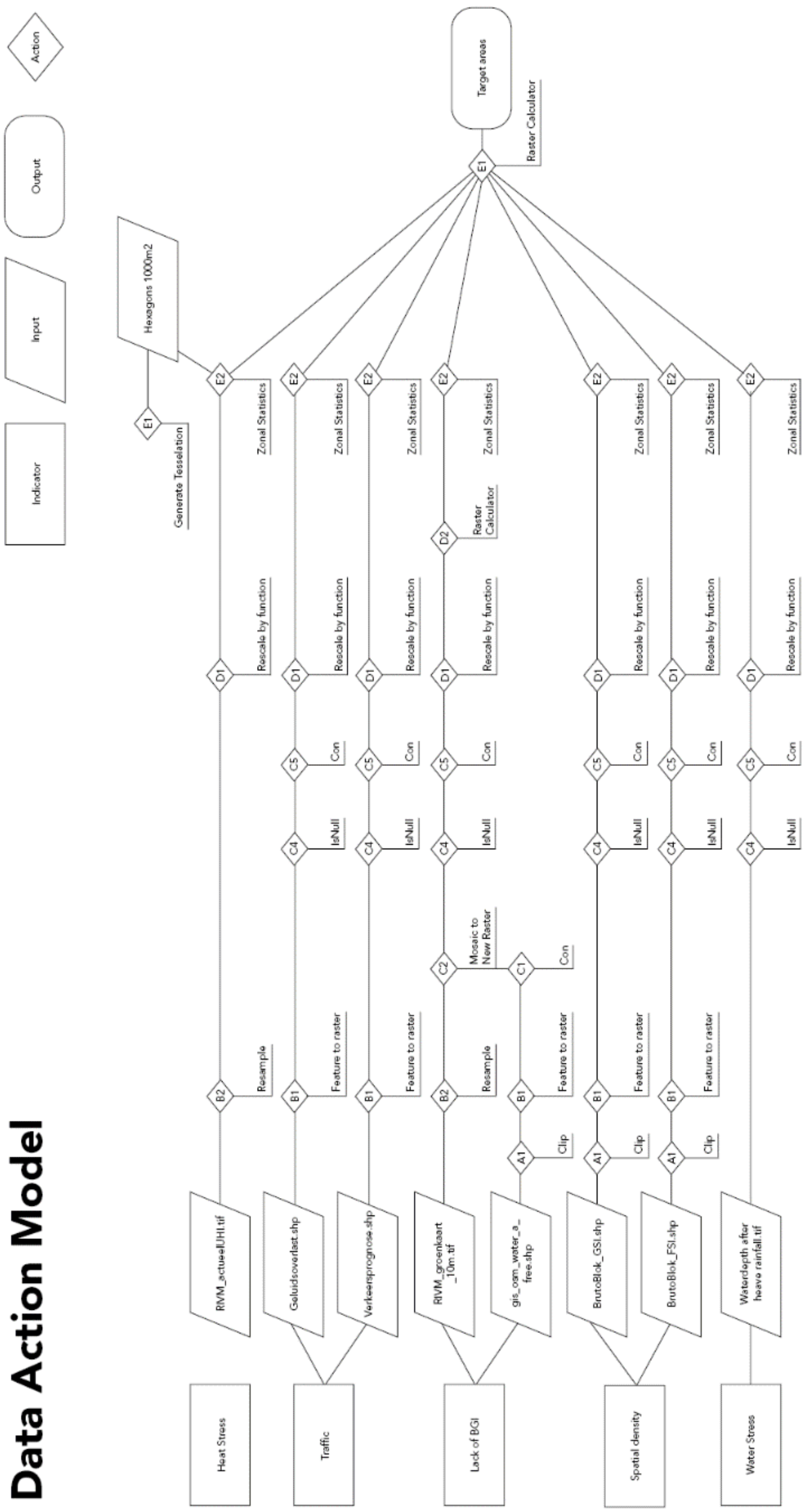


Figure 29: Floor Space Index Map

Appendix 2. Data Action Model



Appendix 3. *Table of available plant species*

Name	*Type*	*Native*	*Ever-green*	*Bio-diverse*	*Height in m*
Lonicera periclymenum	*Twining*	*Yes*	*No*	*I, B, N*	*4-6*
Akebia quinata	*Twining*	*No*	*No*	*I, B*	*5-10*
Humulus lupulus	*Twining*	*Yes*	*No*	*I, N*	*3-4*
Aristolchia marcrophylla/durior	*Twining*	*No*	*No*	*I, N*	*5-10*
Lonicera henryi	*Twining*	*No*	*Yes*	*I, B, N*	*3-5*
Wisteria sinensis 'Prolific'	*Twining*	*No*	*No*	*I, N*	*10-20*
Clematis vitalba	*Tendril*	*Yes*	*No*	*I, B, N*	*3-30*
Clematis armandii	*Tendril*	*No*	*Yes*	*I, N*	*3-5*
Clematis montana	*Tendril*	*No*	*No*	*I, N*	*5-8*
Vitis vinifera	*Tendril*	*No*	*No*	*I, B*	*4-12*
Trachelospermum jasminoides	*Tendril*	*No*	*Yes*	*I*	*3-4*
Actinidia deliciosa	*Scrambling*	*No*	*No*	*I, B*	*8-10*
Pyracantha 'Orange Charme'	*Scrambling*	*No*	*Yes*	*B, N*	*2-4*
Jasminum nudiflorum	*Scrambling*	*No*	*No*	*I, N*	*2-3*
Rosa 'Sympathie'	*Scrambling*	*No*	*No*	*N*	*2-4*
Rosa filipes	*Scrambling*	*No*	*No*	*I, B, N*	*5-10*
Rosa 'Gertrude Jeckyll'	*Scrambling*	*No*	*No*	*N*	*2-5*
Hedera helix	*Clinging*	*Yes*	*Yes*	*I, B, N*	*< 30*
Campsis radicans	*Clinging*	*No*	*No*	*I*	*6-10*
Parthenocissus tricuspidata	*Clinging*	*No*	*No*	*I, B, N*	*10-20*
Hedera algeriensis	*Clinging*	*No*	*Yes*	*I*	*< 4*
Schizophragma hydrangeoides	*Clinging*	*No*	*No*	*I, N*	*< 10*
Hydrangea anomala petiolaris	*Clinging*	*No*	*No*	*I, N*	*< 4*

Table 5: Available plant species edited from the municipality

Case Study Interviews

Three case study interviews are conducted. Two of them are semi-structured, containing open questions and the possibility to ask additional questions. These are the interview with the green expert from the municipality and the housing corporation. The interview with the residents is structured. The interview with the municipality is with Blanca Schwarz, an original urban planner who is currently a green specialist and works on vertical greening projects. This interview has been recorded. The interview with the housing corporation is with Marjan Kootwijk, a green specialist at Ymere. This interview has not been recorded but an email was sent to confirm certain statements made in the interview.

Appendix 4. Survey questions

1.
Q: Do you know what a green façade is?

A: - Yes - No

2.
Q: Are you interested in a green façade?

A: - Yes - No - Maybe

3.
Q: What is most important to you?

A: - Biodiversity & climate - Energy saving - Aesthetic value

4.
Q: Are you willing to contribute to the maintenance of the green façade?

A: - Yes - No - Maybe

5.
Q: Which attributes would you like the green façade to have?

A: - Evergreen - Bird friendly - Insect friendly
- All previous three - Not insect friendly - Doesn't matter

6.
Q: Which of these plant species do you prefer?

A: Depending on the previous answer, plant species that have the preferred attributes are listed. The entire plant species list is shown in the appendix (Table 3).

Appendix 5. Municipal Green Specialist: Blanca Schwarz

Q: What are the municipalities goals regarding vertical greening?

A: In 2020, the green vision was confirmed and published, and in it a motion was passed saying that much more vertical greening should be implemented in the city. The municipality is looking at their own real-estate, focusing on climbing plants because it must be sustainable in the long run.

Q: How does the municipality work with monumental facades?

A: Monumental care should be consulted about the possibilities of vertical greenery implementation. Monumental tiles in the sidewalk are a main obstacle to consider because it is not permitted to do anything to them. But monuments have the option to be greened, only proper consultation and requesting permission is required. Therefore, monuments should not be eliminated from the selection process only due to their monumental value. This opens a lot of options in the center of Amsterdam.

Q: How do you decide which climber plant is most suitable for a façade?

A: A climber plants guide is developed by the municipality to make this decision a lot more comprehensible. Monumental care was also consulted to ensure that the species selection considered the damage to a façade that can be done. A well-maintained façade is still required for self-adhesive species. The municipality prefers hedera helix (Ivy) in the entire city, because it is evergreen and native, but the species is self-adhesive which makes it almost always not applicable on older and monumental buildings. But there are very few other native climber species, and none of them possess all the other attributes that Hedera Helix does have.

Q: How do you decide which climbing support is most suitable for a façade?

A: Deciding which type of climbing support should be discussed with the architect and welfare committee. If the architect is deceased, any bureau connected with the original architect should be contacted. But relatively small greenery applications do not necessarily require permission. The height of the façade should be carefully considered. This influences the type of maintenance is possible. It is most practical to combine this maintenance with other maintenance that must be performed either way.

Appendix 6. Ymere Green Specialist: Marjan Kootwijk

Q: What makes vertical greening interesting for Ymere?

A: The most important reason to implement vertical greenery on our property is to improve the appearance of the complex and the liveability of the neighborhood. Next to that, the contribution that vertical greenery makes to biodiversity is also important. It also overlaps with the municipality imposing on the housing corporations that they should build nature inclusive, and vertical greening is one of the ways to do that.

Q: What about the energy saving potential of vertical greenery?

A: This is very interesting for Ymere but is not a viable option currently. Ymere works with 'climate-labels' that are given to their property and indicate how sustainable the building is. If some buildings have a very low climate label, measures such as vertical greenery systems that can save energy become more interesting. In the future it will probably become a way to save on energy cost but not at this moment.

Q: What makes vertical greening unappealing for Ymere?

A: The main disadvantage is that it is inconvenient for maintenance. You can't reach the facade as easily and you must consider the flora and fauna law. The maintenance of the greenery itself is also sometimes budgetary, especially if you must use an aerial platform to do the maintenance.

Q: Are there any other obstacles to vertical greening for Ymere?

A: It can be that some residents do not want a vertically greened façade. This can be due to the maintenance that might be required of them, or the increased number of insects that will reside in and near the façade. A contribution to or responsibility for the maintenance could be asked from the residents but this has not shown to be a method which ensures proper maintenance of a green façade. Secondly, not all the property is owned by Ymere. Some buildings are only maintained by Ymere. Therefore, Ymere is not able to install green facades on those buildings.

Q: Does Ymere see vertical greening with climber plants as a viable greening method?

Yes but, implementing vertical green is currently not a main priority for Ymere. This is because it does not only create benefits, but also hinders the mandatory maintenance their facades require. To conclude, Ymere currently sees vertical green as an interesting option for improving the aesthetical value of their property and neighbourhood and to increase biodiversity. Saving costs on energy prices with vertical greenery systems is not an advantage that is currently considered but will be interesting in the future. If it is clear how much this would cost, how long it will take to earn the invested money back, and how much money could be saved, Ymere would reconsider the possibility of installing other types of vertical greenery systems.

Appendix 7. Residents

The survey was conducted in person but was also made possible to fill in online. I was able to speak to two residents in person, the other respondents filled the survey in online. The results of the responses show that everyone answers yes on the two first questions. So, they know what a green façade is and are interested in one. The third question is split, each respondent has chosen one of the three options. So, they all think something else is most important about a green façade. All respondents answered 'yes' on the fourth question. One of the respondents was a woman who already takes care of the current façade garden, the contributed maintenance of the two other respondents would be additional. In the fifth question, two of the respondents said to prefer evergreen species, and one of the respondents was fine with every type of climber plant. Therefore, two of the respondents were able to pick evergreen species, and the other respondent could pick any type of climber plant preferred. One of the respondents that preferred evergreen species chose all species available. The other preferred the Ivy, Evergreen Honeysuckle, and the Firethorn. The respondent that did not prefer any specific attributes chose the Wild Honeysuckle, Chinese Wisteria, and Star Jasmine. The low number of responses has led to no outliers. Based on these responses, the three evergreen species that have been voted for twice are most popular. Therefore, one of these species will be the proposed species to use in the green façade.

8. Bibliography

Ahern, J. (2013). Urban landscape sustainability and resilience: The promise and challenges of integrating ecology with urban planning and design. *Landscape Ecology*, *28*(6), 1203–1212. https://doi.org/10.1007/s10980-012-9799-z

Ahsan, M. M., Cheng, W., Hussain, A. B., Chen, X., & Wajid, B. A. (2022). Knowledge mapping of research progress in vertical greenery systems (VGS) from 2000 to 2021 using CiteSpace based scientometric analysis. *Energy and Buildings*, *256*, 111768. https://doi.org/10.1016/j.enbuild.2021.111768

ArcGIS Pro. (2007). *Why hexagons - Documentation*.

Arroyo Ohori, K., Ledoux, H., & Peters, R. (2022). *3D modelling of the built environment*.

Aterlier GROENBLAUW. (2020). *Bouw groen en blauw*. https://www.rainproof.nl/sites/default/files/downloads/bouw_groen_en_blauw.pdf

Azkorra, Z., Pérez, G., Coma, J., Cabeza, L. F., Bures, S., Álvaro, J. E., Erkoreka, A., & Urrestarazu, M. (2015). Evaluation of green walls as a passive acoustic insulation system for buildings. *Applied Acoustics*, *89*, 46–56. https://doi.org/10.1016/j.apacoust.2014.09.010

Başdoğan, G., & Çiğ, A. (2016). Ecological-social-economical impacts of vertical gardens in the sustainable city model | Sürdürülebilir kent modelinde dikey bahçelerin ekolojik-sosyal-ekonomik etkileri. *Yuzuncu Yil University Journal of Agricultural Sciences*, *26*(3), 430–438.

Bhatia, R. (2014). Noise Pollution: Managing the Challenge of Urban Sounds — Earth Journalism Network. In *20 May*. http://earthjournalism.net/resources/noise-pollution-managing-the-challenge-of-urban-sounds

Burke, G. L. (1966). *Greenheart metropolis: Planning the Western Netherlands*. Macmillan.

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

Čekić, S., Trkulja, T., & Došenović, L. (2020). Typology of vertical greenery system. *Gradjevinar*, *72*(11), 1011–1019. https://doi.org/10.14256/JCE.2721.2019

Croeser, T. (2016). Biological potential in cities: An estimate from Melbourne. *Urban Forestry and Urban Greening*, *16*, 84–94. https://doi.org/10.1016/j.ufug.2016.01.012

Cunningham, W. P., & Cunningham, M. (2017). Evolution, species interactions and biological communities. *Principles of Environmental Science*.

Curtis, A. J., Helmig, D., Baroch, C., Daly, R., & Davis, S. (2014). Biogenic volatile organic compound emissions from nine tree species used in an urban tree-planting program. *Atmospheric Environment*, *95*, 634–643. https://doi.org/10.1016/j.atmosenv.2014.06.035

Dahanayake, K., & Chow, N. (2015). Electric vehicle role in PV self-consumption optimisation. In *Proceedings of the 14th International Conference on Sustainable Energy Technologies – SET 2015 25th to 27th August 2015, Nottingham UK: Vol. III* (Issue August).

Demuzere, M., Orru, K., Heidrich, O., Olazabal, E., Geneletti, D., Orru, H., Bhave, A. G., Mittal, N., Feliu, E., & Faehnle, M. (2014). Mitigating and adapting to climate change: Multi-functional and multi-scale assessment of green urban infrastructure. *Journal of Environmental Management*, *146*(August), 107–115. https://doi.org/10.1016/j.jenvman.2014.07.025

Douglas, A. N. J., Morgan, A. L., Rogers, E. I. E., Irga, P. J., & Torpy, F. R. (2021). Evaluating and comparing the green wall retrofit suitability across major Australian cities. *Journal of Environmental Management*, *298*(March), 113417. https://doi.org/10.1016/j.jenvman.2021.113417

Escobedo, F. J., & Nowak, D. J. (2009). Spatial heterogeneity and air pollution removal by an urban forest. *Landscape and Urban Planning*, *90*(3–4), 102–110. https://doi.org/10.1016/j.landurbplan.2008.10.021

Feitosa, R., & Wilkinson, S. J. (2018). Attenuating heat stress through green roof and green wall retrofit. *Building and Environment*, *140*, 11–22. https://doi.org/10.1016/j.buildenv.2018.05.034

Fernández-Cañero, R., Pérez Urrestarazu, L., & Perini, K. (2018). Vertical greening systems: Classifications, plant species, substrates. *Nature Based Strategies for Urban and Building Sustainability*, 45–54. https://doi.org/10.1016/B978-0-12-812150-4.00004-5

Foster, K. P. (2004). *The Hanging Gardens of Nineveh Author (s): Karen Polinger Foster Source : Iraq , 2004 , Vol . 66 , Nineveh . Papers of the 49th Rencontre Assyriologique Internationale , Part One (2004), pp . 207-220 Published by : British Institute for the Study of I*. *66*(May 2021), 207–220.

Frey, H. W. (2000). Not green belts but green wedges: The precarious relationship between city and country. *Urban Design International*, *5*, 13–25. https://doi.org/10.1057/palgrave/udi/9000003

Fuller, R. A., & Gaston, K. J. (2009). The scaling of green space coverage in European cities. *Biology Letters*, *5*(3), 352–355. https://doi.org/10.1098/rsbl.2009.0010

Gantar, D., Kozamernik, J., Erjavec, I. Š., & Koblar, S. (2022). *From Intention to Implementation of Vertical Green : The Case of Ljubljana*.

Garbisu, C., Hernández-Allica, J., Barrutia, O., Alkorta, I., & Becerril, J. M. (2002). Phytoremediation: a technology using green plants to remove contaminants from polluted areas. *Reviews on Environmental Health*, *17*(3), 173–188. https://doi.org/10.1515/reveh.2002.17.3.173

Gemeente Amsterdam. (2020a). *Amsterdam maakt ruimte voor de voetgange, inspraakversie beleidskader*.

Gemeente Amsterdam. (2020b). *Groenvisie*.

Haaland, C., & van den Bosch, C. K. (2015). Challenges and strategies for urban green-space planning in cities undergoing densification: A review. *Urban Forestry and Urban Greening*, *14*(4), 760–771. https://doi.org/10.1016/j.ufug.2015.07.009

Hachoumi, I., Pucher, B., De Vito-Francesco, E., Prenner, F., Ertl, T., Langergraber, G., Fürhacker, M., & Allabashi, R. (2021). Impact of green roofs and vertical greenery systems on surface runoff quality. *Water (Switzerland)*, *13*(19). https://doi.org/10.3390/w13192609

Hindle, R. L. (2012). A vertical garden: Origins of the Vegetation-Bearing Architectonic Structure and System (1938). *Studies in the History of Gardens and Designed Landscapes*, *32*(2), 99–110. https://doi.org/10.1080/14601176.2011.653535

Irga, P. J., Burchett, M. D., & Torpy, F. R. (2015). Does urban forestry have a quantitative effect on ambient air quality in an urban environment? *Atmospheric Environment*, *120*, 173–181. https://doi.org/10.1016/j.atmosenv.2015.08.050

Ismail, M. R. (2010). *The effect of building density and size on the propagation of sound through the* *urban fabric.* JAUES.

Jim, C. Y., & Chen, W. Y. (2008). Assessing the ecosystem service of air pollutant removal by urban trees in Guangzhou (China). *Journal of Environmental Management*, *88*(4), 665–676. https://doi.org/10.1016/j.jenvman.2007.03.035

Jongman, R. H. G., Külvik, M., & Kristiansen, I. (2004). European ecological networks and greenways. *Landscape and Urban Planning*, *68*(2), 305–319. https://doi.org/https://doi.org/10.1016/S0169-2046(03)00163-4

Katz, P. (1994). *The new urbanism: Toward an architecture ofcommunity.*

Koch, K., Ysebaert, T., Denys, S., & Samson, R. (2020). Urban heat stress mitigation potential of green walls: A review. *Urban Forestry and Urban Greening*, *55*(July), 126843. https://doi.org/10.1016/j.ufug.2020.126843

Köhler, M. (2008). Green facades-a view back and some visions. *Urban Ecosystems*, *11*(4), 423–436. https://doi.org/10.1007/s11252-008-0063-x

Lin, B., Meyers, J., & Barnett, G. (2015). Understanding the potential loss and inequities of green space distribution with urban densification. *Urban Forestry and Urban Greening*, *14*(4), 952–958. https://doi.org/10.1016/j.ufug.2015.09.003

Ling, T. Y., Hung, W. K., Lin, C. T., & Lu, M. (2020). Dealing with green gentrification and vertical green-related urban well-being: A contextual-based design framework. *Sustainability (Switzerland)*, *12*(23), 1–24. https://doi.org/10.3390/su122310020

Lundegren, M. (2016). *Green Walls Vs. Green Facades*. https://archanatura.com/2016/02/01/green-walls-versus-green-facades/

Madre, F., Clergeau, P., Machon, N., & Vergnes, A. (2015). Building biodiversity: Vegetated façades as habitats for spider and beetle assemblages. *Global Ecology and Conservation*, *3*, 222–233. https://doi.org/10.1016/j.gecco.2014.11.016

Madureira, H., & Monteiro, A. (2021). Going green and going dense: A systematic review of compatibilities and conflicts in urban research. *Sustainability (Switzerland)*, *13*(19), 1–20. https://doi.org/10.3390/su131910643

Mayer, H. (1999). Mayer: Cities. *Atmospheric Environment*, *33*(24), 4029–4037.

Mayrand, F., & Clergeau, P. (2018). Green roofs and greenwalls for biodiversity conservation: A contribution to urban connectivity? *Sustainability (Switzerland)*, *10*(4). https://doi.org/10.3390/su10040985

Morancho, A. B. (2003). A hedonic valuation of urban green areas. *Landscape and Urban Planning*, *66*(1), 35–41. https://doi.org/10.1016/S0169-2046(03)00093-8

Mumm, O., Zeringue, R., Dong, N., & Carlow, V. M. (2022). Green Densities: Accessible Green Spaces in Highly Dense Urban Regions—A Comparison of Berlin and Qingdao. *Sustainability (Switzerland)*, *14*(3). https://doi.org/10.3390/su14031690

Neuman, M. (2005). The compact city fallacy. *Journal of Planning Education and Research*, *25*(1), 11–26. https://doi.org/10.1177/0739456X04270466

Nicholls, S., & Crompton, J. L. (2005). The impact of greenways on property values: Evidence from Austin, Texas. *Journal of Leisure Research*, *37*(3), 321–341. https://doi.org/10.1080/00222216.2005.11950056

Nul20. (2022). *Woningvoorraad Amsterdam | NUL20*. https://www.nul20.nl/dossiers/dashboard-amsterdam-woningvoorraad

Opstal, C. Van. (2022). *A GIS-based MCDM method for the selection and allocation of Blue-Green Infrastructure*.

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

Ottelé, M., van Bohemen, H. D., & Fraaij, A. L. A. (2010). Quantifying the deposition of particulate matter on climber vegetation on living walls. *Ecological Engineering*, *36*(2), 154–162. https://doi.org/10.1016/j.ecoleng.2009.02.007

Parhizkar, H., Khoraskani, R. A., & Tahbaz, M. (2017). Green facade system for indoor air purification Green façade system for indoor air purification. *In 12th Conference on Advanced Building Skins. Bern: Advanced Building Skins GmbH*, *June*, 1151–1160. https://www.researchgate.net/profile/Roham-Afghani-Khoraskani/publication/325472626_Green_facade_system_for_indoor_air_purification/links/5b265e51458515270fd54636/Green-facade-system-for-indoor-air-purification.pdf

Pérez, G., Rincón, L., Vila, A., González, J. M., & Cabeza, L. F. (2011). Green vertical systems for buildings as passive systems for energy savings. *Applied Energy*, *88*(12), 4854–4859. https://doi.org/10.1016/j.apenergy.2011.06.032

Perini, K., Ottelé, M., Fraaij, A. L. A., Haas, E. M., & Raiteri, R. (2011). Vertical greening systems and the effect on air flow and temperature on the building envelope. *Building and Environment*, *46*(11), 2287–2294. https://doi.org/10.1016/j.buildenv.2011.05.009

Pungetti, G. (2004). *Ecological Networks and Greenways: Concept, Design, Implementation*. https://doi.org/10.1017/CBO9780511606762

Rajak, M. K., Kumar, R., & Biswas, R. (2022). Vertical Greenery Systems: a comprehensive review. *ICRRD Quality Index Research Journal*, *3*(3), 117–135. https://doi.org/10.53272/icrrd.v3i3.3

Rakhshandehroo, M., Mohd Yusof, M. J., Arabi, R., & Jahandarfard, R. (2016). Strategies to improve sustainability in urban landscape, literature review. *Journal of Landscape Ecology(Czech Republic)*, *9*(3), 5–13. https://doi.org/10.1515/jlecol-2016-0011

Reade, J. (British I. for the S. of I. S. (2009). Alexander the Great and the Hanging Gardens of Babylon. *British Institute for the Study of Iraq*, *62*(2000), 195–217.

Roehr, D., Laurenz, J., & Kong, Y. (2009). Green envelopes: Contribution of green roofs, green facades, and green streets to reducing stormwater runoff, CO2 emissions, and energy demand in cities. *Low Impact Development for Urban Ecosystem and Habitat Protection*, *May 2018*. https://doi.org/10.1061/41009(333)13

Schettini, E., Blanco, I., Campiotti, C. A., Bibbiani, C., Fantozzi, F., & Vox, G. (2016). Green Control of Microclimate in Buildings. *Agriculture and Agricultural Science Procedia*, *8*, 576–582. https://doi.org/10.1016/j.aaspro.2016.02.078

Scott, A. J., & Storper, M. (2015). The nature of cities: The scope and limits of urban theory. *International Journal of Urban and Regional Research*, *39*(1), 1–15. https://doi.org/10.1111/1468-2427.12134

Shanahan, D. F., Miller, C., Possingham, H. P., & Fuller, R. A. (2011). The influence of patch area and connectivity on avian communities in urban revegetation. *Biological Conservation*, *144*(2), 722–

729. https://doi.org/10.1016/j.biocon.2010.10.014

Sheweka, S., & Magdy, N. (2011). The living walls as an approach for a healthy urban environment. *Energy Procedia*, *6*(December), 592–599. https://doi.org/10.1016/j.egypro.2011.05.068

Shi, J., Zhang, G., An, H., Yin, W., & Xia, X. (2017). Quantifying the particulate matter accumulation on leaf surfaces of urban plants in Beijing, China. *Atmospheric Pollution Research*, *8*(5), 836–842. https://doi.org/10.1016/j.apr.2017.01.011

Spacey, J. (2019). *Green Walls vs Green Facades - Simplicable*. https://simplicable.com/new/green-walls-vs-green-facades

Stangl, R., Minixhofer, P., Hoerbinger, S., & Kermer, L. (2019). The Potential of Greenable Area in the Urban Building Stock. *IOP Conference Series: Earth and Environmental Science*, *323*(1). https://doi.org/10.1088/1755-1315/323/1/012080

Tang, V. T., Rene, E. R., Hu, L., Behera, S. K., Phong, N. T., & Thi Da, C. (2021). Vertical green walls for noise and temperature reduction–An experimental investigation. *Science and Technology for the Built Environment*, *27*(6), 806–818. https://doi.org/10.1080/23744731.2021.1911154

Tassicker, N., Rahnamayiezekavat, P., & Sutrisna, M. (2016). An insight into the commercial viability of green roofs in Australia. *Sustainability (Switzerland)*, *8*(7), 1–25. https://doi.org/10.3390/su8070603

Tavares, R., Calmet, I., & Dupont, S. (2015). Modelling the impact of green infrastructures on local microclimate within an idealized homogeneous urban canopy. *ICUC9 - 9th International Conference on Urban Climate Jointly with 12th Symposium on the Urban Environment Modelling*, 1–6.

Tian, Y., Jim, C. Y., & Tao, Y. (2012). Challenges and Strategies for Greening the Compact City of Hong Kong. *Journal of Urban Planning and Development*, *138*(2), 101–109. https://doi.org/10.1061/(asce)up.1943-5444.0000076

Van den Biesen, J. (2018). *Participating in Vertical Gardens : A stakeholder analysis on the implementation of vertical gardens in the urban environment*.

Verhorst, D. (2019). *Governing Vertical Greenery*. Wageningen University Research.

Wang, C., Ren, Z., Dong, Y., Zhang, P., Guo, Y., Wang, W., & Bao, G. (2022). Efficient cooling of cities at global scale using urban green space to mitigate urban heat island effects in different climatic regions. *Urban Forestry and Urban Greening*, *74*(April), 127635. https://doi.org/10.1016/j.ufug.2022.127635

Wang, X., Gard, W., Borska, H., Ursem, B., & van de Kuilen, J. W. G. (2020). Vertical greenery systems: from plants to trees with self-growing interconnections. *European Journal of Wood and Wood Products*, *78*(5), 1031–1043. https://doi.org/10.1007/s00107-020-01583-0

Wolfram, M., van der Heijden, J., Juhola, S., & Patterson, J. (2019). Learning in urban climate governance: concepts, key issues and challenges. *Journal of Environmental Policy and Planning*, *21*(1), 1–15. https://doi.org/10.1080/1523908X.2018.1558848

Wong, N. H., Tan, A. Y. K., Tan, P. Y., Sia, A., & Wong, N. C. (2010). Perception Studies of Vertical Greenery Systems in Singapore. *Journal of Urban Planning and Development*, *136*(4), 330–338. https://doi.org/10.1061/(asce)up.1943-5444.0000034

Yang, J., Rong, H., Kang, Y., Zhang, F., & Chegut, A. (2021). The financial impact of street-level greenery on New York commercial buildings. *Landscape and Urban Planning*, *214*(October 2020), 104162. https://doi.org/10.1016/j.landurbplan.2021.104162

Zupancic, T. (2015). *The impact of green space on heat and air pollution in urban communities : A meta-narrative systematic review*. *March*.